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A Company-led Methodology for the Specification of Product Design Capabilities in Small and Medium Sized Electronics Companies

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Abstract

It is the aim of the research reported in this thesis to improve the product design effectiveness of small and medium sized electronics companies in the United Kingdom. It does so by presenting a methodology for use by such firms which will enable them to specify product design capabilities which are resilient to changes in their respective business environments. The research has not, however, concerned itself with the details of particular electronics component technologies or with the advantages of various CAD or CAE products, although these are both important aspects of any design capability. Nor is it concerned with the *implementation* of the product design capability. The methodology, which represents a significant improvement on current practice, is a structured, company-driven approach which draws extensively upon the lessons of international design best practice. It uses well-proven tools and techniques to guide firms through the entire process of creating such capabilities - from the development of an appropriate Mission Statement to the identification of cost effective and appropriate design system solutions which can readily be translated into action plans for improvement. The work emphasises the importance of adopting a holistic, systems approach which acknowledges the interrelationship between the management of the design process, as well as its operational and supporting activities.

The research has been structured around the experiences of companies which have implemented electronics design systems and which "own" the problem in question. Hence, a research strategy was adopted which was based upon a case study approach and upon the development of close collaborative links with two leading design automation tool vendor companies. Case study interviews were undertaken in 18 U.K. and European electronics companies and in 11 U.S., Japanese and Korean electronics firms. The work proceeded in two distinct phases. Firstly, the author participated with other researchers to jointly develop a functional specification of an electronics designers' toolset to support the process of product design in an integrated manufacturing environment. The first phase provided the context for Phase 2, the development of the *AGILITY* methodology for specifying product design capabilities which represents the author's individual contribution.

The contribution to knowledge made by the research lies in the creation of a process methodology which, for the first time, will help U.K. electronics companies to define *for themselves* product design capabilities which are robust and which support their wider business objectives. No such methodology is currently available in a form which is both accessible and affordable to smaller firms. Furthermore, the author has uncovered no evidence of the existence of such a methodology even for use by *large* electronics firms. Validation of the methodology is subject to an ongoing process of feedback.

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Acknowledgements

I dedicate this thesis to the memory of my parents, George and Joanna.

> *"They that wait upon the Lord shall renew their strength; they shall mount up with wings as eagles; they shall run and not be weary; and they shall walk and not faint." (ISIAH XL. 31.)*

I also dedicate this work to my wife Emiko and to my children Naomi, Chiori, Stefan and Ciaran. Without their love and support I could not have endured the pain or found the strength to soldier on.

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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.

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Relevant electronics design and manufacturing conferences were attended at which a number of papers were presented. The conferences included:

- The Concurrent Engineering/Design Automation Conference, Bournemouth, 1991
- Eighth International Conference on CAD/CAM, Robotics and Factories of the Future, Metz, France, 1992
- International Conference on Factory 2000, York, 1992
- Seventh International Conference of the UK Operations Management Association, Manchester, 1992
- First International Conference of the European Operations Management Association, Cambridge, 1994
- Second Technology Transfer and Innovation Conference, London, 1994

The following publications were produced from the research:

Culverhouse P.F. and Bennett J.P., Specification of a Designers' Toolbox for Electronics Design, *Proceedings of the International Conference on Concurrent Engineering and Design Automation (CEEDA'91)*, Bournemouth, UK, pp 60 - 67, 1991

Bennett J.P.H., Culverhouse P.F. and Hughes D.R., World Class Performance by Design, *Seventh International Conference of the Operations Management Association, International Operations -- Crossing Borders in Manufacturing and Service*, UMIST, Manchester, UK, June 23/24, 1992

Bennett J.P., Culverhouse P.F. and Hughes D.R., Electronics Product Design Best Practice – An International Perspective, *Third International Conference on Factory 2000*, University of York, UK, 27 – 29 July 1992

Culverhouse P.F., Bennett J.P. and Hughes D.R., Electronics Product Development Practice – East versus West, *8th International Conference on CAD/CAM, Robotics and Factories of the Future*, Metz, France, August 17 - 19 1992

Bennett J.P. and Culverhouse P.F., Reusing Company Knowledge and "Wisdom" to Improve the Electronics Design Process, *First International Conference of the European Operations Management Association*, Cambridge, UK, June 26 – 28, 1994

Bennett J.P., Childe S.J. and Hughes D.R., Improved Electronics Product Innovation through the Creation of Flexible Design Capabilities, *Second International Technology Transfer and Innovation Conference*, London, July 18 – 20, 1994

Signed ______________________

Date 3/4/95

Glossary of Acronyms

ACME	Application of Computers to Manufacturing Engineering
ANSI	American National Standards Institution
ASIC	Application-specific Integrated Circuit
AMT	Advanced Manufacturing Technology
BSI	British Standards Institution
CAD	Computer-Aided Design
CAE	Computer-Aided Engineering
CAM	Computer-Aided Manufacturing
CAPM	Computer-Aided Production Management
CE	Concurrent Engineering
CI	Continuous Improvement
CIM	Computer Integrated Manufacturing
CIM-OSA	Computer Integrated Manufacturing - Open Systems Architecture
CRS	Commercial Requirements Specification
CSCW	Computer Supported Cooperative Work
DFD	Design for Disposal
DFMA	Design for Manufacture and Assembly
DFT	Design for Test
EDA	Electronics Design Automation
EDT	Electronics Designers' Toolbox (project)
Email	Electronic mail
HDTV	High Definition Television
HRM	Human Resource Management

IC	Integrated circuit
ICAM	Integrated Computer Aided Manufacturing
IDEF	*I*CAM *Def*inition Method
IGES	Initial Graphical Exchange Specification
ITT	Invitation to Tender
IS	Information Systems
ISO	International Standards Organisation
JIT	Just-in-time
KAIZEN	Process of continuous improvement (Japanese)
LSI	Large Scale Integration
MPS	Master Production Schedule
MRPII	Manufacturing resource planning
OJT	On the job training
OSI	Open Systems Interconnection
PCB	Printed circuit board
QA	Quality Assurance
QFD	Quality Function Deployment
SERC	Science and Engineering Research Council
SME	Small and Medium Sized Enterprise
TQM	Total Quality Management
VLSI	Very Large Scale Integration
VTR	Video Tape Recorder

Chapter 1.

Overview of the Thesis

The work reported in this thesis was carried out as part of the Electronics Designers' Toolbox (EDT) Project, a 3 year research initiative funded as Grant GR/E83924 by the ACME Directorate of the Science and Engineering Research Council (SERC). The overall aim of the research was to improve the product design-to-manufacture capabilities of small and medium size[1] UK electronics companies.

To place this work in perspective, the objectives of the EDT Project will be outlined, together with the author's contribution to that project. The aims and scope of this thesis will then be described. The chapter continues by discussing a number of key issues and problems of relevance to the creation of product design capabilities and it concludes by presenting the work's contribution to knowledge.

1.1. The author's contribution to the EDT project

The overall aim of the research was to functionally specify a "Designers' Toolbox" to support the process of electronics product design in an integrated manufacturing environment. By addressing many of the shortcomings of current generation electronics design automation (EDA) toolsets, the project sought to provide SME users of computer-aided design (CAD) tools with a better understanding of how to apply design best practice and to support best practice with appropriate design tools.

The technical aspects of the functional specification were the subject of the work of the author's research colleague, Dr. Phil Culverhouse. During the early stages of the work, the author and Dr. Culverhouse collaborated in the development of an electronics design process model. This work eventually also resulted in the creation of a four path model of product design (Bennett *et al*, 1992; Culverhouse, 1993). The model categorises designs

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1. *While a number of authors (for example, Bamberger, 1989; Lefebvre et al, 1992; Liberatore et al, 1991) have proposed various definitions of a small and medium size firm, for the purposes of this study the author has chosen to adopt the European Commission's definition which regards a SME as a firm which employs up to 250 staff*

according to the amount of change required in the production processes and according to the percentage of new technical knowledge design engineers must assimilate. It categorises designs as *Repeat Designs*, *Variant Designs*, *Innovative Designs* and *Strategic Designs*.

From the point of view of the design capability methodology, the four path approach has provided the author with a useful framework for allowing firms to define a portfolio of product design and development activities which will allow them to compete across as many of these categories as possible, particularly where *Innovative* projects are concerned. It will also enable firms to reduce the amount of risk involved in carrying out the design and manufacture of those products. The author's research has indicated that the level of risk in a product development project increases with growth both in the amount of change required in the production processes and the percentage of new technical knowledge design engineers must assimilate.

The primary thrust of the author's work on the EDT Project was, however, concerned with the identification of best practice in the management and control of the product design process itself. It emerged from this work that investment in design automation tools is, of itself, insufficient to enable firms to develop ongoing, robust design capabilities since current electronics design software does not, on the whole, embody and enforce best design practice.

To be used most effectively, the software must be embedded in a well planned infrastructure consisting of a variety of organisational and cultural elements, as well as a well-conceived set of policies, procedures and practices (Childe, 1991). The nature of an electronics design infrastructure will be described in greater detail in Chapter 7.

1.2. Aims and scope of the thesis

It is the aim of the research reported in this thesis to improve the product design effectiveness of electronics SMEs. It does so by providing a methodology which gives such companies the *internal* wherewithal to specify product design capabilities which are resilient to changes in their respective business environments. This has been achieved through the adoption of a "company-driven" approach which builds upon the key lessons derived from the author's research into international product design best practice.

While a "user-led" approach has previously been advanced as one answer to the problem of vendor-defined solutions described in Section 1.5., in the context of this work the author prefers to employ the term "company-driven" since it identifies both the organisation and the individual employees of that organisation as "users" of the overall design system.

In so doing, the term denotes an approach in which senior management of the company set the agenda for specifying the flexible product design capability and then drive forward the process of creating such a specification. Such a top down approach would ultimately guarantee the commitment of all senior managerial participants to the specified solution. A variety of authors (for example, Meredith, 1981; Checkland, 1981; Mumford and Weir, 1979; Hirscheim, 1985; Olson and Ives, 1981) have noted the critical importance in IT and manufacturing system design and implementation of ensuring that end users are given a full role in all aspects of systems development.

The research has not, however, concerned itself with the details of particular electronics component technologies or with the advantages of various CAD or CAE products, although these are both important aspects of any design capability. Nor is it concerned with the *implementation* of the product design capability.

In the following sections of this chapter, the author will briefly outline the major themes and concepts which underpin his design capability methodology and which provide the subject matter for Chapters 3 to 9 of this thesis.

1.3. Creating design capabilities

The concept of a "capability" has been discussed by a number of authors (for example, Bowen *et al*, 1994; Teece *et al*, 1992; Hamel and Prahalad, 1991; Stalk, 1988). In a recent paper, Bartmess and Cerny (1993) describe capabilities as:

"a company's proficiency in the business processes that allow it to distinguish itself continually in ways that are important to its customers. (. . .) Capabilities like these reside in the company's people and are supported by its procedures, culture and infrastructure. (. . .) the critical capabilities are those that are difficult to develop."

This definition fails, however, to acknowledge the role that technology may play in enabling a firm to "distinguish itself" in the eyes of its customers – a crucial omission where product design is concerned. Hence, for the purposes of this thesis, the definition of "capability" adopted by the author is the one advanced by Leonard-Barton *et al* (1994) who, in describing a core capability as a "capacity for action," state that:

"(. . . .) capabilities (. . . .) each consist of four elements whose interaction determines how effectively the organisation can exploit it (sic). Those elements are: knowledge and skills *- technical know-how and personal 'know-who' (. . . .);* managerial systems *- tailored incentive systems, in-house educational programs or methodologies which embody procedural knowledge;* physical systems *- plant, equipment, tooling and engineering work systems (. . . .) and information systems that constitute compilations of knowledge; and* values *- the attitudes, behaviours and norms that dominate a corporation."*

The concept of an electronics design capability will be discussed in greater detail in Chapter 3 of this thesis. The components of such a capability will be presented in Chapters 5, 6 and 7.

1.4. Electronics design best practice

Product design is the central component of a strategic corporate activity (Whitney, 1988; Rzevski, 1991) known as "new product introduction" or "product development." It involves both the industrial design of the product enclosure (encapsulating the lifestyle and recyclability aspects of the product, including its user interface) and the design of the electronic core of the product comprising its essential functionality and features. As such, product design has a vital role to play alongside marketing, purchasing, human resource management, engineering, test and production in a cross-functional effort to ensure that superior products are delivered to the marketplace in the shortest possible time.

The issues addressed in this thesis are therefore significant since, in today's highly competitive commercial environment (Gupta and Wilemon, 1990), not only are many electronics firms being compelled to undertake increasing numbers of design projects, they are also under pressure to design and manufacture innovative products for their OEM customers and, in many cases, to create products which match the lifestyle and aesthetic requirements of millions of increasingly discerning end-users.

The author's research into international design best practice has indicated that, in such circumstances, the effective design of electronics products requires that firms should create and evolve product design capabilities. Chapter 4 of this thesis reviews best practice in electronics product design while Chapters 5, 6 and 7 describe how the lessons of international best practice may be utilised to structure a product design capability around three interrelated components, namely:

- The essential managerial aspects of product design (such as project management and risk minimisation);
- The "core" or operational resources (such as design automation hardware and software) and activities;
- The supporting infrastructure (including the provision of technology support for routine administrative activities and inter-personnel communications, as well as the enactment of policies and procedures aimed at bringing about the alignment of individual goals with organisational objectives).

1.5. Requirements for a design capability methodology

Of particular concern to the U.K. electronics industry is the non-existence, in many companies, of a total or "holistic" view of design (Culverhouse *et al*, 1991). Many U.K. firms continue to employ "over the wall" design practices, for example, in which designs are produced almost without regard for their manufacturability. Furthermore, design is often viewed by senior management as merely of tactical significance and the introduction of design automation systems such as CAD and CAE often becomes an "act of faith" rather than the end result of a careful selection, acquisition and implementation process (Currie, 1989). Such ad hoc approaches can be particularly problematic for SMEs which usually lack the breadth of experience and expertise in making decisions in this complex area (for example, Lefebvre *et al*, 1990).

Support tool vendors recognise, on the other hand, that the mere purchase by manufacturing companies of sophisticated CAD and CAE systems provides no guarantee that design engineers will produce good designs. However, many vendors have difficulty advising their customers regarding how best to design, test, manufacture and support their products. Indeed, the toolsets they are creating have been developed principally to provide "point solutions" to specific problems in the product design process (Culverhouse *et al*, 1991) and do not embody and enforce electronics design best practice.

Furthermore, vendors have generally been incapable of helping client companies implement design systems which are sufficiently resilient not only to satisfy their current design requirements, but which will also enable them to cope with changes to their technological and infrastructural needs. In such circumstances, unforeseen integration requirements, for example, or rapid changes in either the nature or volume of designs would undoubtedly make such firms highly vulnerable to costly systems failure.

What electronics SMEs currently lack is a "roadmap" which, by providing a route to success, will reduce the risk involved in creating their own product design capabilities (Bennett *et al*, 1994). The design capability methodology must therefore provide firms with sufficient knowledge and a rigorous approach to ensure that the decisions about a design capability are not made naively, removing the need to trust key decisions to automation vendors. The requirements for such a methodology are presented in Chapter 8 of the thesis.

1.6. The design capability methodology

The process of specifying a flexible electronics product design capability must be a team effort which draws upon a wide range of skills, knowledge and expertise (see Meredith, 1981, for example). According to Childe (1991), the methodology-based approach provides a way of managing the large number of issues that arise in such circumstances. It avoids mistakes which have been made by previous, essentially *ad hoc*, approaches and makes available techniques which have been found to be successful.

As Childe (1991) observed in the context of Computer-Aided Production Management (CAPM) Systems, success comes not merely from the development of solutions, but from the process by which the company itself develops the solutions to its problems.

> *"The greatest problem of an approach which is imported into a company from outside is the extent to which it can deal with the specific problems of the particular company"* (Childe, 1991)

Therefore the approach which forms the basis of the author's methodology (called *"AGILITY")*, and which is described fully in Chapter 9, is one which concentrates upon the development of a structured, methodical process for constructing a design capability during which various activities are specified in order to build up the information required for decision making. Senior managers are obliged, for example, to define an improvement opportunity "envelope" with which the company can move forward and the methodology explicitly ties the design capability to this future "vision" rather than to the current situation.

The process therefore ensures that the right questions are asked and provides tools and techniques to help at various stages of the analysis. It also ensures that important issues are dealt with and that the required information relating to the business context of electronics design is articulated. Furthermore, the design capability methodology seeks to enlist the skills and expertise of the participants in a way which can be applied to many different company types. The mechanisms which are used to bring this about are a series of preliminary activities and workshops – orchestrated by a facilitator who guides and manages the entire process.

As indicated earlier in this chapter, such a company-driven approach was believed to be the only feasible one for use in the rapidly changing electronics industry since the companies themselves would determine which issues were important for their businesses and, using these issues as a baseline, would devise the most suitable means for achieving their goals. Such a structured approach would avoid some of the pitfalls inherent in the methods adopted by design automation vendors.

The methodology, which took 6 man years to complete, has been considerably inspired by the example of Japanese electronics manufacturing firms which allocate a high, early priority to product engineering and place design and engineering at the heart of effective strategy. It acknowledges the crucial role the *Kaizen* or continuous improvement ethos plays in the commercial success of Japanese electronics firms, particularly where it encourages and facilitates organisational learning. Such learning has been shown (for example, Yamanouchi, 1989; Nonaka, 1991) to be effective in improving the speed and flexibility with which firms are able to undertake product, process and systems innovation, and to reduce the risk involved in undertaking such projects.

1.7. Contribution to knowledge

The contribution to knowledge made by the research will stem from its creation of a company-driven process methodology which, for the first time, will help U.K. electronics companies to define *for themselves* product design capabilities which are robust and which support their wider business objectives. The author's literature survey and international electronics design case studies have revealed that there is currently no such methodology available in a form which is both accessible and affordable to SMEs. Furthermore, the author has uncovered no evidence of the existence of such a methodology even for use by *large* electronics firms.

A company-driven methodology will enable firms to implement best design practices in their businesses and to support those practices with appropriate design software tools. Indeed, not only will such a "best practice" methodology enable firms to avoid repeating the mistakes made by others, it will also provide an affordable means for firms to regularly evaluate and improve their design operations. Significantly, too, the application of a company-driven methodology would help to create far greater ownership of and commitment to the implemented design automation solutions.

The design capability methodology, which views electronics design as one of a portfolio of corporate activities which must be considered from a strategic viewpoint (Bennett *et al*, 1992; Adler *et al*, 1989), will enable an electronics firm to:

- Create a robust design capability which embodies product design best practice with regards to the management of design, design operations and the infrastructural or support elements of design;
- Evolve product design support systems or infrastructures which facilitate organisational learning. A systematic approach to "learning from experience", exemplified in the *Kaizen* approach to continuous improvement, would enable firms more effectively to capitalise upon their knowledge resources;
- Harmonise the technological and infrastructural components of the design capability in order to provide the best overall solution.

While the methodology aims to facilitate the creation of product design capabilities in electronics SMEs, it is nevertheless the author's belief that such a methodology would be equally useful for both medium and large U.K. firms, despite the gulf in organisational, human and technological resources which lies between the smaller and the larger enterprises.

1.8. Structure of this thesis

Chapter 1 has established the orientation of the research to develop an alternative to the unstructured, usually piecemeal and technology focused methods currently used to specify and implement electronics product design systems. The concepts underlying the work include the company-driven approach and the incorporation of design into business strategy through the process methodology, with an emphasis on capability building.

Chapter 2 describes the methodology used for the research while Chapters 3 and 4 respectively explore the concept of a "capability" as it relates to electronics product design and present the key findings obtained from the author's international case studies. Chapter 4 places electronics design best practice into an infrastructural framework, encompassing the management, operational and support aspects of product design, which highlights the key role played by organisational learning in Japanese electronics firms.

Chapters 5, 6 and 7 describe in greater detail the managerial, operational and support components of the product design capability while Chapter 8 recommends a set of requirements for a company-led methodology capable of guiding and supporting the task of specifying a design capability. Chapter 9 provides an outline description of the methodology.

Chapter 10 concludes the work by evaluating the progress made and suggesting ways in which the work may be developed in the future.

1.9. Conclusions

This chapter has sought to place the author's work in context and to define the aims and scope of the research. In so doing, the Electronics Designers' Toolbox project has been described and the major focus of the author's research during that project has been contrasted with that of his colleague Dr. Phil Culverhouse.

In outlining the major themes and concepts which underpin his design capability methodology, the author has drawn attention to the fact that product design is increasingly being recognised as a strategic corporate activity. However, it is an area of their businesses in which many U.K. electronics firms have demonstrated significant shortcomings, most notably through a failure to adopt a capabilities-based approach.

The chapter points out, however, that the creation of electronics design capabilities is a complex process which must simultaneously address the organisation's knowledge and skills, managerial systems, physical systems and values. Smaller electronics firms, in particular, require help in defining *for themselves* product design capabilities which are robust and which support their wider business objectives.

The contribution of this work lies in the fact that, for the first time, it provides electronics firms with a company-driven methodology which will not only enable them to specify "best practice" design capability solutions but will enable them to do so in a manner which secures far greater ownership and commitment from staff at all levels in their businesses.

To date, no such methodology exists in a form which is both accessible and affordable to SMEs.

In the following chapter, the author describes the research methodology used to examine the design capability problem.

Chapter 2.

Research Methodology

In advance of chapters which examine the need for a capabilities-based approach to electronics product design and which report on the results of the author's research, some contextual account should be made of the research methodology adopted.

The work reported here has an engineering orientation which seeks to understand and solve a real world problem. The emphasis is on "making things work better" rather than developing an empirical understanding of phenomena. It aims to develop techniques of analysis and intervention which can be used in an immediately practical way to produce the required outcomes. The research takes a "systems view" (Wilson, 1984) of the electronics product design process which is concerned more with "Does it work?" than with "Have we learned anything?" (Checkland, 1981). The design process model, which will briefly be described in Chapter 5, arose from observation of actual companies. This may be regarded as a "Grounded Theory" approach (Glaser and Strauss, 1967).

It was felt to be important to structure the research around the experiences of companies which have implemented electronics design systems and which "own" the problem in question. Hence, the chapter begins by describing a research strategy based upon a case study approach and upon the development of close collaborative links with two leading design automation tool vendor companies. A plan of the research is then presented and each element of the plan is briefly described.

2.1. Research strategy

2.1.1. Case study approach

According to Meredith *et al* (1989), research in operations is still overwhelmingly artificial in nature. They prescribe a much stronger movement than has hitherto occurred towards naturalistic paradigms (especially direct observation, case, action and field studies) and existential (primarily interpretive) paradigms. Earlier, Deising (1972) had observed that, while quantitative analysis can indicate certain relationships within an organisation, it cannot identify the actual inner or interpersonal transactions which bring them about.

A case study approach was thus adopted to carry out the research which is reported in this thesis. This approach opens up opportunities for exploring specific factors influencing the product design process in large and small electronics firms. Rickwood *et al* (1987) noted that

> *"the adoption of a case study approach provides opportunities for overcoming the restrictions of response imposed by the questionnaire in investigating the heterogeneity of procedures and their relationship with the context in which they are adopted."*

The case study approach has allowed the author carefully to evaluate potential insights into how management and environmental factors interact to affect the product design process in a sample of electronics firms based in the U.K., continental Europe, the United States and the Far East. In adopting the case study approach, Romano (1989) states that the researcher has the opportunity to utilise a single- or multi-site case approach. He observes that a multi-site case study analysis provides further insight into the research problem. Furthermore, Miles and Huberman (1985) state that

> *"by comparing sites or cases one can establish the range of generality of findings or explanation and at the same time pin down the conditions under which that finding will occur. There is much potential for both greater explanatory power and greater generalizability than a single case study can deliver."*

This thesis draws upon research carried out in 11 U.S., Japanese and Korean electronics research and production facilities, as well as in 18 U.K. and European case study companies.

2.1.2. Industrial collaboration

The fact that electronics design automation tools are developed by vendor organisations made it imperative, as part of the research strategy, that close links should be forged with leading design tool manufacturers. Both Mentor Graphics (U.K.) Ltd and Racal Redac, No. 1 and No. 2 design automation vendors in the world respectively, collaborated actively on the project. As a result. it also became possible to enlarge the sample of contact companies to include a number of their customers who were driving developments in a variety of electronics technologies.

The research interaction with the design tool vendors also made it possible to formulate an awareness of future trends in the electronics industry and to identify specific design tool application areas in which those vendors were devoting considerable research and development resources.

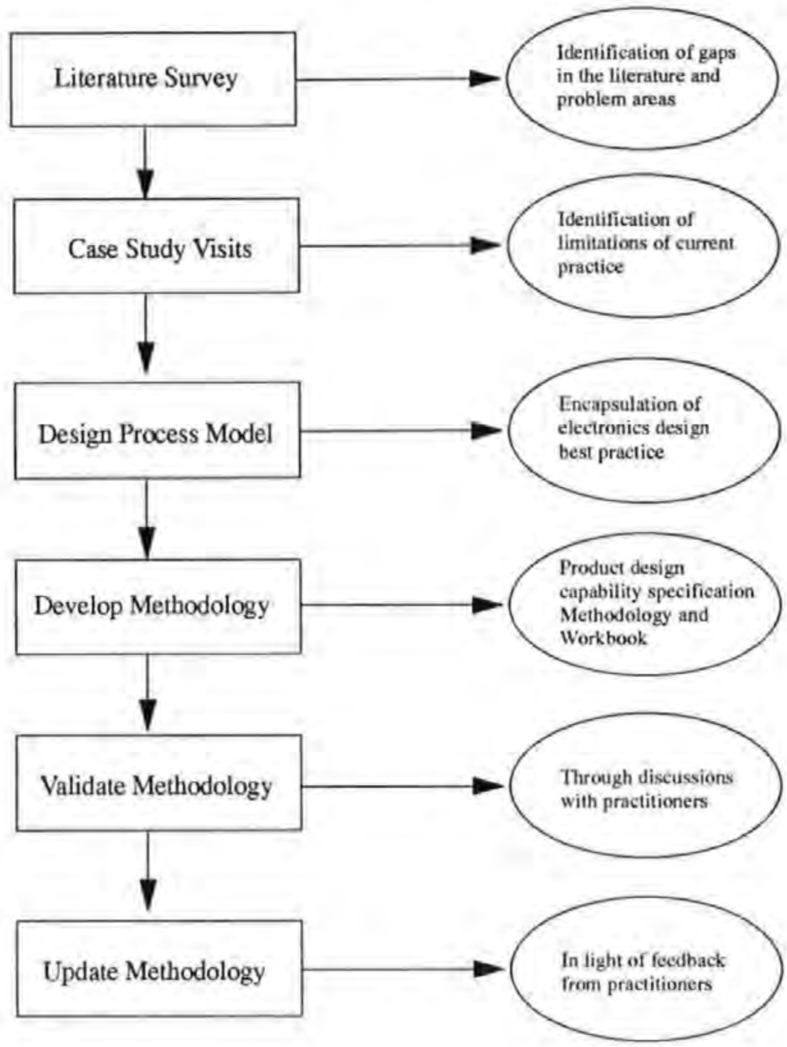
2.2. Research plan

As illustrated in Figure 1, the author's research began with a survey of the literature in order to identify current approaches to electronics design and design system specification and to highlight key problem areas and gaps in existing research. A series of U.K. and international case study visits were then carried out during which a range of different sized companies was visited. The aim of these visits was to deepen the author's understanding of problems and limitations in existing approaches to electronics product design and of the reality of problems facing electronics designers.

A process model was developed which sought to offer a generic approach to design for the electronics industry. The model contains the major developmental stages in the evolution of a product's design and describes the documentation required to capture all relevant product development information and knowledge. The design capability methodology was then developed. The methodology was validated through discussions with practitioners and was revised in light of feedback from those practitioners.

Each element of the author's research plan will now briefly be described. It should be noted that the research process did not take place entirely in the linear fashion described in Figure 1. For the purposes of clarity on the diagram, however, feedback loops have not been included.

Figure 1: Plan of Research



2.2.1. Literature survey

Literature searches were used to provide a theoretical background to the work and to provide more cases to add to the material from the companies visited. Extensive use was made of online databases of abstracts made available through the University of Plymouth's library service, especially the ABI-Inform, Inspec and Compendex databases.

An initial survey of the literature was carried out in order to elaborate on some of the salient electronics design concepts and ideas originally outlined in the research proposal document. The survey addressed requirements for future generation PCB and Integrated Circuit CAD systems and sought to shed light on existing electronics design and manufacturing approaches. In addition, it examined electronics design in the context of

VLSI and PCB manufacture, it explored knowledge-based approaches to CAD and highlighted a number of product data standardisation problems currently being faced by CAD systems users. The survey also briefly examined several state-of-the-art CAD toolsets.

An ongoing review of the literature was undertaken by the author throughout the research, however, particularly in the following areas:

- Organisational learning
- Methodologies
- Product design management
- The product design process
- Culture
- Manufacturing systems
- Integration
- Japanese methods
- Technology Management
- Flexibility
- Human factors
- Tools and techniques
- Business Process Re-engineering
- Standards
- Implementation issues
- Infrastructures
- Capabilities
- Design coordination support

The problem of specifying a design capability which comprises computer and human elements designed to perform the various functions involved in product design has received scant attention in recent years, although the problem has been addressed at a more general level by Wheelwright and Clark (1992). Writers who address these and other relevant issues will, where appropriate, be referred to later in this thesis.

The author was particularly concerned to establish, from the literature, whether any other work was being carried out to develop process methodologies aimed at helping electronics firms to specify and develop flexible design capabilities. In fact, the literature survey revealed that no such methodology currently exists. Nor was there any evidence indicating that another methodology of this kind is currently being developed.

2.2.2. Case study visits

There appears to be a consensus among authors and industry practitioners that the U.K. lags behind in electronics product design and that there are no U.K. electronics manufacturers able to demonstrate world leadership in product design and manufacture. The author's research visits to 18 U.K. and mainland European electronics manufacturing companies had confirmed that view, although the visits did demonstrate that there were companies, in all the countries visited, which exhibited aspects of "World Class" capability in this field.

It became clear, therefore, that without the input of such state-of-the-art knowledge as could be gained from an international study tour, the author would be forced to work to an inadequate model of electronics design and manufacture and that, consequently, the functional specification produced for a next generation electronics designers' toolbox would ultimately be of little value to the U.K. electronics industry. The trip, which was jointly funded by SERC's ACME Directorate and Mentor Graphics (U.K.) 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 organisations visited are described in outline in Section 2.2.2.2.

2.2.2.1. Information requirements

It was decided to seek information 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. Where appropriate, information would also be sought in the areas of manufacturing methods, quality programmes, information storage and distribution methods as well as approaches to customer and supplier development.

In view of the fact that the work was concerned with future generation electronics design toolsets, the research also sought to uncover evidence of awareness of emerging technologies (production and non-production), use of new materials other than silicon and appreciation of environmental concerns in light of their possible impact on the design and manufacturing processes.

Other areas of interest included:

- Nature of design tools used and problems with their use;
- Integration of design function and other computer–aided parts of the organisation;
- Design environment/company culture;
- Risk assessment at conceptual design stage;
- Simulation techniques/software used;
- Engineering change control policies and methods;
- Design/production interfaces;
- Component policies;
- Standards;
- Impact of different manufacturing approaches (for example, Just–in–Time and MRPII) on the design operation.

2.2.2.2. Outline descriptions of overseas case study organisations

While both large and small companies were visited during the U.K. case study visits, the overseas firms were overwhelmingly large and well resourced and, particularly in Japan, were world leaders in electronics product design and manufacture. For reasons of brevity, only the overseas companies and research organisations visited are described in outline below. Each U.K. and overseas case study organisation is described in greater detail in Appendix 2. For confidentiality reasons, however, the U.K. firms cannot be identified and are simply numbered consecutively from 1 to 18.

2.2.2.2.1. 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.

2.2.2.2.2. MIT Computer Architectures Group -- Boston

At the time of the research visits, the MIT Computer Architectures Group was involved in a number of electronics research projects, some of which were funded through the U.S. Department of Defence.

2.2.2.2.3. 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 the United States. The division has four plants world wide, two of which (in Japan and Mexico) are joint-venture companies.

2.2.2.2.4. 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.

2.2.2.2.5. 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.

2.2.2.2.6. 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).

2.2.2.2.7. 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.

2.2.2.2.8. Fujitsu Mainframe Division -- Kawasaki

The Mainframe Division is part of Fujitsu'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.

2.2.2.2.9. Samsung Colour TV Division -- Suwon City

Samsung's Colour TV Division employs some 2,500 employees and has a revenue of $1 billion. Work has recently begun to conduct research into High Definition Television (HDTV). 80% of their products are exported to the United States. At the time of the visit, the author observed no significant design activity.

2.2.2.2.10. Samsung VTR Division -- Suwon City

Samsung's VTR Division manufactures 350,000 VTRs per annum. At the time of the visit, the author observed no significant design activity.

2.2.2.2.11. Samsung ASIC Research Centre -- Seoul

The ASIC Research Centre was established around 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.

2.2.3. Interviews

Research data were collected through a series of lengthy semi-structured interviews, on many occasions lasting for up to two days, at each of the design sites visited. The interviews were usually conducted by two members of the research team who questioned groups of design and production managers and staff. In this way a considerable number of very senior design, R&D and executive staff managers, particularly in Japan and Korea, were able to be 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 visits around production facilities.

During the discussions, a wide variety of questions were posed to the interviewees. The answers to these questions provided a significant input to the development of the design process model. The process model is discussed briefly in Section 2.2.5.

It was also felt to be vitally important for the author to understand how the host companies had positioned themselves strategically in the marketplace. Strategic plans determine levels of investment in advanced technology and, in particular, of investment in research and development of "in-house" electronics design and manufacture capabilities. Such insights could only be gained by talking to Board-level personnel, including the Managing Directors, of the various companies.

In addition, senior design and production managers, as well as senior design and production engineers, were questioned regarding product design-for-manufacture. The same personnel were questioned regarding such issues as quality, manufacturing flexibility, use of concurrent engineering techniques, state-of-the-art process and design technology/software and supplier relationships. A list of all personnel questioned may be found appended to this thesis. Furthermore, a schedule of questions (see Appendix 1) was constructed for use in eliciting the data described above. The question set was originally tested in the U.K. and mainland European case study companies, and was continuously refined as those visits progressed.

Research data from the U.K. and European company visits have been collected together in Electronics Designers' Toolbox Project (1990) while data from the U.S. and Far Eastern case studies have been presented in Bennett (1991). The analysis of the overseas visits is reported in Bennett *et al* (1991). Analyses of the U.K./European and the U.S./Far Eastern case study visits are reported in Culverhouse *et al* (1991), Culverhouse *et al* (1992) and

Bennett *et al* (1992). Three examples of the case study data are presented in Appendix 5 of this thesis.

2.2.3.1. Confidentiality

Most of the U.K. and European companies who took part in this research did so only on the strict understanding that their commercial confidentiality would be protected. These companies will therefore not explicitly be identified in this thesis. This stricture does not apply to the U.S., Japanese and Korean companies.

2.2.4. Data collection quality control

Miles and Huberman (1984) caution us to be "especially watchful in qualitative research about the multiple sources of potential analytic bias that can weaken, or even invalidate, our findings." They state that data quality can be assessed using twelve tactics for confirming conclusions which include checking for representativeness, checking for researcher effects and looking for negative evidence. Various other writers have suggested ways of ensuring that quality control is maintained during the collection of descriptive data. Webb (1978) proposes the concurrent application of different data-gathering techniques to the same problem, Denzin (1978) suggests triangulation and Diesing (1972) suggests the use of multiple sources of evidence.

Romano (1990) states, however, that the selection of data quality control methods for use in a case study methodology should be based on practical usefulness and easy implementation. In the case of the research reported in this thesis, considerable effort was made to ensure that the individuals interviewed in each company were drawn from different backgrounds and different authority levels, each field visit was undertaken using a standard set of issues and topics and the emerging results of the work were regularly validated through discussions with independent industry practitioners. These procedures gave the data collection a balanced approach.

2.2.5. Design Process Model

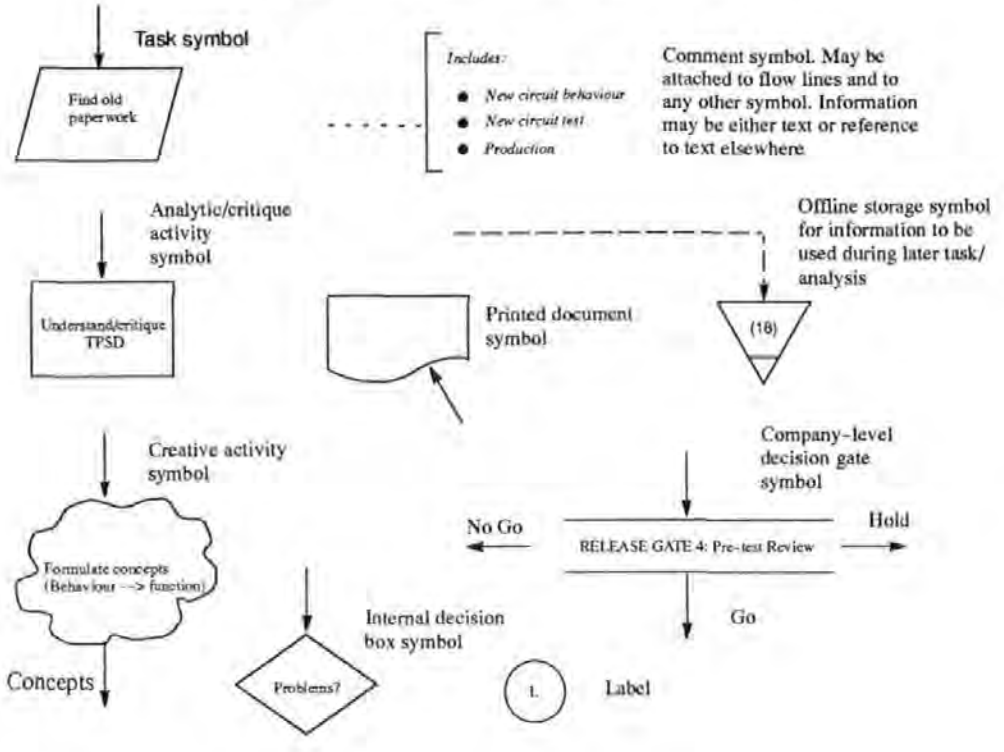
The knowledge gained concerning current approaches to electronics product development, both in the U.K. and in Europe, encouraged the author and his research colleague to produce their own model of the electronics design process. It was initially proposed to accomplish this using the $IDEF_0$ structured modelling methodology developed by the U.S. Airforce ICAM programme (Le Clair, 1982). However, a number of significant problems were uncovered in attempting to use $IDEF_0$ to model what is essentially an extremely creative and complex activity. These problems included:

- Important events are hidden deep in the heirarchy – It was felt that the manner in which $IDEF_0$ partitioned the various product design activities was artibrary and was constrained not by the natural boundaries of the activities and responsibilities of the personnel involved in the design process, but rather by the limit of six boxes in each $IDEF_0$ level;
- Decisions are not represented explicitly;
- Specific activities are not represented in any different way – It was found that the uniform diagrammatic structure of $IDEF_0$ tended to hide differences in the actual design process (for example, the difference between creative and analytical tasks and activities);
- Time is not made explicit - The handover of the product design from design to production was not easy to describe in $IDEF_0$.

It was therefore decided to proceed by developing a modelling approach, based upon a number of widely used systems modelling methodologies (for example, European Computer Manufacturers Association, 1966; British Standards Institution BS6224, 1982), which overcomes many of these shortcomings. Figure 2 describes the modelling notation used.

The model was validated and refined and, as part of that process, feedback was solicited by distributing the model, together with an accompanying commentary, as widely as possible among those parties participating in the research.

Figure 2: Process Modelling Notation



The author's contribution to the development of the process model lay principally in the areas of design management and in the creation of product development infrastructures.

2.3. Validation of results

2.3.1. Publications

The results of the author's research have been published widely to the academic and practitioner community and, to date, have remained unchallenged.

Papers based upon the research were published at the following conferences:

- First International Conference on Concurrent Engineering and Electronics Design Automation (CEEDA '91), Bournemouth, U.K., 1991;
- Eighth International Conference on CADCAM, Robotics and Factories of the Future, Metz, France, 1992;
- International Conference on Factory 2000, York, 1992;
- Seventh International Conference of the U.K. Operations Management Association, Manchester, 1992;

- First International Conference of the European Operations Management Association, Cambridge, U.K., 1994;
- Second International Conference on Technology Transfer and Innovation, London, U.K., 1994.

Copies of each of the above mentioned papers are presented in Appendix 4.

2.3.2. Testing

Whilst the design capability methodology was based upon findings from the research and the contribution from experienced practitioners in the area, an approach which on the face of it would appear to work, it must be tested by users in the field before it can be claimed to have empirical validity or true usefulness.

The ultimate demonstration of the success of the design capability methodology would be the proof that the work had led to the implementation of successful systems which had possessed the required robustness and responsiveness to withstand the test of time in real companies. However such a longitudinal test was beyond the scope of the project because of the time which would be required (and the difficulty in determining a suitable target lifetime) and because of the lack of a control experiment for comparison.

A more practical test, considering the engineering approach of the work, was to ensure that the design capability methodology could be applied. If it was not found to be workable in practice, the elegance and sophistication of the solutions which may hypothetically have been generated would be without value. Thus despite the need for better electronics design system solutions to be implemented, the focus was placed upon improving the specification process. This would be expected to lead to better solutions and would have the added advantage of making the process available to the company as a tool for repeated analysis and adjustment. Elements of the process could be used as necessary to deal with changes and developments in the business. Thus the design capability methodology would transfer additional benefits to the company in the form of knowledge and experience of applying various tools and techniques.

It was therefore hoped that the design capability methodology could be tested by real life use during the latter stages of the research if a suitable company could be found. The experience of the "road test" would be expected to add to the detail of the design capability methodology (as "action research") and to validate the principles developed. This test would assess the suitability of the process of the methodology.

Ultimately, however, the main means of evaluating the work would be the views of users and others in the field. Since no methodology had previously been developed to guide the activities of electronics design capability developers, the usefulness of a well-structured approach was self-evident. The correctness of the methodology, in terms of appropriateness and completeness of its content, could only be assessed by independent comment.

A validation exercise would therefore be carried out in order to have the research findings examined by a group of practitioners and academics who could reasonably be expected to be independent of the "taken for granted" assumptions of the research team and those connected with the work. This test would evaluate both the process and the content of the design capability methodology. Where appropriate, any criticisms or suggestions would be incorporated into the methodology.

2.4. Conclusions

In order to produce a practical tool which would be useful to companies having to deal with real-life situations, the research methodology took an engineering approach which sought to understand the design capability problem from the "user's" perspective. The work was thus grounded in experience rather than in conjecture.

An approach was adopted which opened up opportunities for exploring specific factors influencing the product design process in large and small electronics firms. Emphasis was placed upon deriving an understanding of the capability building process rather than upon how the solutions were implemented.

To this end, 18 case study visits were initially carried out in the U.K. and Europe. These were followed by visits to 7 leading electronics firms and research organisations in the United States, Japan and Korea. In the course of all the visits, discussions were held with senior design and production managers. In Japan and Korea interviews were also held, where possible, with Board-level personnel, including the Managing Directors, of the various companies.

In addition, close links were established with leading design automation tool vendors in order to formulate an awareness of future developments in the electronics industry. These links also helped in evaluating vendors' ability to specify and create design capabilities for their clients which are resilient to changing demands upon their managerial and operational activities as well as upon their supporting infrastructures.

The research orientation thus dictated that the outcome of the research would be a tool enabling electronics firms to derive *for themselves* resilient product design capabilities, rather than focussing upon the value of any particular design automation solution. No such tool was discovered to exist during the period of the research and, hence, this is believed to be an original approach which has wide applicability.

Chapter 3.

Creating Electronics Design Capabilities

Electronics firms are frequently confronted by a marketplace which is characterised by decreasing product lifecycles and by increasing product diversity, quality requirements, competition, innovation speed, integration and miniaturisation (for example, Gupta and Wilemon, 1990). That marketplace is now irrevocably demand rather than supply driven and the needs of survival have quickly forced firms to abandon the old mass production strategies derived from notions of economies of scale.

Operating effectively in a buyer's market is not straightforward, however, and a growing body of literature suggests that the ability to create and then to capitalise upon a number of "core" capabilities has become one of the most important competitive attributes for manufacturing firms in the 1990s. From the point of view of product design, the need for a capabilities-based approach has been driven by the very real difficulties firms experience in attempting to predict future markets for their products (Bentley, 1987). For example, a firm may experience severe problems if, having committed resources to the purchase and installation of a design automation system, it is subsequently discovered that the system is incapable of meeting the requirements of a changed marketplace.

This chapter makes the case for the development of electronics design capabilities. It describes the competitive changes currently taking place in the electronics sector and proposes three dimensions of product design instability, namely *nature*, *intensity* and *scope*, currently facing electronics firms. The chapter continues by exploring the concept of an electronics design capability, and concludes by proposing a framework for categorising the components of such a capability.

3.1. Changes in the nature of electronics sector competition

A great many informed academics (of whom Fine and Hax, 1984; Peters, 1989; Porter, 1990; Skinner, 1974; Hayes and Wheelwright, 1984; Hayes and Pisano, 1994 represent but a small sample) and industrialists have, in the last few years, investigated the loss of

Western manufacturing industry's market shares, jobs and leadership in equipment and process technologies to its Far Eastern competitors. Such competitive pressures are being felt most acutely in the electronics sector, where many companies are being forced to introduce new products every 12 to 18 months, on average, merely to maintain their market positions (Cole, 1989). In some areas, such as personal computers, the product lifetime is as little as a year or less and the product introduction opportunity window (usually defined as the first half of a product's lifetime) is now no more than six months.

Indeed, one communications equipment manufacturer visited by the author reported failure costs of getting to market a year late with one of its products to have been "several million" pounds. A six month delay caused by the need to redesign the user interface on another product also cost that firm millions of pounds. Two surveys of U.K. manufacturing attitudes (Computervision, 1992; PA Consulting Group, 1992) reveal, however, that an alarming number of U.K. manufacturing executives dismiss time to market as a factor in determining market share. Nevertheless, Vesey (1991) predicts that during the 1990s, the emphasis in manufacturing companies will be time to market -- the elapsed time between product definition and product availability.

> *"The new competitors are time-to-market accelerators that focus on speed of engineering, sales response and customer service."* (Vesey, 1991)

In reality, the problem is a multi-dimensional one which goes wider than simply competing on the basis of time. In addition to reducing lead times, electronics firms are also seeking market advantages by competing on quality, price and responsiveness. Furthermore, there appears to be a consensus emerging in the literature that there is a strong correlation between corporate success and a firm's ability to learn (see Chapters 4 and 7 for a more detailed examination of organisational learning).

Evidence for the changed competitive paradigm comes principally from Japan where intense competition in the domestic electronics market has had a profound impact upon the product development strategies adopted by the leading manufacturing firms.

3.1.1. Following the Japanese lead

In high growth markets, such as those for consumer electronics where total sales have sometimes increased by up to 100% per annum, Abbegglen and Stalk (1987) describe a tendency among Japanese companies to exploit these opportunities by competing intensely for market shares and then leaving the market once it matures and growth stops. They also note that Japanese obsession with market share is driven by the desire to continually increase production volume. This in turn opens up opportunities for cost reduction through production rationalisation.

Stone (1984) contrasts Japanese and Western expectations of future market development in growth areas:

> *"The Japanese view would be that a high proportion of potential users would become actual users quickly if the price could be cut deeply, and if distribution channels were available to get the product to the market. The Western view would be that product diffusion would be slow and steady, with price falling more gently and distribution channels adapting to the product more slowly."*

Within this highly competitive context, Buur (1989) reports on the product development strategies of the best Japanese companies. He identifies four measures which appear to characterise those strategies:

- Fast reaction to competition changes;
- Shortening the product cycle to spur demand;
- Emphasis on competitive product properties;
- Planning for new opportunities.

Each of these measures will now briefly be described.

3.1.1.1. Fast reaction to competition changes

Hamel and Prahalad (1991) have observed that, partly as a result of the intensity of the domestic competition, the task of creating new markets dominates the agendas of senior managers in the major Japanese electronics firms.

"New competitive space does not stay new for long. Building one new business after another, faster than competitors, is the only way to stay ahead."

Buur (1989) indicates that such rapid response is facilitated by intense study of competitor moves and by copying competitor products.

3.1.1.2. Shortening the product cycle to spur demand

For Japanese electronics companies, the interval separating the introduction of succeeding product models is generally a very short one. Evans (1985) describes how the design strategy of Japanese companies is determined by product cycle time:

"Where cycle times are shorter, for instance in consumer electronics, there is more emphasis on beating the competition to the marketplace and then staying one jump ahead. If product cycles are longer, as with office automation (photocopiers take up to four years to develop), heavy patent protection and investment in process technology take over as the strategy."

Buur (1989) comments on the fact that the product strategy of Japanese consumer electronics firms seems to be one of total product re-designs alternating with version-up models incorporating only incremental changes. The product re-designs may be carried out within a comparatively long cycle (Brother introduces completely re-designed sewing machines every four years), whereas the product variants (changes in colour, small additional features) occur in an intervening series of mini-cycles. The competitive benefits of such a strategy are considerable.

"By completing two development cycles while European companies do one, the Japanese engineers get an amazing training in product development. Design becomes a standard procedure and engineers have a better chance of learning by experience and correcting their mistakes . . . A natural consequence of the shorter product cycle is that product development projects have to be completed in shorter time." (Buur, 1989)

Hamel and Prahalad (1991), having analysed the new product introduction strategies of a number of leading Japanese consumer electronics firms, conclude that they sought to accumulate understanding as quickly as possible, and so lessen the risk of new market entry, by undertaking "a series of low-cost, fast paced market incursions."

> *"The practical problem . . . is how to maximise the capacity for frequent low-risk market incursions. In the first instance, the solution depends upon minimising the time and cost of product iteration. (. . . .) Each product iteration unfreezes one or more aspects of the product design and thus provides and opportunity for a company to apply what has been learned from the marketplace and improve the product for another incursion."* (Hamel and Prahalad, 1991)

3.1.1.3. Emphasis on competitive product properties

A product or service will succeed when it contains the optimal blend of functionality, price and performance required to penetrate its target markets quickly and deeply. The fact that product functionality and features sell products means that it is crucial to successfully interpret, and even anticipate (Senge, 1990; Hamel and Prahalad, 1991), customer's needs, aspirations and tastes and to react accordingly. Stone (1984) notes that Japanese firms include a wealth of functions in their products. Buur (1989) describes how, by using the latest technologies in every new development, Japanese firms attempt to ensure that consumers replace their products.

> *"Japanese consumers have an immense curiosity for new technologies which certainly helps in making products obsolete . . ."* (Buur, 1989)

According to Stone (1984) there is even a different design philosophy regarding product reliability between Western and Japanese companies.

> *"Japanese choice of length of life is normally determined by the period after which the average buyer would want to replace his product, given that technological progress will have made it obsolescent. There is no point in designing a product to last for 10 years if it will be obsolescent in 5. (. . .) Designing for a limited but reliable life should produce a cheaper product."*

Many Japanese electronics firms are intensely conscious of customer lifestyle. According to Smalley (1987) this means:

> "*. . . an awareness that products alone, no matter how clever, are not enough. They have to respond to changing social attitudes and behaviour by coming up with products that fit today's lifestyle – or, like the Sony Walkman, help to develop a lifestyle.*"

Japanese companies often compete by offering the market a large number of product variants with similar functions, but slightly different specifications. Abbegglen and Stalk (1987) describe the Japanese tendency to enter a new market with only one or two product variants, produced in focused, low cost factories, in order to compete with existing manufacturers. Then, when the demand decreases, the variety will be increased to sustain production growth.

3.1.1.4. Planning for new opportunities

Hamel and Prahalad (1991) argue that simply *reacting* to events in the market place is no longer sufficient. Even being customer-led is not enough. Japanese firms have become past masters at understanding how emerging technologies might allow customers' unmet needs to be satisfied and their existing needs to be better served. They are obsessed with uncovering ways of leading customers to where they want to go before the customers know it themselves.

Buur (1987) describes the Japanese product planning approach which aims to match technology seeds with customer needs. He identifies two main approaches to generating new product concepts:

- Technology led – for example, a prototype produced in a R&D laboratory;
- Customer need driven.

The customer need driven approach requires information about new technology seeds to be widely disseminated because the people studying customer needs will often be non-engineers. Evans (1985) comments on the problem of interpreting needs and creating needs:

"There is much talk about needs and seeds, but often customers have a need satisfied that they did not even know existed. There is a subtle distinction between giving people what they want or what they get."

A number of authors (Buur, 1987; Hamel and Prahalad, 1991; Evans 1985) describe how Japanese firms have responded to the increasing consumer concern for human interface, product identity and life-style by establishing life research centres. Buur (1989) also describes a variety of methods used by Japanese design engineers to help them capture lifestyle attributes. These methods include the use of keywords and maps, the Key-Needs Method (Umezawa, 1985) and the K-J Method (Kawakita, 1982).

3.1.1.5. Organisational learning

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 (Nevins and Whitney, 1989). It also requires that such learning be systematised and include such elements as expert knowledge, best practice, current versus previous case histories and support for bid estimation procedures.

The author's work has revealed that organisational learning plays a crucial role in Japanese companies since managers view their organisations as learning social systems within the context of which out of date wisdom is "unlearned" and knowledge of successful projects is systematically processed and transferred into other projects. More general success patterns are disseminated throughout the company as "corporate wisdom."

Bowen *et al* (1994) have indicated that organisational learning plays a key role in the development of "core" capabilities. The reality of most Western companies, however, is that effective dissemination of information relating to product design, quality, reliability and manufacturability rarely occurs since, on a day-to-day basis, the linear organisational approaches adopted in those firms invariably result in a considerable amount of information loss (Smithers, 1985).

3.1.2. Sources of design instability

Based on his reading of the literature, as discussed in Section 3.1.1., and from the evidence of his field research, the author has therefore concluded that, at the product level, electronics firms are currently having to cope with considerable instability along three major product design dimensions:

- The *nature* of the designs being undertaken;
- Design *scope*;
- Design *intensity*.

Each dimension of product design instability will be described in the following sections of this thesis. In addition, each is used by the author in his design capability methodology (Chapter 9) to provide a structure within which electronics firms can determine the boundaries of a design capability "envelope." Determining those boundaries requires a detailed examination of the firm's customers, markets and competitors in order to chart the impact that developments in these areas will have upon its overall product portfolio and upon its ability to design those products.

3.1.2.1. Nature of design

As suggested in Section 3.1.1. of this chapter, the *nature* of the product design activities undertaken by Japanese firms covers a wide spectrum, from complete product re-design through to small-scale incremental improvement. In this regard, Wheelwright and Clark (1992) propose a range of product development projects. These include:

- Research and Advanced Development;
- Breakthrough;
- Platform or Next Generation;
- Derivative;
- Repeat Order.

They stress the need for firms to compete across as many of these product development activities as possible. They are particularly concerned, however, at U.S. manufacturing firms' failure to recognise the importance of *Platform* projects. These projects involve the creation of new "system" solutions for a broad range of core customer needs. Hence they require significant change on either the manufacturing process dimension (for example, Surface Mount Technology), the product dimension (for example, movement from analogue to digital circuits) or both.

> *"Platform projects are especially important to electronics firms, and deserve special emphasis in developing the firm's overall project plan, because they provide a base for a product and process family which can be developed and enhanced over several years."* (Wheelwright and Clark, 1992)

Bennett *et al* (1992) have observed a similar pattern of failure to invest in innovative products in the U.K. electronics sector. They discovered that many U.K. electronics firms are mostly undertaking *Repeat* and *Variant* design projects. The former require no (or near zero) new knowledge to complete them, either in design or in manufacturing, while the latter involve incremental product and/or process changes and may be supported using existing know-how. Very few of the firms visited were found to be undertaking *Innovative* or *Strategic* designs, both of which might trigger significant change on either the manufacturing process dimension (e.g. Surface Mount Technology), the product dimension (e.g. move from analogue to digital circuits) or both.

Adoption of a broader product development strategy, which encompassed Repeat, Variant, Innovative *and* Strategic designs, would allow U.K. electronics companies to structure themselves to engage in both "Aggressive" and "Consequential" design (Bennett *et al*, 1992). Consequential design focuses on cost reduction and design to product efficiency. In order to excel at this kind of design, companies must be capable of exerting detailed control over their design and manufacturing capabilities whilst, at the same time, making incremental refinements to their products.

Aggressive design, on the other hand, demands an ability to respond rapidly to external competitive demands. This may involve the engineering of completely new designs or the use of new technologies in either design or manufacturing. The adoption of a joint aggressive/consequential design strategy would push the company towards a state where it routinely develops creative and innovative products, *in addition to* its "bread and butter" Repeat and Variant designs.

The Four Path approach to electronics product design (Culverhouse, 1993) is described in greater detail in Chapter 5 of this thesis.

3.1.2.2. Scope of design

In the electronics industry, particularly in the consumer electronics field, the competitive climate is forcing firms to dramatically extend the scope of their design activities. The Fordist age of supplying customers "with any car they want so long as it is black" has long disappeared and the modern electronics firm must pay detailed attention to consumer needs and to designing products which have "more identity, more independence, more innovation (Gerlach, 1991)". In some markets, electronics firms must lead their customers in the directions they want to go before the customers themselves are aware of those directions. The ability to achieve this naturally requires deep insight into the needs, lifestyles and aspirations of today's and tomorrow's customers (Hamel and Prahalad, 1991, p 85; Buur, 1989).

This "buyer's market" also heightens the need for products to be manufactured to the highest possible standards of quality and at the lowest cost. Electronics firms are thus having to adopt a wide variety of tools and techniques in order to achieve these seemingly conflicting objectives. Concurrent Engineering (CE), probably the best known of these techniques, integrates a number of methods which can be used to improve the quality and manufacturability of the product (Shina, 1991a). Such methods include Design for Manufacture and Assembly (DFMA), Design for Test (DFT) and Quality Function Deployment (QFD).

Finally, in today's environmentally conscious world, it is becoming increasingly urgent that designers evaluate their designs in terms of environmental impact (Beitz, 1990; Dagger, 1992; Dillon, 1994).

McKenzie (1991) argues that designers influence environmental impact directly through their role as setters of style and tastes and he maintains that they now have the opportunity to

> *". . . demonstrate that environmental considerations, along with social and ethical concerns, occupy a central position within mainstream design thinking."*

Writing about the automotive industry, Dagger (1992, p 4) insists that engineers should be concerned not only with the construction but also the *destruction* of automobiles. In the author's opinion, this design for disposal (DFD) approach should equally be adopted by designers in the wider electronics industry. Evidence from the research indicates, however, that much has yet to be done before DFD is comprehensively adopted – particularly in Japan. Furthermore, Dillon (1994) has identified some major obstacles to cost-effective recycling in the electronics industry, notably the fact that electronics products entering the waste stream today were not designed with recycling in mind. She notes that:

> *"A lack of information about their composition, material variety, purity of recyclates, and hazardous constituents presents hurdles to their being successfully recycled, particularly plastics."*

Dillon (1994) lists the kinds of product design changes which will be required for cost-effective recycling. These include:

- Product simplification;
- Standardisation of components and product configuration;
- Modular designs, especially with components for reuse;
- Standardisation of material types;
- Easily detachable parts;
- Reduction in the number of pieces requiring disassembly;
- Easily accessible components in products;
- Reduction in number of material types to reduce sorting.

3.1.2.3. Design intensity

According to Gomory and Schmitt (1988), "a higher rate of new product introduction in many foreign firms results in more rapid learning, which translates into more rapid improvement of design and manufacturing processes."

While it was evident from the research that many of the U.K. and European companies visited appeared to be undertaking more design than in the past, there is little doubt that constant changes in both competitive environments and customer requirements will oblige U.K. electronics firms to be able even more rapidly to undertake a greater number of product design projects.

The answer does not lie in instituting an intense design regime for its own sake, however. As Bowen *et al* (1994) cogently point out, product development projects provide "the best opportunities for a manufacturing company to renew itself constantly so that it can attain and then retain a leadership position." By enabling the creation of new products and processes and by facilitating the development of new skills, new knowledge and new systems, "development projects provide a comprehensive, real-time test of the systems, structures and values of the whole organisation."

In other words, greater *intensity* of design must be accompanied by an ability to learn lessons from past projects which are subsequently applied to future ones. The author observed precisely this phenomenon in the Japanese firms he visited and he discusses the need for organisational learning in more detail in Chapters 4 and 5 of this thesis.

3.1.3. Components of the product design capability

The change in competitive forces outlined above represents a paradigm shift (Furukawa, 1992) which is forcing electronics companies to confront problems with which they have, to date, been ill-equipped to cope. Firms are being forced to respond *simultaneously* along a broadening expanse of manufacturing concerns, including products, processes and organisation.

Hamel and Prahalad (1991), Morden (1989), Hamilton and Singh (1992) and Teece *et al* (1992) are all agreed that the answer lies in the creation and evolution over time of distinct "competences" or "capabilities." As Hamel and Prahalad (1991) put it, the company should be conceived as

> *"a portfolio of core competencies rather than as a portfolio of products . . ."*

A competence may be defined as an essential skill set or capability, in areas such as sales, marketing, customer service, product and process design and development and manufacturing, required to deliver one or more targeted product attributes (Helming, 1994). This definition encompasses people (skill sets, experience, training, education), "physical" process capabilities (physical plant, equipment, systems and the associated expertise) and related business practices. According to Prahalad and Hamel (1990), "core" competences are those which satisfy three main criteria:

- They make significant contributions to perceived customer benefits in the end product;
- They are difficult for competitors to imitate;
- They provide access to a wide variety of markets and product families.

For the purposes of this thesis, however, the definition of "capability" adopted by the author is the one advanced by Leonard-Barton *et al* (1994) who describe core capabilities as a "capacity for action." They further state that:

> *"(. . . .) capabilities (. . . .) each consist of four elements whose interaction determines how effectively the organisation can exploit it (sic). Those elements are:* knowledge and skills - *technical know-how and personal 'know-who' (. . . .);* managerial systems - *tailored incentive systems, in-house educational programs or methodologies which embody procedural knowledge;* physical systems - *plant, equipment, tooling and engineering work systems (. . . .) and information systems that constitute compilations of knowledge; and* values - *the attitudes, behaviours and norms that dominate a corporation."*

Where electronics design is concerned, a useful means of categorising the key components of this core capability is provided by the Computer Integrated Manufacturing – Open

Systems Architecture (CIM-OSA) model of manufacturing (AMICE ESPRIT, 1989) which employs a "Manage", "Operate" and "Support" framework. According to the CIM-OSA model, "Manage" activities are those which support strategy formulation and direction setting as well as business planning and control while "Operate" activities are classed as those which are directly concerned with satisfying the requirements of the external customer.

"Support" activities typically act in support of the Manage and Operate activities. They include the financial, personnel, facilities management and Information Systems (IS) provision activities. In the context of this thesis, the Support component of an electronics design capability is also taken to include all those activities required to foster and encourage organisational learning. Such learning involves the systematic gathering and sharing of expert knowledge, best practice, current vs previous case histories, lessons from past mistakes and the kind of wisdom, mostly of the classical engineering kind, which provides the engineer with a "feel" for the technology in question.

Each of these components of a product design capability will be discussed in greater detail in Chapters 5 to 7 of this thesis.

3.2. Conclusions

The competitive changes currently taking place in the electronics sector highlight the need for firms to adopt a capabilities-based approach in their businesses. Many Japanese electronics firms have proven particularly adept at capability building, a skill which has been underpinned, in the author's view, by the consistent emphasis they have placed upon organisational learning.

As already indicated in Chapter 1 of this thesis, however, the creation of electronics design capabilities is a complex process which must simultaneously address the organisation's knowledge and skills, managerial systems, physical systems and values. Here, the author has proposed a framework for categorising the components of an electronics design capability which utilises the CIM-OSA manufacturing model. The author's framework thus regards electronics product design as a set of "Manage", "Operate" and "Support" activities.

Within the context of this framework, the author's research has also highlighted the need for electronics firms both to create and to develop the ability to cope with three dimensions of product design instability brought about by changes in the *nature*, *intensity* and *scope* of product design activities

The following chapter presents a "best practice" view of electronics product design based upon evidence from the author's field research and from the literature.

Chapter 4.

Electronics Design Best Practice

This chapter describes industrial best practice in the area of electronics design. It discusses major issues affecting product design, based upon evidence obtained from the literature and from an international review of product design and manufacture practice.

The case study visits highlighted a considerable number of shortcomings in both the management of the design process and in the computer-based support for that process. They also provided important insights into design-to-manufacture "best practice."

A number of the most significant international case study findings will be presented, highlighting differences in both the technological and managerial approaches to electronics product development adopted by the companies visited. The chapter concludes by presenting a number of practical ways in which firms, by learning from international "best practice," can effect major improvements in their design-to-product capabilities.

4.1. Evidence from the U.K. and European case studies

In general, the eighteen U.K. and mainland European case study visits undertaken by the author revealed that all participating companies were successful in getting their respective products to the marketplace in the face of severe competition. However, those successes were overshadowed by 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" approaches to design and inadequate testing.

In addition, most designers in the study focused largely on producing products which perform a function at an acceptable standard of cost. They seldom appeared to think in terms of design for low inventories, for example, for minimum number of parts/processes or for high yield, nor did the companies appear to regard product design as an activity which had strategic implications for their businesses. The visits also confirmed the fact that existing, computer–based support tools only provide "point solutions" to specific bottlenecks in the product design process.

The following seven sections of this chapter will briefly discuss a number of the key design to manufacture shortcomings discovered during the research. These issues will be presented under the following headings:

- Design policy;
- Parts and materials selection;
- Concurrent engineering;
- Defect control;
- Document management;
- Organisational learning;
- Design management.

4.1.1. Design policy

A design policy is defined by the U.S. Department of the Navy (1986) as:

> *"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."*

The research indicated, however, that the existence of such 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. The author discovered considerable evidence of violated design policies, including, for example, 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.

4.1.2. Parts and materials selection

The companies visited appeared to exercise far more control in the parts and materials selection domain. Many 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 offered a list of components to the engineer. If a component was selected which has anything other than "standard" or "approved" against its entry in the component library, that fact was made visible on the schematic. The program also highlighted use of commercial grade components with deviations of this nature being reported in a log file for clearance at the appropriate design review.

However, the author also encountered a number of significant problems. For example, one company left the choice of components entirely to its design engineers who were 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 was 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 performed only a service function.

4.1.3. Concurrent engineering

The firms being investigated were engaged in the development of only a very small number of entirely new products each year. Most of their design activities were concerned with making incremental improvements to existing product lines. Only one company was found to have successfully adopted the Concurrent Engineering (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.

The CE approach to product design and manufacture is more fully discussed in Chapter 6 of this thesis.

4.1.4. Defect control

All the companies placed the issue of Quality Assurance (QA) high on the list of critical success factors for their respective businesses. They all had systems in place for assuring the quality of their finished products. 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 experimental design methods and the Quality Function Deployment (Sullivan, 1986) approach was disappointingly low, particularly among the smaller companies visited. Problems were also experienced getting QA metric information back to design.

4.1.5. Document management

Engineering project administration can best be achieved by keeping documentation to a minimum. A *system* of documentation should nevertheless be established, particularly in companies where different projects are undertaken concurrently and where those projects 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 customer's request that a previous order be repeated, for example, 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 design process is manual and also that designs are essentially paper-based. Hence, if computer support tools are to be successfully integrated with existing systems, it will be necessary to interface those tools to existing methods and to existing archive formats. This approach will ensure that simple linkages are established between people, manual methods, paper documentation and computers.

The merging of data and information to produce a uniform company knowledge base is an extremely complex task, however. To achieve these linkages, and to overcome the kinds of knowledge storage and retrieval problems described by many authors (for example Larson and Christensen, 1993; Engeström *et al*, 1990), the author and his research colleague (Bennett and Culverhouse, 1994) have proposed an electronic product book system as a direct replacement for relational databases and paper-based textual archives.

4.1.6. Organisational learning

An important factor which limits corporate product development effectiveness is the absence, in most manufacturing firms, of mechanisms for capturing, storing and distributing the substantial body of knowledge generated while developing an electronics product (Smithers, 1988). Research has been carried out in this area (Burrow, 1989) but it has concentrated on CAD systems for mechanical engineering.

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 (Nevins and Whitney, 1989). It also requires that such learning be systematised and include such elements as expert knowledge, best practice and current versus previous case histories.

Organisational learning plays a crucial role in Japanese companies (Karlsson, 1990) since their managers view their organisations as learning social systems within the context of which out of date wisdom is "unlearned" and knowledge of successful projects is systematically processed and transferred into other projects. More general success patterns are disseminated throughout the company as "corporate wisdom." The reality of many Western companies, however, is that effective dissemination of information to do with various aspects of product design, quality, reliability and manufacturability rarely occurs since, on a day-to-day basis, the sequential approaches they use to design their products invariably result in a considerable amount of information loss (Smithers, 1985).

The case studies revealed little evidence of systematic efforts to capture and exploit manufacturing knowledge. Almost without exception, the companies visited lacked any formal "institutional memory" which would easily allow lessons from past experience to be fed back into current practices. They were, in effect, "reinventing the wheel" during each project. 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 included: 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 was being held where or, indeed, what value the information was to the company and engineers being denied access to cost information.

4.1.7. Design management

Electronics product design involves the application of a wide diversity of human skills over extended periods of time. In the modern context, it is likely also to require close collaboration between geographically dispersed engineering staff.

Control of such activity is invariably complex, particularly where a firm is simultaneously attempting to manage several product development projects. Perhaps not surprisingly, therefore, the research revealed considerable shortcomings in the management and control of design among the companies visited. It emerged, for example, that while the Bill Of Materials (BOM) of a design might be religiously monitored, little effort would be made to keep track of the number of circuit board iterations carried out during the design process. The research also highlighted cases where the time a design engineer booked to a project was rigourously controlled, yet interactions with production engineering were neither encouraged nor monitored.

Such examples serve to highlight the need for senior executives of electronics companies to acknowledge the potentially devastating impact of poor product design on corporate fortunes and to emphasise the critical importance of management during the product design process. The effective management of design would facilitate detailed planning, the measurement of performance in relation to the firm's product 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.

4.2. Evidence from the U.S. and Korea case studies

Significantly, neither the U.S. nor the Korean visits uncovered any more advanced design practices and software tool usage than those found in the U.K. and Europe. On the contrary, the visits revealed that electronics firms in the U.S. 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 he visited.

Of the U.S. organisations visited, only Hewlett Packard (HP) in Palo Alto, California clearly demonstrated an advanced approach to design–for–manufacture.

4.3. Evidence from the Japanese case studies

The Japanese company visits, on the other hand, demonstrated product design–to–manufacture capabilities which exceeded any the author had seen elsewhere. In particular, these visits confirmed the author's view that design must be regarded as a strategic corporate activity 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.

4.4. Key Lessons

The comparison of international electronics product design practice presented in Table 1. highlights a number of key lessons for U.K. and European electronics companies. Issues have been grouped under three general headings derived from the CIM-OSA model (AMICE ESPRIT, 1989), namely:

- Design management;
- Design operations;
- Support for design.

4.4.1. Design management

From a management perspective, the case study visits demonstrated that it is vital for U.K. firms to regard product design as a strategically important activity and effectively to manage and control the design process.

The author did not discover any typical Japanese strategy for managing product design. At Fujitsu's Mainframe Division in Kawasaki, however, 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.

Table 1: Comparison of International Product Design Practice

	Category \ Country	JAPAN	U.K./EUROPE	UNITED STATES
THE MANAGEMENT OF DESIGN	DESIGN MANAGEMENT	Matrix organisation in all companies visited; multi-disciplinary team-based approach	Strongly organised along departmental lines; some matrix structures	Strong departmental organisation supported by corporate support groups e.g. Design for manufacture
	CORPORATE ATTITUDE TO DESIGN	Design regarded as one of a series of strategic activities	Generally design given low priority, especially in regards investment	Mixed response, some took a strategic view, others gave design a lower priority
	INITIATION OF DESIGN PROJECTS	Top down & bottom up, with young staff encouraged to design products they themselves would like to buy	Top down	Top down
	FOCUS OF INVESTMENT INTENTIONS	Design for market & DFM; aesthetics, lifestyle, next generation tools	Design for Manufacture	Design for Manufacture
	KNOWN AND DOCUMENTED PROCEDURES	Procedures are known & are enabled through technology and "social system"	One or two companies had developed design guides	Some Design for manufacture manuals and procedures (e.g. HP Palo Alto)
	DIFFERENT METHODS FOR DIFFERENT DESIGN PROBLEMS	Explicitly acknowledge different levels of risk in different types of product	Little awareness demonstrated	Little awareness demonstrated
DESIGN OPERATIONS	DESIGN-FOR-MANUFACTURE	Design for manufacture is the prevalent approach	Widely varying: some Design for manufacture	Widely varying; some Design for manufacture
	DESIGN TOOLS	2nd or 3rd generation in-house tools; some bought-in	Almost entirely bought-in	Almost entirely bought-in
	SOURCE OF TOOLS	Multi-vendor supplemented by extensive in house tool development	Major vendor, little/no in house development	Major vendor, some additional tools from specialist providers
	EXTENT OF TOOL SUPPORT	Support for design management; laptops for documentation/ communications; mainframe access via engineering workstations for high level simulation	Drafting office well supported; design office support patchy -- varying from PC to shared workstation	Drafting tools; design mostly manual with schematic capture
	INTEGRATION WITH OTHER APPLICATIONS	Explicitly linked to cost, quality, management and upstream parallel development concept	Limited downstream integration to manufacturing activities; limited parallel integration to quality/cost; no upstream integration to aesthetics and lifestyle	Design for manufacture (Hewlett Packard)
DESIGN SUPPORT	ORGANISATIONAL LEARNING	Yes, at all levels in the organisation. Facilitated by use of *KAIZEN* techniques	None observed. Concern expressed at how much knowledge was *only* in peoples' heads but no attempt to capture and reuse knowledge	Only observed in Hewlett Packard's attempts to develop a DFM manual
	TRAINING	Strong philosophy regarding training; on the job training common; basic design skills acquired through apprenticeships	Very mixed approaches; no apprenticeships for basic skills; some evidence of buying in skills	Very mixed approaches; no apprenticeships for basic skills; tendency to buy in skills and to quickly dismiss staff who don't measure up
	DESIGN STAFF TURNOVER	<2%; no key staff turnover	10% - 20%, including key staff	10% - 20%, including key staff

During the design of large mainframe computer systems, for example, Fujitsu's project managers define system performance requirements down to LSI level. Once partitioning of tasks, and specification of precise targets for each task, has been undertaken, engineers are then free to implement the design in any manner they choose. Support for this part of the design process may be sought through consultation with colleagues as well as through open access interrogation of Fujitsu's engineering database.

As Figure 3 indicates, information concerning LSI use/implementation methods is freely circulated among engineers, both verbally and by memo and tight communication links are maintained between CAD development engineers, technology development engineers and systems design engineers. Formal information exchange takes place between hardware and software development engineers, often through small group meetings, especially when new system functions and architectures are being defined.

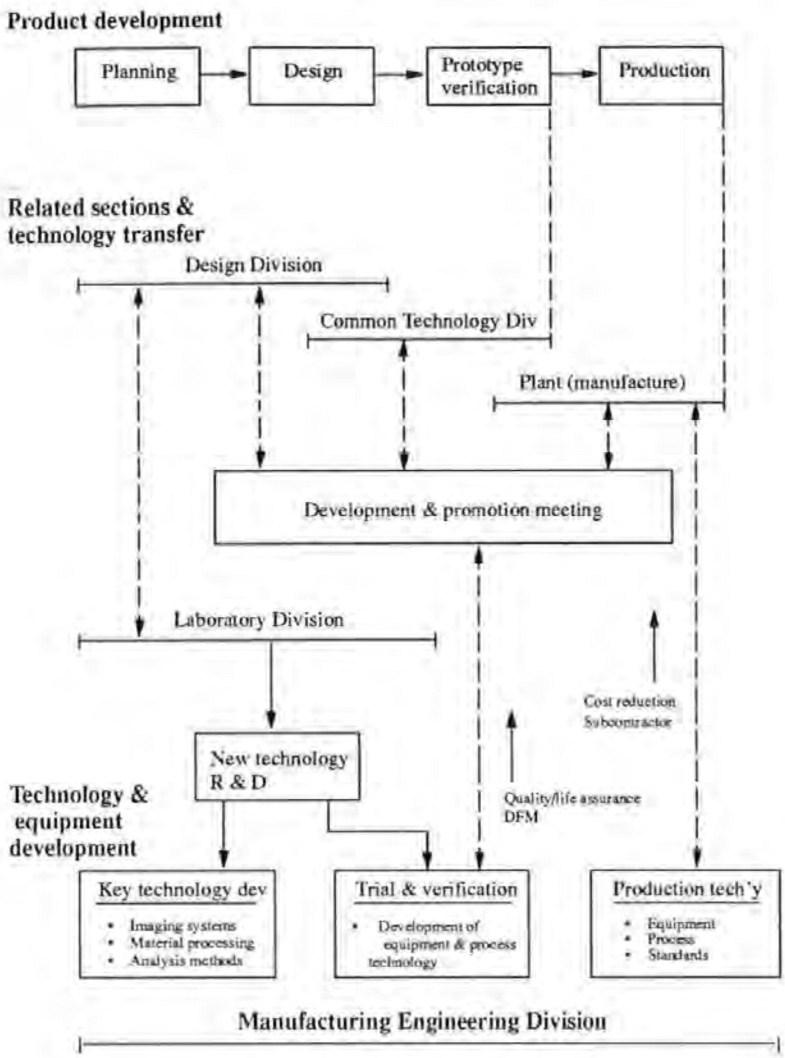
Figure 3 also demonstrates that, as part of the overall product planning to production process, quality, life assurance and design-for-manufacture knowledge are communicated back from production. Subcontractors, who contribute significantly to Fujitsu's product development success, are taught how to use new technology, for example, and how to reduce costs.

4.4.2. Design operations

Operate activities are classed as those which are directly concerned with satisfying the requirements of the external customer. These are sometimes referred to as "core" activities and include:

- All activities in the design process itself which are required to realise the product;
- The provision of design automation computer support tools;
- The provision of effective integration between different databases;
- Use of concurrent engineering practices.

Figure 3: Fujitsu Mainframe Division Product Development Process



4.4.2.1. The design process

As Table 1 demonstrates, the author's research has highlighted a patchy appreciation, by many companies, of the importance of company-wide design procedures and methodologies. However, the Japanese companies appeared to be particularly effective in organising their design efforts and in developing design methodologies. In contrast, only a few Western companies appeared to assign any significance to the establishment of corporate design methodologies, with the predominant U.K. view being that product design is a "black art" and should be left alone.

Design for Test (DFT), Design for Manufacture (DFM), Design for Assembly (DFA) are all acronyms used, and applied, in various sectors of electronics production engineering in both the U.K. and the United States. However, few design engineers interviewed in these countries appeared interested in the issues which lie behind such concepts, and even fewer realised that it should be their concern. Further, design appeared to be compartmentalised in many U.K., U.S. and Korean companies, with industrial design, product function design and product assembly and test design being done by different groups of people in different parts of a company, with little routine communication between them.

In Japan, on the other hand, the case study companies routinely marshall whatever resources are required to accomplish a particular product development goal and, in so doing, place great emphasis on effective communication, both horizontally between small development teams and vertically with regard to strategic product planning.

In addition, U.K. companies did not appear to recognise the importance of classifying design projects according to the amount of engineering risk involved, or according to their degree of difficulty. One case study company discovered the danger of adopting this approach when it launched the development of a strategic product in an attempt to "leapfrog" the competition. The project quickly ran over budget and behind schedule because it had not initially been recognised that a considerable amount of R&D work needed to be carried out, over and above the normal product development activities.

4.4.2.2. Computer support tools

At the operational level, heavier workloads for design engineers and the increased complexity of the designs they are being asked to undertake has placed a premium on investment in computer-driven technology. According to Hax (1989), the right technology, if used wisely and in a timely fashion, can significantly enhance a firm's design-to-manufacture capabilities. Its use can also help to reduce costs, improve product quality and raise employee morale.

The Japanese companies provided some insight into future directions for design automation systems, particularly with regard to the manner in which they have developed their own electronics design toolsets, but also through their efforts at integrating commercially available design software into their design processes. The companies have each had vigorous in-house

CAD/CAM/CAE/CIM development programmes in place for a number of years, and they have been using this work to extend the boundaries of product design. In other words, they are moving away from a narrow, merely technological focus in design and are increasingly venturing into design management, the development of design infrastructures, design-for-manufacture and even into aesthetics and lifestyle design.

This trend to in-house engineering software development is being driven both by high (currently around $50,000 per seat) commercial licensing costs of software for product design workstations, and by demographic pressures. Japan's declining birth rate is causing shortages of engineering staff and is forcing electronics companies to automate as much of the design process as possible. For example, Toshiba is currently developing its own new CAD environment. However, despite the fact that the company's JCAD system was scheduled for completion in March 1992, the company already had plans to complete a next-generation CAD system (Super-JCAD) by the end of 1994.

While the earlier project allowed Toshiba engineers to carry out system simulation for midrange computers, for example, they were unable to simulate personal computing devices such as hard- and floppy-disk controllers because of the complexity of their LSI functions. This personal equipment simulation capability was to be one of the enhancements embodied in the Super-JCAD system. Fujitsu engineers, on the other hand, were using the company's most powerful mainframe products to design the next generation top-of-the-range computers and, since simulation plays such an important part in this process, the company had developed a special logic simulation processor for that purpose.

4.4.2.3. Integration

Electronics firms typically use a range of advanced manufacturing technologies, including CAD/CAE systems, automatic insertion machines, automatic test equipment, robotic assembly and conveyor systems and either flow or re-flow soldering equipment. However, different manufacturing and assembly operations are usually run on different – often interconnected – computer-driven machinery 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, however. In particular, the International Standards Organisation (ISO) has produced a reference model, known as the Open Systems Interconnection (OSI), for organising the tasks involved in communications and networking (Morgan 1986).

There is an important distinction to be made here between "linking" and "integration" which is especially true in light of competitive imperatives currently driving many companies towards Computer Integrated Manufacturing (CIM). Linking usually involves the transmission of data, in some neutral format, between a series of modules, either CAD system to CNC machine, 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 CAM such links are becoming increasingly formalised through the adoption of such standards as the Initial Graphics Exchange Specification (IGES).

Links from design through to the shopfloor are haphazard in the electronics sector, where drill tapes and artwork can be transferred in machine readable format, but the control of test equipment and 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.

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 (Harrison *et al*, 1985). The importance of this issue is highlighted by Maull *et al* (1990) which indicate that one of the principal factors contributing to Computer-Aided Production Management (CAPM) 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 CAPM systems when it became apparent they would not integrate with existing Sales Order Processing systems, for example, or with new CAD systems.

The design automation systems used in all the Japanese companies had achieved a degree of integration with other computer-aided aspects of their operations not witnessed elsewhere in the world. In particular, their toolsets are strongly integrated backwards into manufacture and, additionally, considerable efforts have been made to effect parallel integration of the various design functions with costing, quality, industrial design and management systems. Where gaps are uncovered between the toolsets themselves, Japanese design engineers -- many of whom also have software engineering skills -- are encouraged to write their own "bridging" software.

4.4.2.4. Concurrent engineering

The manufacture of electronics products requires the application of the knowledge and skills of a wide variety of people, from industrial designers and social scientists to personnel from marketing, product design, purchasing and inventory control. In the past, such people were invariably involved in a time-consuming "relay race" (Takeuchi and Nonaka, 1986) during which one group of functional specialists passed the product development baton to the next. The project went sequentially from phase to phase: concept development, feasibility testing, product design, product development, pilot production and final production. Such an approach is still widely used and leads to costly delays as errors, which could have been avoided, surface late in the development cycle.

There is a wide body of literature, (Burton and Dabney, 1990; Wilson and Greaves, 1989; Bunza, 1990; Reich, 1989 for example) which suggests that Western manufacturers must abandon the "relay race" in favour of an approach which concurrently designs both products and process and which requires all parts of a firm to be directly involved, through the use of multi-disciplinary teams, in the conceptualisation, specification, development, manufacture and support of new products. This approach, known as Concurrent

Engineering, has a vital role to play in the operational aspects of electronics design and will be discussed in more detail in Chapter 6.

4.4.3. Support for design

At an organisational level, the research has revealed that electronics firms need to create new organisational structures and cultures which can more effectively support their product design activities.

Two features of any supporting company environment must be the provision of electronic communications which facilitate easy sharing of information among teams and individual design engineers and an infrastructure which enables engineering knowledge and "wisdom" to be retained within the company.

A number of cultural and infrastructural issues related to the support for electronics design will now be presented.

4.4.3.1. Design culture

While the application of formal management techniques remains an important contributor to good product design, Fairhead (1987, p 9) notes that it is much too subtle and complicated a process for everything to be controlled in this way. He suggests that instead, senior managers in successful companies seem to be trying to sympathise with and manage the fundamental assumptions that underlie the way their people think and act.

> " . . . . *effective product design is largely the result of a culture that is relatively open, responsive, co-operative and action-oriented.*" (Fairhead, 1987)

In order to facilitate the creation of a strong and flexible culture, Fairhead emphasises the need for firms to improve their use of both financial and non-financial reward systems in motivating their staff. He also recommends that firms should get better at recruitment, training and development.

From a cultural perspective, the research demonstrated that U.K. electronics firms should foster a more "aggressive" approach to product design where design engineers are encouraged to take risks and where mistakes and failure are, within limits, more easily tolerated.

Indeed, during his visit to the Sony plant in Japan, the author discovered a culture in which "designers have a general tendency to be aggressive." Furthermore, he learned that, working within this kind of design milieu, groups of designers feel "unable to stand still" and are constantly urged to take more risk. On an individual level, he was informed that designers are "aggressive" in their desire to improve their own personalities, their own positions and their own knowledge.

Furthermore, the author discovered that the Japanese companies visited all encouraged their (predominantly young) designers to design products they themselves would like to own. Hence, as Table 1 indicates, 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.

In addition, it appeared that all engineers in the case study firms had free access to corporate information, including so called "secret" information. The lifetime employment system these firms operate means very few employees ever leave, and there is little danger of such information "leaking" to competitors. Such practices differ markedly from those encountered in the West, and particularly in the U.K. where many engineers are denied access even to component cost information.

4.4.3.2. Electronic communications

Effective support for a firm's design activities also requires the provision of a set of basic IT resources which support and promote communication among teams and individuals. Despite the ongoing importance of person-to-person communications in the context of a multi-disciplinary, team-based approach to electronics product design, it is evident that increases in both company size and product complexity are requiring firms to improve their electronic 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.

A company which uses computer support tools should logically have them networked in order to allow the transfer of information between the personnel using the computers, rather than using paper based internal mail systems. Recent developments in electronic mail (or email) have revolutionised the way in which mailing operates. Traditionally, email has operated as a simple text-based message passing system. However, the Microsoft email system, amongst others, now offers the ability to send mail from any application programme written to interface to it, to any other application programme. For example, a person using a spread sheet under Microsoft Windows could email the contents of the spread sheet to another person on the network.

This is a useful capability, since it may enable an engineer developing a circuit schematic diagram to 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 violated.

In addition to facilitating day-to-day inter-personnel communications, an electronic mailing system is also essential if both design control and engineering change control are to be effective. The organisation of meetings may also be simplified using computer based meeting schedulers and even on-line personal diaries.

4.4.3.3. Organisational learning

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 their 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.

In marked contrast to Japanese human resource management practices, which seek to retain and develop the firm's skilled engineering resources, the research indicates that many firms consider a 10% - 20% annual engineering staff turnover to be an acceptable, even desirable means for them 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. This 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. Indeed, a comparison of Japanese on-the-job-training (OJT) and design apprenticeship techniques with U.K., European and U.S. practice in this field highlights the fact that the Japanese generally adopt a longer-term view even of personnel recruitment than do their Western competitors.

The U.K. and European companies which took part in the author's survey had few formal, enforced procedures specifically aimed at 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.

4.5. Conclusions

Using evidence obtained from the literature and from an international review of product design and manufacture practice, this chapter has highlighted major weaknesses in the electronics product design practices of U.K. electronics firms. It has also described a number of key issues in electronics design best practice and has grouped those issues in accordance with the three elements of the author's design capability framework, namely "Manage", "Operate" and "Support."

From a management perspective, the author has noted the importance of regarding product design as a strategically important activity and of effectively managing and controlling the design process. At the operational level, heightened design intensity and the increased complexity of the designs which engineers are being asked to undertake has placed a premium on investment in computer-driven technology. Such factors have also made it necessary for electronics firms to formalise their approaches to product design, particularly through the adoption of DFM, DFT, DFMA and Concurrent Engineering techniques.

While effective design undoubtedly relies heavily upon the use of appropriate methodologies and design automation tools, the author has shown that it also requires the establishment of a supporting infrastructure for design. From a cultural perspective, such a "design friendly" infrastructure would adopt more enlightened approaches to staff recruitment, training and development. The requirement to design increasing numbers of more complex electronics products means that U.K. electronics firms must recruit the best people and, having recruited them, should ensure that they are educated and trained on a continuous basis.

Furthermore, the research has shown that U.K. electronics firms should foster a more "aggressive" culture where product design is concerned. Design engineers should be encouraged to take risks and mistakes and failure should, within limits, be more easily tolerated.

In addition, the supporting infrastructure would provide an appropriate reward and recognition environment which, by enabling engineering knowledge and "wisdom" to be retained within the company, would facilitate organisational learning. Such an infrastructure would encourage team working by providing staff with more effective means of communication - particularly where team members are geographically dispersed.

The following chapter provides a detailed account of the management aspects of an electronics design capability.

Chapter 5.

The Management of Product Design

Modern electronics products are invariably an amalgam of complex, integrated parts and technologies, both mechanical and electronic. On the electronic side, the rapid growth in integrated circuit device complexity, for example, has been made possible by the miniaturisation capabilities of state-of-the-art lithographic technologies.

Designing such products is inevitably a complex, highly creative process which begins with the development of a customer specification. However, it has generally been thought, certainly within Western electronics companies, that product design is a creative activity which either cannot be managed or, as Constable asserts, is typically managed "in terms that are fuzzy . . . (using) monitoring systems that wobble" (Constable, 1994).

It is the author's view, however, that product design is a 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.

Product design management requires the integration of project strategy, project execution and project performance (Wheelwright and Clark, 1992). For the purposes of this thesis, however, the discussion of product design management will focus upon the need to control product design projects in order to reduce delays and overspends, the need to minimise risk in such projects and the requirement to enhance both the product's time-to-market *and* its manufacturability.

5.1. The need for management in the electronics design process

5.1.1. Design is strategic

Electronics product design may be regarded as a strategic activity, and hence one which merits rigorous management and control, because design choices directly affect such aspects of product development as materials, fabrication methods, assembly methods and inspection and test techniques.

It has been estimated, for example, that between 70% (Nevins and Whitney, 1989; Daetz, 1987) and 85% (Fleischer and Liker, 1992) of a product's lifecycle cost are determined when it is designed while, in the case of Surface Mount Technology (SMT), that figure can rise to 90% of the total PCB assembly cost (Owen, 1990). Hence, by the time a product reaches detailed design, its final performance, quality and cost are already locked in.

Child *et al* (1991) estimate that as much as 80% of costs, 50% of quality, 50% of time and about 80% of business complexity can be influenced through product and process design.

5.1.2. Design transformations

The importance of managing the product design process also becomes apparent when one considers that a product is designed at many levels within a company, with differing requirements at each level. Starting with the customer specification, the product may be viewed as undergoing a number of transformations, each of which requires diverse engineering information about the company capabilities and other constraining factors.

Regardless of whether the customer is an internal or external client, the first product design transformation which occurs is the transformation from "model of product held in customer staff" to "model of product held in company staff" (Culverhouse, 1990). This transformation generally takes place as a result of the interaction which occurs between experienced company engineers and customer engineers. The result is a specification of requirements, detailing product function, cost, project time, volume, size, environmental and test requirements.

The second transformation is from legal document to block diagram or flow diagram. Such a transformation is made to partition the design in order to allow for modular construction. Such partitioning would need to take into account a variety of mechanical, electrical and packaging requirements, for example. Ideally, a number of different design solutions would be developed at this point and evaluated to determine cost, time, resource and risk impacts on the company. An optimal solution would be developed further.

The third transformation is from functional specification to circuit specification. At this stage, the electronic functional specification, a blend of block diagrams and performance figures, would be translated into a circuit notation drawing (to an internal or external drafting standard) which could be mapped directly into functional blocks. These could be fabricated in house, or purchased and assembled into a real, working circuit.

According to Culverhouse (1990), the personnel involved at each transformation stage are routinely applying their knowledge to ensure that all the constraints are fulfilled and that the additional levels of detail demanded are added. At the same time, they are attempting to ensure that an accurate representation of the prior model exists in the new model. This transformation-interpretation cycle can lead to errors, however, since the nature of the task is often unintentionally modified by the people carrying out the transformations as they seek to understand and interpret the design. Although this may seem fanciful, the work of Baker *et al* (1989) indicates that expert engineers engaged in high level design specification make several types of error when under pressure. These errors include:

- Mathematical notation inconsistency, leading to incorrect expansion of the expression;
- Diagrammatic inconsistency between levels of description, leading to an incorrect circuit description;
- Incomplete acquisition of design specification data, leading to an incomplete model of the product and missing information in subsequent transformations of the design.

Hence, the degree to which an electronics company is able successfully to design and manufacture its products may not be so heavily dependent upon the speed at which its is able to expedite the design transformations. Instead, success is more likely to depend upon the accuracy of the transformations and upon the firm's ability to capture and reuse the considerable amount of information and knowledge generated during the design phases.

However, the author's research has shown that, in most companies, much of that information and knowledge is lost and needs to be recreated as design teams move from one project to the next. As Chapter 7 of this thesis explains, it is also typical for companies to lose experienced staff, many of whom take with them a considerable amount of vital knowledge and "wisdom". It is important, therefore, that documentation of all information and knowledge generated during product development be carried out in accordance with an agreed set of rigorous corporate standards.

5.2. The control of product design

The British Standards Institution (BS7000, 1989) stipulates that the control of product design projects should occur at three levels:

1. The management of product design at a corporate level;
2. Managing product design at project level;
3. Managing the design activity itself.

5.2.1. Management at the corporate level

At the corporate level, BS7000 specifies that effective product design requires the establishment of precise and, where possible, quantified corporate objectives which should be communicated to and understood by all concerned. Design management also involves the production of a number of plans, for example, a business plan, a product plan and a resource plan, and it requires the establishment of a set of organisation-wide policies covering such areas as design protection, product liability, recording design data and engineering change control.

5.2.2. Management at the project level

At the project level, the British Standard deals with those aspects of managing product design which are project specific. These include the establishment of project objectives, the development of project plans and the creation of a project control regime aimed at bringing each project to a successful conclusion.

5.2.3. Management of the design activity

According to BS7000, the management of the design activity itself involves ensuring that the product design meets the design brief, that the necessary resources are planned and deployed and that the design process – from concept to realisation – is implemented and controlled.

5.2.4. Project management

Various approaches to project management have been proposed (for example Turner, 1993; Harrison, 1985; Downs *et al*, 1992), each of which generally requires the firm first to undertake a series of planning and control activities using a number of procedures and techniques.

Wideman (1989) has defined a function-process-time model of project management in which project functions include scope, quality, time and cost specification; risk and human resources management; communications provision and management; post-termination monitoring of product performance. The management process component includes project planning, organisation, execution, monitoring and control. The time dimension is comprised of the four project lifecycle stages: concept, planning and development, execution and termination.

Senior executives of electronics companies should put in place effective project management capabilities in order to facilitate 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.

While undertaking product design projects, firms need to learn and improve, both technically and in relation to the way they manage their projects. However, while current project management methodologies may seek to enable firms to learn from past success and to avoid past mistakes via the post-project audit mechanism (Turner, 1993), they do not provide firms with the means to identify, record and classify, absorb/routinise and retrieve for reuse key project knowledge and experience. Indeed, the author has found little evidence of any work which has sought to apply the principles of organisational learning to project management, particularly with regard to the management of technological innovation projects in SMEs.

Planning may be undertaken for individual projects in order to control timing and cost management, or across projects to balance the use of resources and specialist skills to support each individual project.

5.2.4.1. Multi project tracking

In today's competitive environment, where considerably more designing needs to be undertaken, personnel and equipment must be allocated to particular projects in a company wide manner in order to ensure that the required combinations of mechanical, electronic and production engineering skills are brought to bear at the appropriate project phases. Critical paths for personnel across a portfolio of projects allows the type of knowledge being placed in projects at particular points in time to be tracked for project delay and cost impact. In this context personnel must be defined as being expert, theoretician (book expert) or novice at the identifiable categories of design routinely undertaken in a company.

5.2.4.2. Management functions

There are a variety of management planning and control functions which should be applied to the control of product design projects. These include:

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

- Communications

5.2.4.2.1. 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 (Stone, 1988). All human resource details should be stored on a per project basis, together with a post-hoc rationalisation of the final outcome of the project for reference in later projects.

5.2.4.2.2. Scope control

Scope control involves such project management techniques as the work breakdown structure (Kerzner, 1989), user sign-off, work authorisation procedures (Kerzner, 1989), scope status reporting and specific post-project audit routines (Turner, 1993).

5.2.4.2.3. Financial control

Thorough financial analysis of each project should be undertaken 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.

5.2.4.2.4. Time management

Engineering projects have time and costs associated with each activity. However, the fact that many projects are discrete, non-recurring events means that their time and cost elements can only ever be estimates. Nevertheless, by reducing the consumption of time in every aspect of their businesses through effective management, many manufacturers have been able to reduce costs, improve quality and stay close to their customers (Stalk, 1988).

Indeed, during the course of his fieldwork in Japan the author discovered a general attitude to new product introduction which placed far greater emphasis on getting to the market on time than on minimising costs. For example, Fujitsu Mainframe Division generally puts more emphasis on delivery in order to get its new products to the market on time – even if manufacturing costs are high. However, the company will shift its focus from time to other product attributes (for example, quality, functionality, performance) where a competitor has made a product announcement before Fujitsu.

Toshiba was similarly concerned with shortening the product development cycle. At their Sparc-LT (compatible with Sun Sparc) factory outside Tokyo, the author was informed by a Toshiba engineer that shortening the development lifecycle depended upon the market requirement.

> *"If the market is asking for a smaller machine, whether we can shorten or lengthen the development cycle depends on the status of the technology. But the pressure is always to shorten the cycle."*

5.2.4.2.5. Quality control

Measurements of design quality can usually 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 the author has generally not found this to be a normal part of design monitoring in the U.K., design iterations are relatively easy to track if CAD tools are used to develop the electronics circuitry. Careful discussion of progress with engineering staff can also be effective in this regard, however.

In order to maintain and improve design quality, electronics firms should implement continuous improvement (CI) programmes within the product design process. An essential element of any CI effort would be the establishment of a formal feedback method which would supply design engineers with information on some or all of the following design process parameters:

- 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 time and budget at each project assessment gate

5.2.4.2.6. Communications

Meetings play a crucial role in any organisation's decision-making activities since, in the modern commercial environment, almost everyone belongs to at least one formal or informal group. Meetings can be broadly defined to include any activity where people come together, whether at the same place at the same time, or in different places at different times (Nunamaker *et al*, 1991). Such groups typically get together, among other things, to share information, generate and organise ideas, build consensus, collaborate in writing reports and to draft policies and procedures.

Meetings have assumed added significance in the field of electronics product design, however, as companies recognise the cycle-time shortening potential of employing concurrent engineering methods which rely heavily on the use of multi-disciplinary product development teams. In such circumstances, it is quite possible for engineering staff to be involved in more than one project at a time. This places a premium on such group processes as inter-personnel communications, resource sharing and decision making.

5.3. Minimising risk in product design projects

Stone (1984) comments that Japanese firms are prepared to take risks but that they will make sure that everything necessary is done to make the risk work.

> *"If failure occurs, it is rarely by shooting too low and being overtaken by the competition. Rather, it is by shooting too high."* (Stone, 1984)

It appears sensible to view product design as a process which attempts to minimise the risks associated with a given project, taking into account the needs of the engineer and of the creative aspects of product design. Culverhouse (1993) proposes a Four Path approach to electronics product design which categorises designs according to the amount of risk they represent to the company. In this model, which is more fully described in Section

5.3.2., design risk is directly related to the amount of change or novelty which engineering staff must cope with in undertaking a design.

Risk is also closely related to project control. According to Takeuchi and Nonaka (1988):

> *"Under the sequential or relay race approach, a project goes through several phases in a step-by-step fashion, moving from one phase to the next only after all the requirements of the proceeding phase are satisfied. These checkpoints control risk. But at the same time, this approach leaves little room for integration . . ."*

The final two sections of this chapter examine the role of design reviews in the minimisation of risk, as well as the that played by the adoption of a Four Path approach to product design.

5.3.1. Design reviews

From an engineering project monitoring and control point of view, the design audit or review provides a mechanism enabling the design activity to be carried out "in a balanced and best compromise manner, leading to improved designs and products" (Pugh, 1990). Dieter (1991), Burgess (1984) and Hubka (1980) all describe the activities which should be undertaken in a design review. Buur (1989) indicates that Japanese firms employ *keypoint plans* which describe the main checkpoints in a project. In some or all of these checkpoints the project will undergo design reviews.

Regardless of the type of design being undertaken every product should pass through a series of gates (Cooper, 1991). For a design, or part of a design, to pass through a gate and on to the next phase of the development process it must meet or exceed criteria laid down to ensure that the developing product is likely to be manufacturable, will meet the original customer specification and not exceed company budgets.

These gates are check points for senior management who are responsible for design and manufacturing. A signature is often required as approval to spend more money or commit more resources to a project at such check points, to allow a work programme to continue to the next stage in development. In addition to these external gates (outside the design team), several internal gates may also applied to design and production processes to check project progress on a more day to day basis, these would be conducted by various senior staff working on the design project.

Table 2: Design Assessment Gates	
Gate	**Checklists**
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 - Preliminary assessment of specification and requirements	*• Is it 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 international standards* *• Check if design proposals signal manufacturing changes* *• Check statements on proposed test strategy* *• Check skills and equipment availability plan* *• Check technical specification has been developed* *• Check if 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*

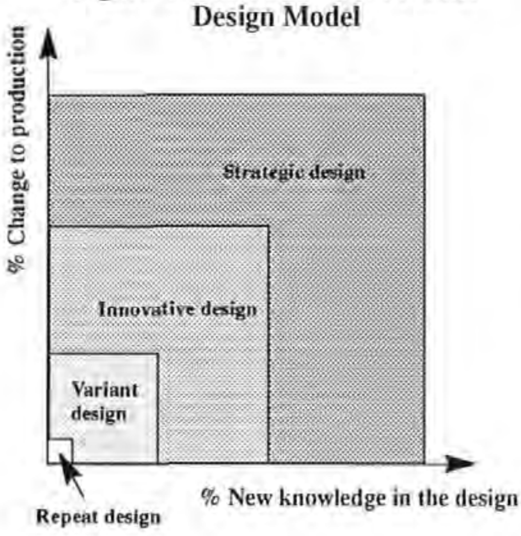
The author's design process model (Culverhouse and Bennett, 1991) provides a mechanism for risk reduction by establishing an audit mechanism via a series of five Release Gates, each of which is conducted by a project-independent product release committee. Table 2 depicts a typical set of checks which may be carried out at three of the five stage gates.

The purpose of the gates is both to monitor the progress of the project and to provide the company with an opportunity to formally evaluate the evolving product design in a systematic and thoroughly documented manner. Operational aspects of design are also catered for through the various activities and tasks outlined in the model. These are discussed in greater detail in Chapter 6 of this thesis.

5.3.2. Four paths

The author's research has shown that electronics engineering managers must appreciate that it is impossible to successfully manage a portfolio of electronics product development projects using a "single track" approach. Clearly, 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.

Figure 4: The Four Path Product Design Model



The design process model addresses this issue by explicitly acknowledging that different categories of product entail different levels of engineering risk. The author with Culverhouse (1993) has proposed 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 4 demonstrates how this approach views designs as *Repeat Designs*, *Variant Designs*, *Innovative Designs* and *Strategic Designs*.

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 dependent on particular circumstances, rather than hard and fast percentages. For the purposes of illustration, the following descriptions refer to the percentage of new knowledge. The percentages depicted in Figure 4 should not be strictly interpreted.

The Four Path model treats a new product as a *Repeat Design* if there is no (or near zero) new knowledge required to complete it either in design or in manufacturing. Repeat Order designs typically involve no extra design or production effort since the firm is simply building more of the previously designed product. This category of design may involve the company in cost reduction exercises to reduce parts, for example, or in manufacturing process optimisation where those processes impact the design of the product.

A design may be classed as a *Variant*, on the other hand, where between one and twenty percent new knowledge is required either in design or production.Variant designs are the most common category of design and may be achieved through, for example, the extension of an existing product through incremental innovation, the refinement of existing technology usage or through the application of modified manufacturing technology.

An *Innovative Design* requires between twenty and fifty percent new design or production engineering knowledge. Radical new designs may be created by combining features from existing products, by the use of new technology in existing solutions or through the application of new manufacturing technology. Finally, *Strategic Designs* are defined as those which require in excess of fifty percent new design and production engineering knowledge. Their development typically involves the development of entirely new basic operating principles.

It is important to point out, however, that each of the design paths described above differs from the others in one major way only: the level of risk involved. Strategic and Innovative designs will involve a company in finding solutions to engineering problems it has never previously experienced. Those solutions may well require the adoption of new design techniques, such as Concurrent Engineering or Design for Manufacture and Test, or they may involve the use of unfamiliar materials and manufacturing processes.

Furthermore, different elements of a *single* product may require firms to pursue a variety of design paths. For example, a systems design or a software configured product may contain pre-existing subsections to which new extensions are added. In such circumstances, the existing parts of the product would be classed as "Repeat Design" while the extensions would be viewed as "Variant" or "Innovative."

5.4. Conclusions

Electronics product design is a strategic corporate activity. Design choices directly affect such aspects of product development as materials, fabrication methods, assembly methods, inspection and test techniques. From a logistics point of view, product design can provide the electronics manufacturer with the opportunity to manufacture different items in different places, to employ flexible manufacturing techniques, to make common use of parts and materials, to easily adapt standard products to special orders or to have final assembly or configuration close to the customer.

However, modern electronics products are invariably an amalgam of complex, integrated parts and technologies, both mechanical and electronic. On the electronic side, the rapid growth in integrated circuit device complexity, for example, has been made possible by the miniaturisation capabilities of state-of-the-art lithographic technologies.

Designing such products is itself a complex, highly creative process which begins with the development of a customer specification. From that point on, the product undergoes a series of transformations, each requiring diverse information about corporate engineering capabilities and constraints. Hence, the author has proposed that senior executives should drive the product design process and, in order to ensure that the process is rigorously managed and controlled, they should implement effective project management procedures at corporate and project levels and at the level of the design activity itself.

Such procedures would facilitate 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. Lessons learned during projects should be captured and stored in an easily accessible format so that they can be applied in succeeding projects.

In order to minimise risk in electronics design, the author has advocated the use of design reviews and the adoption of a Four Path approach to product design. Such an approach recognises that it is difficult, if not impossible, to successfully manage a portfolio of electronics design projects using a "single track" approach and 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. Designs have been categorised as *Repeat Designs*, *Variant Designs*, *Innovative Designs* and *Strategic Designs*.

The following chapter examines the Operational dimension of an electronics design capability.

Chapter 6.

Product Design Operations

Operational activities may be classed as those which are directly concerned with satisfying the requirements of the internal or external customer. These are sometimes referred to as "core" activities because they add value by acting directly on the flow of business (Maull *et al*, 1994).

In product design terms, these Operate activities essentially comprise the design both of the product and the process used in its manufacture. They also consist of the set of methods, tools and techniques used by engineers during the process of product design, for example Concurrent Engineering, Quality Function Deployment (QFD), Design for Manufacture and Assembly (DFMA) and structured brainstorming.

This chapter will examine the various stages of the process of electronics product design. It will describe a range of methods, tools and techniques used by engineers during that process and it will examine a number of available computer-based tools, their scope and possibilities and the hardware on which they run.

6.1. Product design

The product design activity may be viewed from a variety of different perspectives. In artificial intelligence terms it has been described as an explicitly knowledge-based kind of intelligent behaviour (Smithers *et al*, 1989) and as a dialectic between the designer and what is possible in order to construct the description of an artefact which (Mostow, 1985):

- Satisfies a given functional specification
- Conforms to limitations of the target medium (*e.g.* is a chip layout for some fabrication technology)
- Meets implicit or explicit requirements on performance and resource usage
- Satisfies implicit or explicit design criteria on the form of the artefact (*e.g.* style, simplicity, testability, manufacturability)

- Satisfies restrictions on the design process itself, such as its length, its cost or the tools available for doing the design

From an engineering point of view, design has traditionally been defined as a process of transforming information from a customer's statement of requirements to a full description of the proposed technical system (Hubka, 1980; British Standards Institution, 1989).

A number of authors have described the various steps involved in the design of a product. For example, Andreasen and Hein (1987) propose a six phase integrated product development process consisting of:

Phase 1. Recognition of need;
Phase 2. Investigation of need;
Phase 3. Product principle;
Phase 4. Product design;
Phase 5. Production preparation;
Phase 6. Execution.

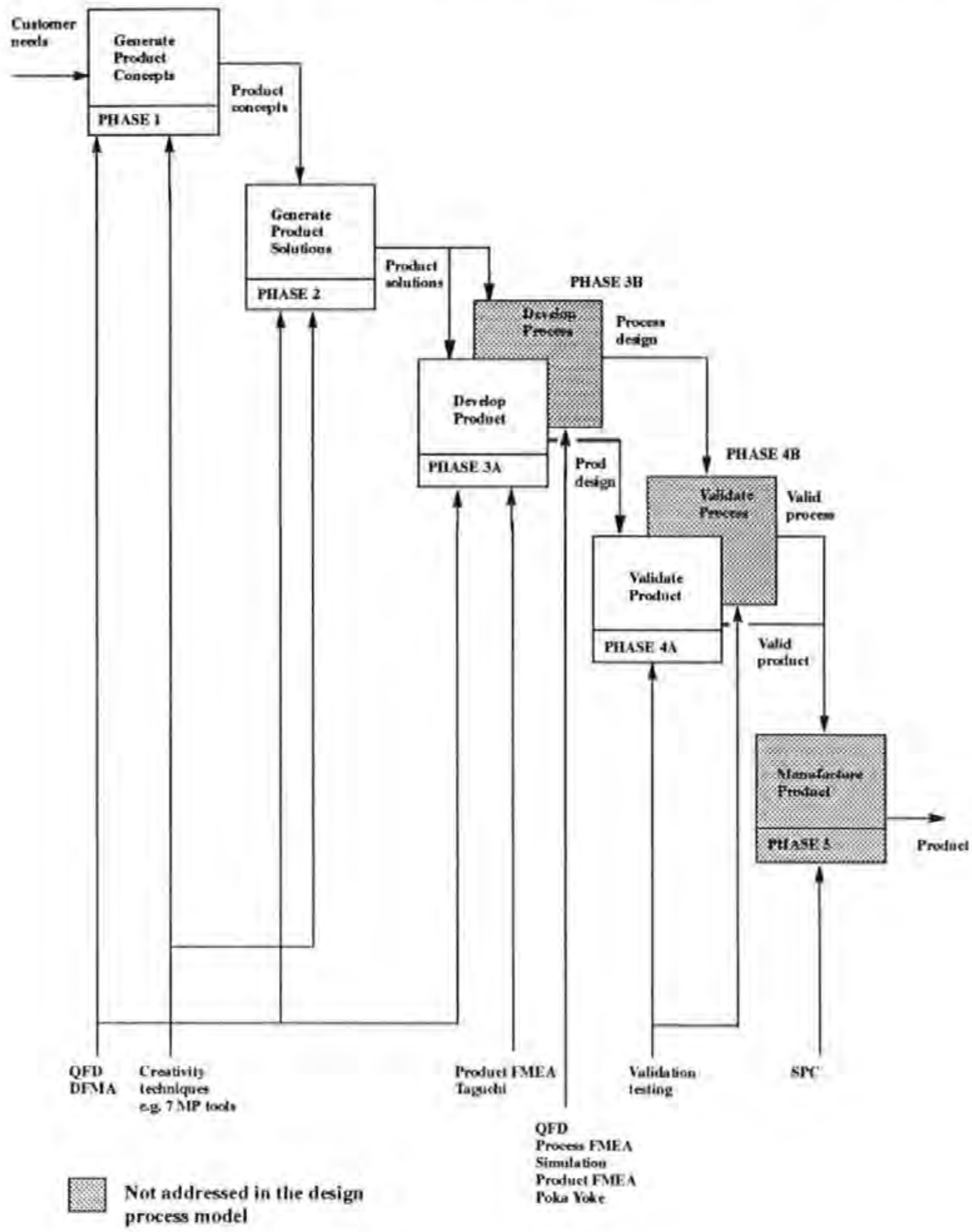
Cooper (1988) describes a stage gate model of product design while Culverhouse and Bennett (1991) have developed an electronics design process model which proposes that the design of an electronic product typically follows a chronological sequence consisting of four phases:

Phase 1. Generate product concepts;
Phase 2. Generate product solutions;
Phase 3. Develop product and process;
Phase 4. Validate product.

A top level view of the process model is presented in Figure 5.

Obviously, the activities summarised in Figure 5 are iterative and one goal of the design teams involved is certainly to ensure that each major step is completed and error free before the next step is invoked. If this is not possible then major costs can be incurred if, for example, the customer requirements specification is altered by a constraint arising in the detailed design phase. Real product design has a number of constraints operating on it

Figure 5 : Top Level View of the Electronic Product Design Process Model



that conspire to modify the smooth flow of the theoretical design path, time to market pressure, unforeseen problems (changes to the customer specification during the development cycle) and personnel availability for example.

The phases of the process model will be described briefly in the next sections of this chapter, with the exception of the Product Validation and the Process Design and Process Validation phases.

6.1.1. 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 (Cooper, 1988). This is especially true of the concept and solution generation phases of the process (Booz, Allen & Hamilton, 1981). Western companies devote most corporate product development resources to the middle and back-end stages while the pre-development activities which determine product success and failure are poorly resourced and carried out (Wilson and Greaves, 1989).

As shown in Figure 6, this phase involves the collection of information about the requirements to be embodied in the solution and also about any constraints. It also involves the establishment of function structures, the search for suitable solution principles and their combination into concept variants (Pahl and Beitz, 1988).

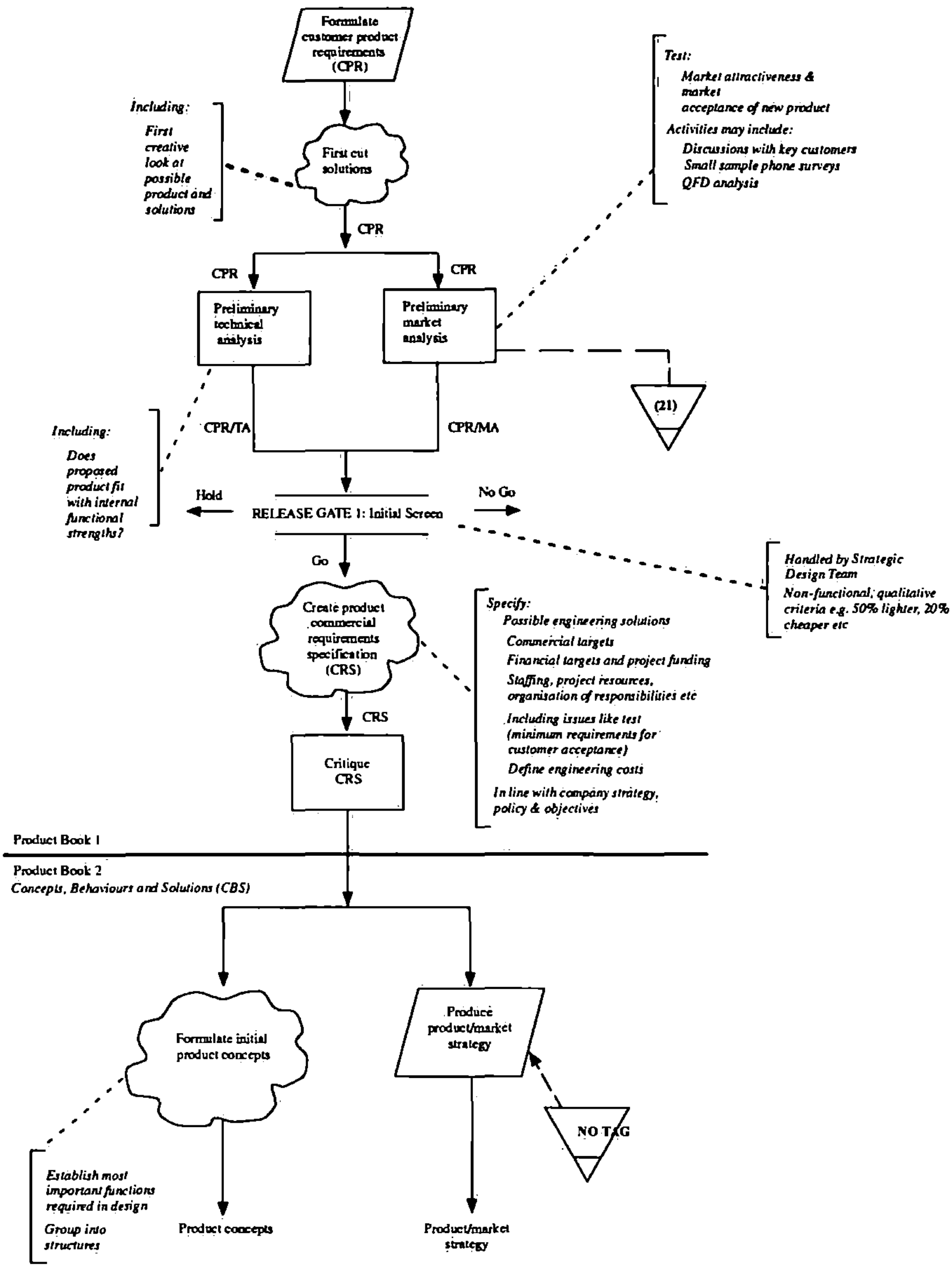
The specification of the product must be complete at an early stage in the overall process of design and manufacture and requires all the constraints on the product, both from the customer and the manufacturing process, to be made explicit. Figure 6 indicates that a Commercial Requirements Specification (CRS) is created during ACTIVITY 6 of the process model.

An optimal solution to these specifications can then be developed, ideally by considering a number of alternatives, rather than just accepting an existing but satisfactory implementation. The detailed aspects of the product follow the generation of this solution, together with interactions with production engineering to ensure that the final product is manufacturable, testable and maintainable within the original remits.

6.1.1.1. Formulate customer product requirements

Close contact between the client or proposer on the one hand and those in charge of the design department on the other is a *sine qua non* for success in this important activity. Customers can play an important part in establishing an optimum set of design specifications for a new product or process and, as such, their role should be an active one

Figure 6: Generate Product Concepts



involving actual partnership in the design and development process (Gardiner and Rothwell, 1985).

It is crucial at this point to develop an unambiguous product requirements definition since, 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. The customer's product requirements should be analysed by the 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 customer's requirements is to identify those items which might:

- Prevent implementation
- Require a longer development period than is available
- Cause design/production difficulties
- Limit production volumes

The customer's requirements should be clearly understood with respect to design and manufacture feasibility and 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.

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 commercial requirements specification document.

Methods such as Quality Function Deployment (QFD) (Sullivan, 1986; Hauser and Clausing, 1988) and Design for Manufacture and Assembly (DFMA) (for example Shina, 1991b) may be used at this stage. It should also be recognised at this stage in any design project that the manufacture of electronics products requires the application of the knowledge and skills of a wide variety of people, from industrial designers and social scientists to personnel from marketing, product design, purchasing and inventory control - as well as from customer and supplier companies. Boothroyd (1990) and Gozzo (1989) suggests that effective design-for-manufacture can best be achieved through the simultaneous or concurrent engineering of electronics products and production processes.

Concurrent Engineering, QFD and DFMA will each be explained in greater detail in Section 6.2.1. of this thesis.

6.1.1.2. Formulate initial product concepts

During this stage, designers seek to generate new ways of solving new and possibly old problems by taking a structured look at the product beyond those attributes specified in the customer product specification and the commercial requirements specification. This may be the first time specific function details are laid down since, until this point, commercial and customer requirements may not have gone into detail over how to achieve specific product facilities. For example, the customer product requirement document and the commercial requirements specification may just say "must have magnetic data reader", but not suggest any conceptual, behavioural or circuit solutions.

Techniques such as brainstorming (Edwards, 1966) and lateral thinking (De Bono, 1977) or structured problem solving techniques such as the Seven Management Planning (7MP) Tools (Brassard, 1989) may be used to encourage creativity.

6.1.2. Generate product solutions

This phase of the design process corresponds to the Pahl and Beitz (1988) Embodiment Design phase. It is defined by the British Standards Institution (1989) as:

> *"The design process in which a structured development of the preferred concept is carried out. The preliminary embodiment of all the main functions to be performed by the product is undertaken and the physical processes are clearly established. The output from this stage could include many functional layouts such as control, power lubrication, electrical, appearance, interface, shape, style and size".*

This activity should be carried out by the same design team that created the initial concepts. The resulting ideas should then be elaborated in terms of behaviour or even circuit description.

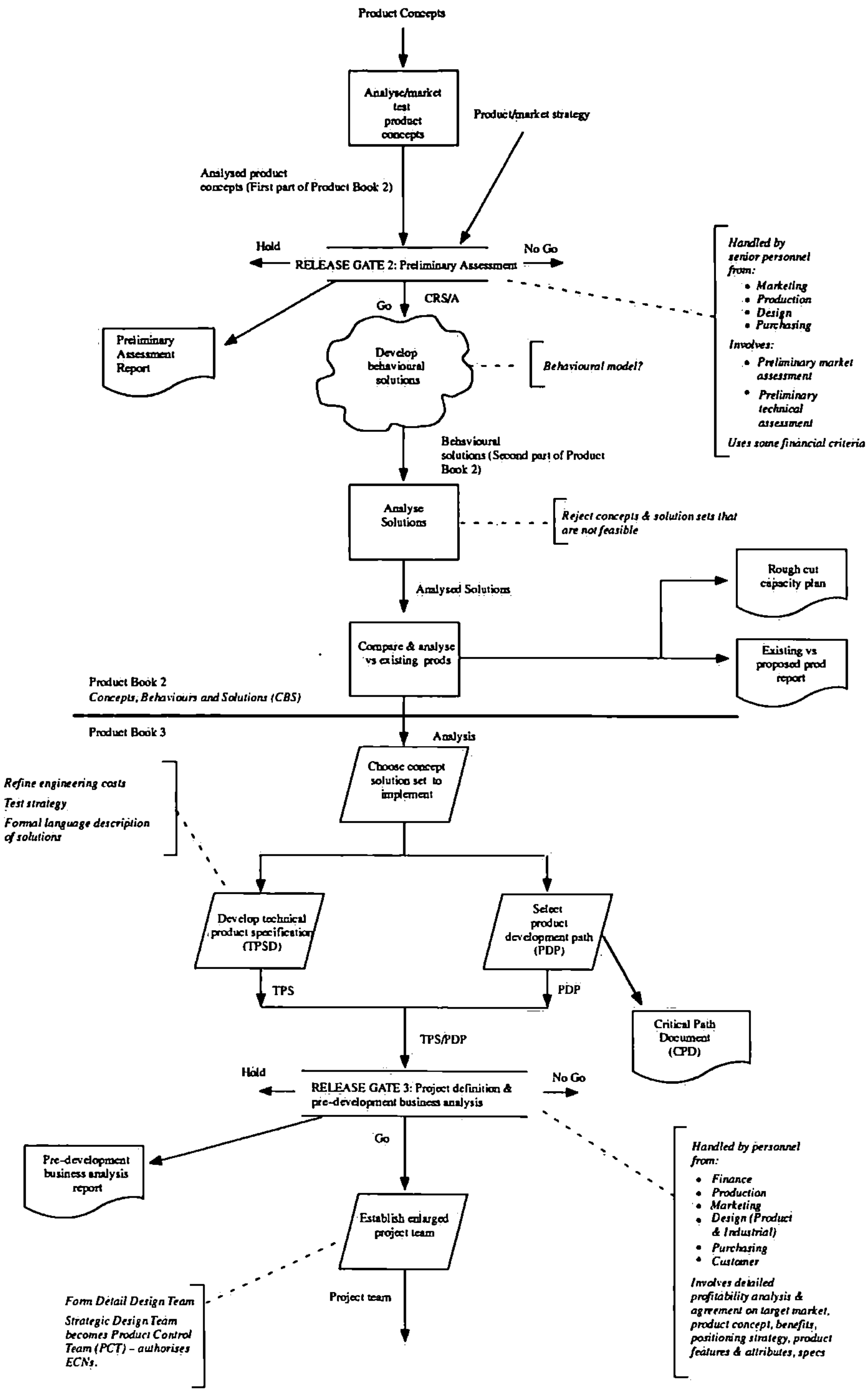
As illustrated in Figure 7, the design team should now develop an understanding of the possible behaviours of the concepts created during the Product Concept Generation. Modelling by simulation or prototyping are currently the most cost–effective methods available, although formal verification may prove a use adjunct to these methods in the future. 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 requirements with an existing product, decide to skip most of the previous stages. This state of affairs would inhibit the evolution of company products as new technologies become available.

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.

After a series of outward looking activities have established the best sets of solutions for the proposed product, it becomes possible to 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. A historical record of how and why the product is evolving as defined should be recorded by

Figure 7: Generate Product Solutions



the company during the early development phase, a time when normally documentation is fragmented and held in marketing, design, accounting, purchasing and management files.

At this point, the degree of "sameness" or compatibility with existing products is known. This will allow production engineering to provide the first estimate of production scheduling requirements during manufacturing. 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.

6.1.3. Develop product

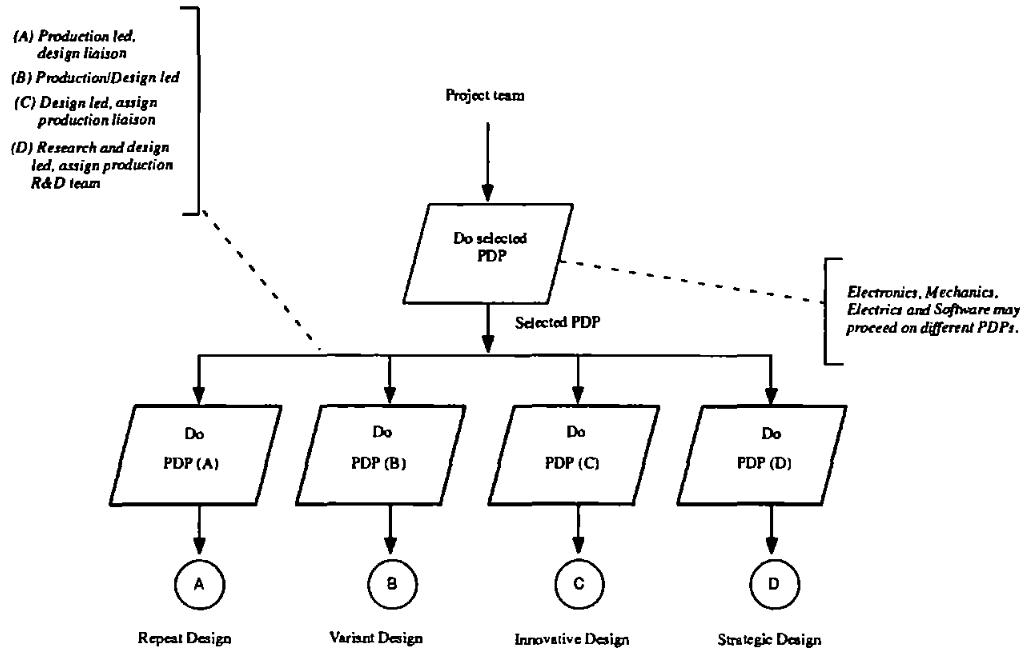
This phase corresponds to the Pahl and Beitz (1988) Detail Design phase. It is defined by the British Standards Institution (1989) as

> *"The design process in which the precise shape, dimension and tolerances are specified, the material selection is confirmed and the method of manufacture is considered for every individual part of the product. The output from this stage consists of information that defines, and can be used in the manufacture of, the product or part of the product".*

It is important to understand that there are four ways of designing an electronic product Bennett *et al* (1992). Each impacts differently on the company in terms of resources required and the product lead times. Therefore, it is imperative that any new project should be categorised in these terms as early as possible in order to make explicit the issues of resourcing and product lead time.

It is also important that senior management recognise the need for 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

Figure 8: Develop Product



product develop accurately as being Repeat Design, 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. This approach is demonstrated in Figure 8. The Four Path approach is explained more fully in Section 5.3.2 of this thesis.

It is unlikely that any real evaluation of the problems of the new development project in these terms is possible until a careful analysis has been made of the proposals and existing product lines already in manufacture. Although it may be company policy to only do Repeat Designs and Variant Designs, a long term company view should highlight the need for Innovative and Strategic development projects.

Failure to take such a perspective has led to a number of company projects in the U.K. being approached as *development* projects when, in fact, they should have been run as strategic or innovative *research programmes*.

6.2. Methods, tools and techniques

Design operations also encompass a variety of design methods and techniques. Jones (1992) presents a number of design tools and techniques, including Value Analysis, Systems Engineering, Brainstorming, Morphological Charts and Interaction Matrix.

For the purposes of this thesis, however, the author will confine himself to an outline description of the Concurrent Engineering design method which incorporates a number of techniques, including Quality Function Deployment (QFD) and Design for Manufacture and Assembly (DFMA). He will also describe a number of available computer-based tools.

6.2.1. Concurrent Engineering

Shina (1991b) defines Concurrent Engineering (CE) as

> *"The earliest possible integration of the overall company's knowledge, resources and experience in design, development, marketing, manufacturing and sales into creating successful new products, with high quality and low cost, while meeting customer expectations".*

The application of CE to product development offers significant benefits in terms of reductions in manufacturing startup and preproduction costs, in product development cycles and in the number of engineering changes generated (Wilson and Greaves, 1989). Nevertheless, it is the author's view that CE is best applied to the development of innovative (20% - 50% different from previous generation) or strategic (50% - 100% different from previous generation) 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.

It is considered that the use of CE is far less appropriate to the development of variant products (up to 10% different from previous generation). 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. However, CE principles in dilute form 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.

The U.K. 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 author 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 appears to be.

In one extreme case, the company concerned had experienced a "war of attrition" between design and production, leading to an almost total collapse in confidence of one department for the other. Similarly, though in a different firm, the authors learned that the benefits of having a production engineer involved at the front end of the product development process were not appreciated simply because the company had a culture of "macho manufacturing" in which production took pride in "always managing to make the product despite design." Again, in another of the companies visited, the lack of a formal CE 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.

CE employs a variety of different techniques to improve the quality of the product. Such techniques include:

- **Quality Function Deployment:** QFD (Hauser and Clausing, 1988) uses the customer as the focus and, via a series of matrices, helps the team to translate customer requirements into clear specifications at every stage of the product design, manufacture and launch process;
- **Taguchi Methods:** The Taguchi system of quality engineering and robust design (Taguchi and Clausing, 1990) includes consideration of tolerance design, process parameter design and a variety of quality controls. One of the principles of the Taguchi approach is that quality should be developed concurrently with the

product design and with the development of both production and support capabilities;

- **Design For Manufacture and Assembly (DFMA):** The DFMA methodology quantifies important manufacturing and assembly difficulties in terms of cost at the early design phase of a product. According to Hall (1991), DFMA focuses on cost so that part complexity can be traded off against number of parts and the difficulty of assembling them.

Successful use of the CE approach requires that the firm should be able to:

- Handle information from different domains uniformly, thereby facilitating the exchange of information and knowledge between engineering groups in a CE team;
- Track the data exchanges to allow release control to be applied to the information and data disseminated between engineers and others within a company;
- Tag data and information during a development programme to ensure that they are understood to be date stamped entities related to a particular product release.

The author's fieldwork revealed that it has long been common practice for Japanese firms to apply CE principles to their product design and manufacture activities. For example, both Sony and Fujitsu typically involve people from different functional areas to achieve a particular product development objective. It is also common for customers and suppliers to be involved early on in the product development process. These groups are not formally recognised as "project teams", however. They are simply regarded as members of a project who are aiming at the same target.

> *"If we don't do things in parallel, we wouldn't be able to achieve high quality products and timely delivery to customers"*. (Fujitsu engineering manager)

6.2.2. Design automation

Over the past decade, company 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 Engineering (CAE) has done much to automate the drafting office and speed the product design process. Computer Aided

Design (CAD), on the other hand, 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. 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.

6.2.2.1. CAD tools

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. Providing the glue to hold the 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. 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 offers circuit schematic capture and limited simulation and layout facilities. The workstation market offers tool integration at company level, and can handle the larger data sets required for more complex design tasks.

6.2.2.1.1. CAD shortcomings

Current CAD tools provide engineering managers with very little computer support during complex design review activities (Culverhouse and Bennett, 1991). Good quality computer-based support, particularly for project management, would be helpful particularly in instances where, for example, multiple projects are being undertaken across several company sites. Design is a small part of a large process and 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.

In addition, such tools generally 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, PCB layout rules for example, 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. 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. Additionally, design "best practice" and company prerogatives are still usually held in the form of paper notes.

Finally, while 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, many 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."

6.2.2.2. CAE tools

Computer Aided Engineering (CAE) has been more fortunate, however, since automation of aspects of the shop floor forces information into design automation tools, where it can be used for management purposes and shop floor control. Links from design through to the shopfloor are haphazard in the electronics sector, where drill tapes and artwork can be transferred in machine readable format, but the control of test equipment and 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.

6.3. Conclusions

Operational activities are directly concerned with satisfying the requirements of the internal or external customer and are sometimes referred to as "core" activities. Where electronics design is concerned, the author has proposed that operational activities comprise the design both of the product and the process used in its manufacture. They also consist of the set of methods, tools and techniques used by engineers during the process of product design.

This chapter has examined the various stages of the process of electronics product design. It has also described various methods, tools and techniques which may be used by engineers during that process and it has described a number of available computer–based tools, their scope and possibilities and the hardware on which they run.

Product design may be regarded as a process which comprises four main phases:

- Generate product concept;
- Generate product solution;
- Develop product and process;
- Validate product and process.

In examining some aspects of these activities, the author has emphasised the importance of the early, conceptual stages of the new product development process and, where formulation of customer requirements is concerned, he has stressed the need for close contact between company and client.

During the Generate Product Solution phase, a number of possible solutions to the customer's "problem" should be analysed and the best set of solutions for the proposed product should be established. These should then be compared with existing products in order to allow production engineering to provide the first estimate of production scheduling requirements during manufacturing.

The Develop Product phase requires the firm to decide upon which of four possible product design paths to follow. The fact that each path will have a different impact on the company in terms of resources required and the product lead times makes it important for any new project to be categorised in these terms as early as possible.

Where design methods are concerned, attention has been focused upon the Concurrent Engineering (CE) approach to electronics product design. CE, in turn, embodies a variety of techniques such a QFD and DFMA. However, it is acknowledged that that CE is best applied to the development of innovative or strategic products where, because the component materials, technologies and manufacturing processes required to realise the end product will largely be unknown, the level of risk to the company will be considerable.

In the final part of the chapter, the author notes that, while great strides have been made in providing design automation support for various aspects of electronics product design, such tools continue to demonstrate a number of shortcomings. In particular, they provide very little project management support during complex design review activities, they generally do not provide any management information in support of the design process and they mostly fail to embody design knowledge other than in the form of circuit schematic diagrams and test vectors.

The following chapter describes a set of infrastructural or support components of an electronics design capability.

Chapter 7.

Support for Product Design

In circumstances where there is likely to be a high level of technical change, Twigg *et al* (1992) indicate that the wider application of the technology in terms of application and information use typically leads to a corresponding need for a high level of organisational adaptation to achieve business success. Similarly, Meredith (1986) stresses the importance of developing infrastructures to maximise the fit between demands made by technology and the skills, needs, values and attitudes embodied in the social and technical structure of the firm.

Where the needs of an electronics manufacturing company are concerned, the design infrastructure may be viewed as 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 IT hardware and software aimed at facilitating day-to-day administrative activities (wordprocessing, spreadsheets) and inter-personnel communications (email). It also embodies a variety of organisational and cultural elements, the most significant of which include:

- The methodologies or guidelines which firms adopt in order to ensure the various design tools are used correctly;
- The procedures necessary for identifying, capturing and reusing 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.

In this chapter, the author will examine those aspects of the supporting infrastructure which include the IT requirements for effective electronics design together with design culture, human resource policies, education, training and learning across design projects.

7.1. IT support

Product design is a cooperative effort in which groups of engineers, other experts and managers work on different facets of the product under the direction of a project leader. According to Reddy *et al* (1991), in Concurrent Engineering (CE) all these project members belong to interdisciplinary groups which rove across traditional departmental boundaries. In order to operate effectively, such cooperating individuals need to be supplied with computer based services which will enable them to transcend the barriers of distance, platform and tool heterogeneity (Reddy *et al*, 1991, p 27).

7.1.1. Cooperative work and computer support

Computer Supported Cooperative Work (CSCW) aims to improve the effectiveness of these group activities by combining "the understanding of the way people work in groups with the enabling technologies of computer networking and associated hardware, software, services and techniques" (Wilson, 1991). CSCW has also been termed "Groupware," "Workgroup Computing" and "Computer-Aided Teams."

Effective use of CSCW requires identification of the components of the group process from the individual, organisational, group work design and group dynamics points of view. Technological support for group activities, on the other hand, can be considered under the following headings (Wilson, 1991):

- **Communication systems** -- advanced email systems; X.500 email directories of group and organisational information; real time "desktop" video conferencing systems incorporated into workstations;
- **Shared work space systems** -- remote screen sharing facilities; face-to-face meeting support using shared individual screens and large public screens; electronically aided, intelligent white boards which provide support for such activities as drawing, listing, collating and printing out;
- **Shared information systems** -- Multimedia, multi-user hypertext systems; shared optical disk or CD-ROM systems; multi-user databases;

Table 3: CSCW Infrastructure Technologies		
CSCW Component	**Infrastructure technologies available today**	**Infrastructure technologies not yet widely available**
Communication Systems		
Advanced email	Local/wide area nets High resolution PCs	High bandwidth networks Voice/video input on PCs X.400 infrastructure
X.500 directory group information		X.500 software products Architecture to incorporate X.500 into corporate and CSCW systems
Desktop video conferencing		High bandwidth networks Voice/video input on PCs Fast signal compression/ decompression systems
Shared Work Space Systems		
Remote screen sharing	Local/wide area nets	High bandwidth networks
Shared screen to support face to face meetings	Back projection systems	High resolution wall screens
Intelligent white boards	Touch screens Pen input devices	High resolution wall screens Appropriate software
Shared Information Systems		
Multi-user hypertext	Local/wide area nets	Distributed database software Flexible, multi-user functionality
Shared optical disk systems	Local/wide area nets High resolution PCs Scanning systems Juke box systems Search/retrieval software	High bandwidth networks
Multi-user databases	Local/wide area nets	Distributed database software Flexible, multi-user functionality
Group Activity Support Systems		
Procedure processors	Procedure processing software	Seamless integration with electronic mail systems
Activity processors/work flow systems	Commitment making software	General purpose, flexible activity processing software Seamless integration with electronic mail systems Tools for defining activities
Group work design tools		Easy to use tools for each part of a coherent group work design process
System development tools		System developers workbench with integral group support tools
Co-authoring tools	Commitment making software	Easy to use software to support all phases of the joint authoring process

Source: Ancona and Caldwell (1990)

- **Group activity support systems** -- Procedure processing or work flow systems enabling electronic forms to be sent on predefined routes of people and roles; activity processors which allow a more general form of work flow/procedure processing; methodologies and support tools for groups to analyse, define and prototype the organisation, procedures and equipment with which they are to carry out a group activity; co-authoring tools to support the joint writing of documents by two or more people; idea generation and prioritising tools to aid group creativity.

The implementation of each of the above mentioned CSCW enabling technologies is contingent upon the availability of a variety of infrastructure technologies. A number of these technologies is presented in Table 3. Some of these are currently available, others are not.

A more general infrastructure requirement for effective CSCW work is that of an open systems environment in which material from different systems (for example, from two different word processing or CAD systems) can successfully be exchanged without losing format or meaning in the process.

Ancona and Caldwell (1990), in discussing intellectual teamwork within new product teams, state they discovered a pattern of activities as the new product development process develops. According to Ancona and Caldwell these activities occur in three phases: *creation*, *development* and *diffusion*, each of which has a "dominant task requirement" demanding different kinds of interaction among team members and between the team and outsiders.

7.1.1.1. Creation phase

During the creation phase, the team's main task requirement is *exploration* since, externally, it must determine what resources are available to it, it must establish the nature of the product and it must explore the technologies available for building the product. Internal to the team, exploration involves getting to know other team members, determining who has particular skills and who can or cannot be relied upon to perform effectively.

According to Ancona and Caldwell (1990), one key aspect of exploration is modelling since the team needs to create a picture of the external environment, including predictions of where resources can be found, who supports the team's efforts and what expectations others have for the team. Information technology (IT) could be used to help the group automatically generate responsibility charts that would enable it to fill in knowledge gaps, direct it to plan meetings with outsiders who need to be encouraged to help or help it to decide which expectations can realistically be met. Exploration also involves exploring ideas and possibilities for the new design and IT could help the team to keep track of its ideas, increase creativity and to evaluate the quality of its work.

7.1.1.2. Development phase

Having explored a variety of alternative designs, the team moves to the development phase requiring commitment to a specific product design. The dominant task requirement here is the efficient *exploitation* of the information and resources the team has collected. Technical problems must be solved and the team must learn to operate efficiently. Externally, the team focuses on co-ordinating, keeping others informed and building relationships with the groups that will receive the results of its work.

IT can support the exploitation task requirement by facilitating coordination among group members, by forecasting schedule delays and by externally reporting team progress.

7.1.1.3. Diffusion phase

In the diffusion phase, the team's major task requirement will be *exportation* of its product to others. There is now a declining need for emphasis on smooth, efficient internal operations and a greater requirement for rediscovering the kinds of external relationships characteristic of the earlier creation phase. To make the product development a success, the team must not only transfer the product itself, it must also communicate a sense of excitement and commitment to the other groups who will be responsible for marketing, manufacturing and servicing the new product.

Information technology tools such as computer conferencing and email can be used to support this task requirement since they allow the team to regularly brief other groups during product development. They would also allow the team to build the knowledge and support of those groups well in advance of product transfer. CAD/CAE systems might be used to ease the communication of technical details across functional boundaries.

7.2. Design culture

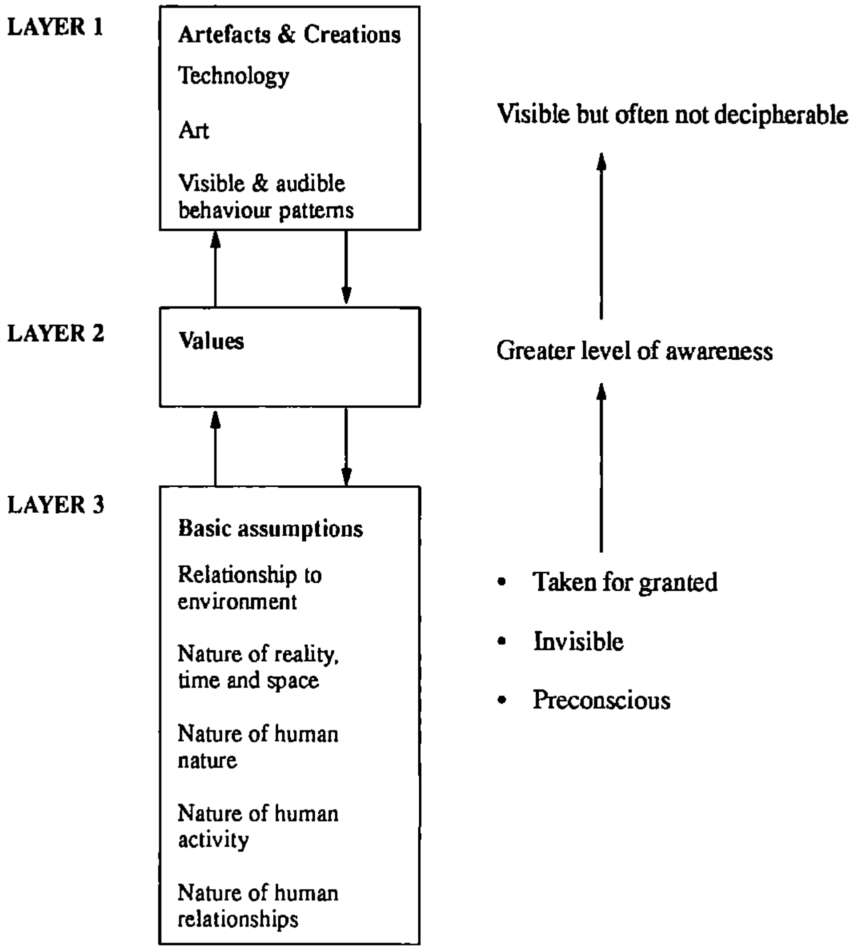
Many of the classical descriptions of organisations are directed towards the formal organisation structures and the description of work performed within these structures. They do not deal with some of the most important and significant aspects of organisational behaviour. These behavioural aspects are very often critical to the success of enterprises and by focusing on the organisation chart alone, factors which are vital to an understanding of the organisation may be missed. The most important of these factors, which forms part of Leavitt's organisational model (Leavitt, 1965), is organisational culture.

In this context, the author's research has revealed that the creation of an effective product design capability rests upon more than simply investing in computer hardware upon which to run a suite of design automation software. It is important that management should also recognise the human and organisational context within which the design activity takes place and acknowledge that it is a complex activity which may have its own culture. Such a culture may be rather well defined, as a part of the firm's mission or reflecting dominant ideas of the organisation's founders or leaders, or it may be relatively obscure.

In discussing the need for manufacturing firms to build a design and innovation culture, it is useful to examine Schein's model (Schein, 1984) which subdivides culture into three interacting layers (see Figure 9).

The most visible aspects of organisational culture, Layers 1 and 2, consist of Behaviour and Creations as well as Values. The third layer, which is usually hidden from view, consists of the organisation's fundamental belief systems.

Figure 9: The Levels of Culture and their Interaction (Schein, 1984)



7.2.1. Action, behaviour and artefacts

This aspect of culture, according to Schein (1984), consists of

> *". . . the constructed environment of the organisation, its architecture, technology, office layout, manner of dress, visible or audible behaviour patterns and public documents such as charters, employee orientation materials and stories"*

Schein (1984) acknowledges the difficulty of analysing this level because data are easy to obtain but hard to interpret. He points out that, while it is possible to describe "how" a group constructs its environment and "what" behaviour patters are discernable among its members, it is not always easy to understand the underlying logic of "why" a group behaves the way it does. In order to analyse why members behave the way they do, it becomes necessary to look at the values which govern their behaviour. These are represented as Level 2 in Figure 9.

7.2.2. Values

Values are difficult to observe directly and, according to Schein (1984), it is often necessary to infer them by interviewing key members of the organisation or to content analyse artifacts such as documents and charters. However, in attempting to identify these values it is important to remember that what an organisation thinks it believes and what it says it believes represent only the manifest or *espoused* values of a culture (Schein, 1984). The espoused values of a firm are most clearly expressed in its Mission Statement which might contain the phrase "This firm believes that survival in the current competitive climate is only possible through our new policy of aggressive product design and innovation."

At this level, Watanabe (1987) believes that company customs, company mottos and company creed in Japanese companies all reflect their corporate culture, company disposition and management style. He states that corporate culture plays an important role in management strategy, particularly with regard to decision-making, development and performance. Fairhead (1988) notes, however, that espoused values are only helpful where they highlight some of the issues which are of real concern to the organisation. To check whether they are deeply believed by individual employees of the firm or whether they are "more honoured in the breach" it is necessary to interpret the actions and behaviours of the people producing the artefacts.

7.2.3. Basic assumptions

According to Schein (1984), real understanding of a culture only comes from delving into its underlying assumptions about "how things really are." Fairhead (1989) describes these as fundamental, interacting beliefs about the nature of the competitive world, the nature of the firm itself, the nature of different groups within the firm and beliefs about what is "appropriate" behaviour and "inappropriate" behaviour. Watanabe (1987) takes the view that, in Japanese firms, a corporate culture forces employees to have specific values, a common viewpoint, a way of thinking and a basis for action.

> *"Company performance is supported by the informal and flexible decision-making process. Problems which occur within the company can be solved without resorting to official procedures. Members of the corporate culture usually adjust themselves, autonomously and emotionally, and reach an agreement based on the standard of value suggested by the corporate culture of the company"* (Watanabe, 1987)

The difference between espoused values and fundamental beliefs in Japanese firms is, however, well illustrated by Russel (1990) who describes the predatory manner in which large manufacturing firms in Japan treat their smaller subcontractor firms. He reports how subcontractors have been forced to accept huge losses in order to maintain favourable pricing for the parent firm and how product and process innovations developed by the subcontractors have been regularly "stolen" by the larger firms.

7.2.4. The importance of culture in product design

The importance of culture in the context of electronics product design is reinforced by the fact that Japanese companies regard design as one of a portfolio of strategic activities in which significant resources are devoted both to the development of in-house design automation tools and to the support of "up front" engineering activities. This point is further illustrated by the manner in which the Japanese firms visited by the author use design to achieve market success. They initially design products in what may be termed an "aggressive" fashion in order to create market share or to offer a level of functionality not found in other products. Having achieved these goals, their design capabilities are then deployed "consequentially" to ensure ease of manufacture and high product quality as part of a low cost business strategy.

The manner in which Sony undertook the development of its successful 8mm family of hand-held VCRs, culminating in its TR55 product, epitomises this approach and, in the author's view, may be regarded as a model which should be emulated by U.K. electronics firms. Indeed, during their visit to Sony, the authors discovered a culture in which "designers have a general tendency to be aggressive." Furthermore, the author learned that, working within this kind of design milieu, groups of designers feel "unable to stand still" and are constantly urged to take more risk. On an individual level, he was informed that designers are "aggressive" in their desire to improve their own personalities, their own positions and their own knowledge.

To a greater or lesser extent, all the Japanese companies visited by the author demonstrated a similar culture and, as part of its "aggressive" approach to product design, each company has created an ongoing design capability which is resilient to change and which supports wider business objectives.

Furthermore, At Fujitsu Mainframe Division, the author was also informed that the company's bottom up culture helps to create a free atmosphere for engineering activities, and that engineering management is encouraged to take risks. They are told to "Try what you want." Managers at Sony Semiconductors, on the other hand, said they weren't familiar with measurement, particularly the measurement of individuals. They explained to the author that they felt responsible as a group and that, within such an environment, it was unusual to condemn people. They prefer only to advise, counsel and help.

> *"Each person's role is not so clear. Even though a person may be an engineer, he may act as a manager. The manager may be technically inferior to many of the people on his team. The head of the group is only a symbol. Choosing the right "head" is one key issue. If the leader doesn't have so much knowledge he will be helped. The leader's most important role is to synchronise. Technical knowledge is not so important. Harmonising people is more important"*. (Sony Engineering Manager)

As with Fujitsu Mainframe Division, managers at Sony Semiconductors said they were encouraged "unhesitatingly" to take more risk.

7.3. Human resource management policies

The author's fieldwork indicates that the effectiveness of a firm's product design activities is heavily dependent upon its human resource management (HRM) policies. The lesson from Japan is that these should particularly focus upon minimising staff turnover through the provision both of education and training facilities focused on key technological areas and of appropriate reward and recognition systems. 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. Such experience is not usually recorded within electronics firms, either in computer databases or on paper.

In marked contrast to Japanese practice in this area, the author's 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.

Indeed, a comparison of Japanese On-the-Job-Training (OJT) and design apprenticeship techniques with U.K., European and U.S. practice in this field highlights the fact that the Japanese generally adopt a longer-term view even of personnel recruitment than do their Western competitors. In this regard, it has been reported by Dixon *et al* (1989) that many of the larger Japanese corporations typically have twice as many staff engaged in human resource management as their Western counterparts. Japanese HRM staff work on training, on recruitment of new employees in schools and universities and on facilitating change within the companies themselves.

7.3.1. Education and training

An increasingly important concern for the electronics industry is the fact that a considerable proportion (industry estimates put this figure as high as 20%) of a firm's entire body of technical knowledge must be updated each year merely to keep abreast of technical advances taking place in the industry. The implications of that figure are, of course, considerable from an education and training perspective since it means that an electronics company's entire body of existing technical knowledge could become redundant every five years. Furthermore, there is every likelihood, given the level of technological change currently engulfing the electronics industry, that the pace at which firms need to take new knowledge on board -- and to jettison out-of-date knowledge -- will dramatically increase in the next decade.

Buur (1989) describes how a young engineer joining a major Japanese company faces at least a one year training programme though, more often, that training could last for between three and five years. Courses are arranged within a company education system, though these tend to be of a generalist nature. Employees become specialists only through OJT systems which rely heavily on the availability of experienced engineering staff to teach preferred engineering techniques to novice engineers, for example, and to pass on design process knowledge.

At Fujitsu Mainframe Division, it is estimated to take one year of OJT to turn a graduate recruit into a proficient designer, despite the fact that Japanese engineering undergraduates are not generally taught how to use CAD/CAE systems at university. However, despite the fact that the company's design review process is based upon previous development experience, with the list of items being reviewed expanded each time they go through the process, it is worth noting that Fujitsu Mainframe Division has not yet succeeded in incorporating design process knowledge into its product design tools.

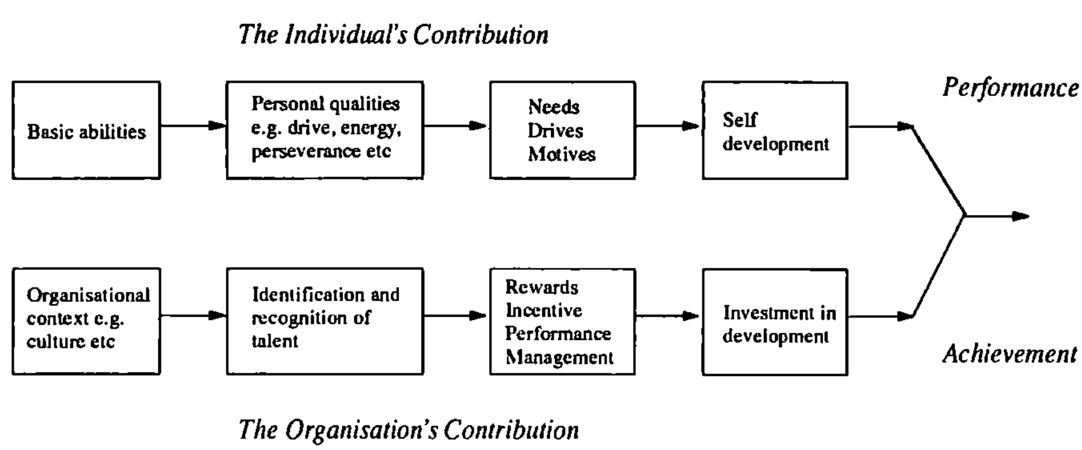
Toshiba places similar heavy emphasis on educating, training and nurturing its key people. The company even has an internal "university" catering for employees who have no university degree.

7.3.2. Reward and recognition

Sadler (1994) reminds us that, at the individual level, possession of talent does not, by itself, guarantee a high level of achievement. Two additional ingredients are necessary, the first of which must be supplied by the individual. Where the individual works in an organisation, the second ingredient is the manner in which he or she is treated by that organisation.

Figure 10 illustrates the fact that individuals must supply a set of qualities of character and temperament which will enable them to harness and focus talent and make it productive. Within the organisation, Sadler (1984, p 29) states that the formula for successfully managing key members of staff "is deceptively simple" – attract the best people, keep them, develop them, motivate them and manage their performance.

Figure 10: Influences on the Performance of Key Employees



Source: Sadler P., Gold Collar Workers: What Makes Them Play At Their Best?, *Personnel Management*, April 1994

From a reward and recognition perspective, Hunt (1992) points out that organisations offer both *extrinsic* and *intrinsic* inducements to the individual to work and to work hard. Extrinsic rewards include wage, salary, bonuses, commission payments, working conditions and pension arrangements. Intrinsic rewards, on the other hand, are those which enable people to satisfy other goals – lifestyle, comfort, a sense of achievement, companionship, status, public acclaim and challenge.

Where electronics design is concerned, it is clear from the above that reward and recognition systems must be designed so that engineering staff are motivated to work creatively and effectively. This can best be achieved by ensuring that designers satisfy *their* intrinsic and extrinsic goals when they perform the tasks required by the organisation.

7.4. Learning across projects

The socio-technical idea that organisations are organisms which can learn emerged with the development of systems thinking in the 1950s. Since then, much has been written about organisational learning and the "learning company" (for example Pedler *et al*, 1991; Argyris, 1982; Senge, 1990; Akkermans and van Aken, 1991; Dodgson, 1993; Levitt and March, 1988; AMED, 1993; Garvin, 1993), although the terms themselves are only of relatively recent origin. Nevertheless, there appears to be a consensus among these authors that such learning is vital to corporate success. Indeed, the view has been expressed (Stata, 1989) that the rate at which companies learn may become the only sustainable competitive advantage.

The emergence of such a consensus has undoubtedly been influenced by the manner in which successful Japanese firms have fostered and encouraged the creation of new ideas and by the way in which they have devoted themselves to learning at all levels within their organisations (see Imai, 1986; Imai *et al*, 1985; Yamanouchi, 1989; Nonaka, 1991; Bowonder and Miyake, 1993, for example).

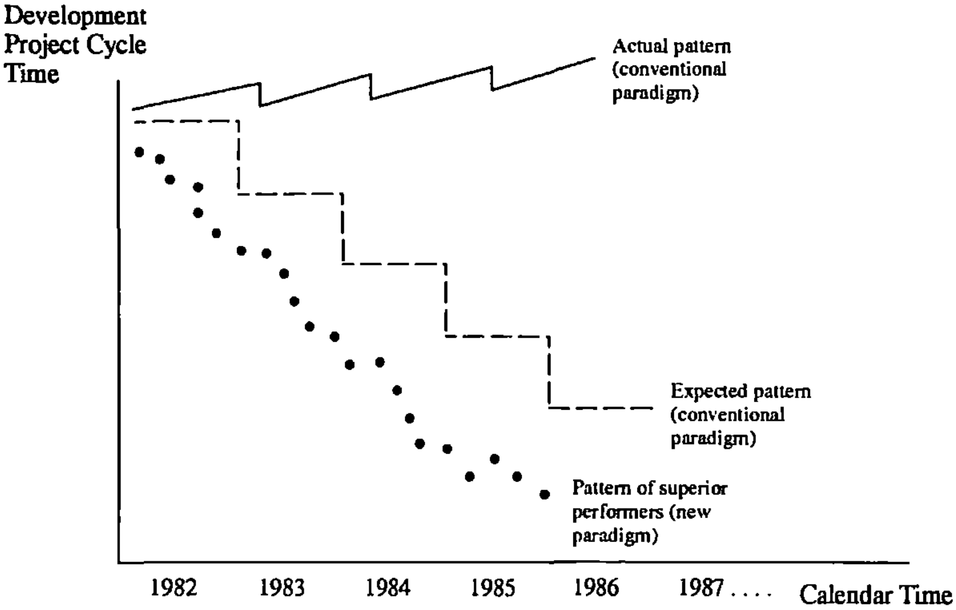
7.4.1. The new design paradigm

According to Hayes *et al* (1988), however, few companies have been able to measure up to this "new paradigm" of continuous learning and improvement which, as Figure 11 illustrates, seeks smaller but more frequent improvements, as indicated by the dotted line. According to Hayes *et al* (1988):

> *"Superior performers manage to learn from each project they undertake, continually streamlining and integrating the overall process . . . they are constantly building and reinforcing the capabilities needed for further improvements."*

The research has shown that the strength of Japanese electronics firms ultimately may be derived from the fact that design is regarded as a strategic corporate activity which must be generously resourced in order to ensure a constant flow of high quality, innovative products. It is also critically dependent, however, upon effective management, and

Figure 11: Two Approaches to Development Improvement



Source: Hayes et al, Dynamic Manufacturing: Creating the Learning Organisation, The Free Press, 1983

particularly upon the development of a managerial culture which fosters and encourages both the creation of new ideas and the transmission of relevant knowledge throughout the firm.

Few U.K. electronics firms have designed and implemented such learning capabilities (Culverhouse *et al*, 1991; Bennett *et al*, 1992), however. Indeed, most firms visited by the author during the course of his research appear to have very little enthusiasm for such a concept, and appear content to "reinvent the wheel" from project to project.

7.4.2. Problems with reusing design knowledge and wisdom

To be successful at electronic product design, a company must have a thorough understanding of its existing product range, including all product functions and technological limits. In order to achieve such an understanding, firms must be able to archive and retrieve all salient product knowledge. However, it is precisely in this area that most electronics companies are highly vulnerable since their ability to develop such products depends, to a significant extent, upon the availability of "old style" expertise -- otherwise known as "wisdom" or "lore" (Culverhouse *et al*, 1991). Unfortunately, such distilled long term interpretation of knowledge is usually only retained by the individual.

Such "migratory" (Badaracco, 1991) expertise is rarely, if ever, systematically identified, captured and reused at the company level.

Levitt and March (1988) point out, however, that the availability of knowledge in an organisation is associated with the frequency of use of a routine, the recency of its use and its organisational proximity. They state that recently used and frequently used routines are more easily evoked than those which have been used infrequently. Conversely, organisations have difficulty retrieving relatively old, unused knowledge or skills. There are additional problems associated with current approaches to electronics design knowledge reuse. These include:

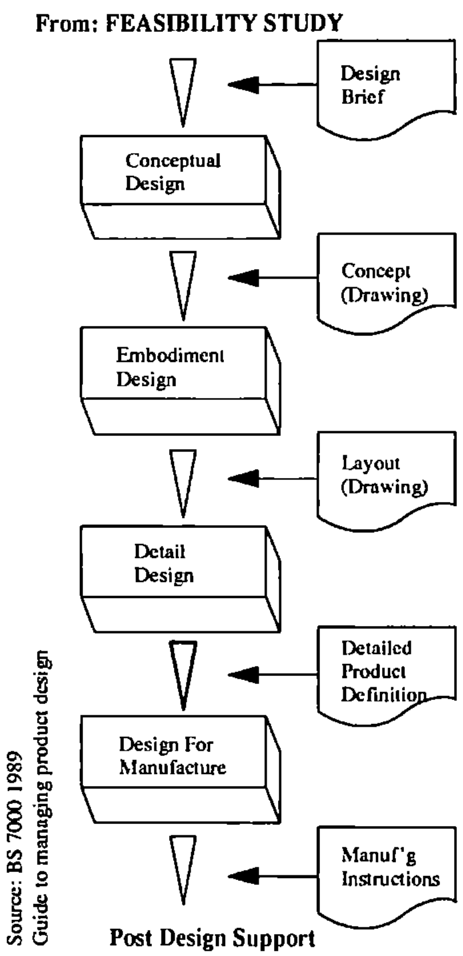
- The failure of manual knowledge capture methods to act as an effective feedback mechanism since recipients (other than designers) often tend to file paper documents away and ignore them;
- The failure of designers to record sufficient *contextual* information and knowledge about an evolving design. In an effort to minimise effort and cost, electronics designers typically only provide documentary evidence of their work in the form of a circuit diagram and a description of its function;
- The idiosyncratic and largely unstructured nature of personal engineering log books. This makes it difficult for other designers to interpret and understand the original designer's decision-making processes;
- Failure by engineering management in many firms to grasp the importance of enforcing a thorough approach to product design documentation as a mechanism for capturing design knowledge and "wisdom";
- Poor use of the knowledge storage and recall capabilities of CAD/CAE tools.

The author and his colleagues (Bennett *et al*, 1992) reported that a number of large Japanese electronics firms had been able to overcome these problems by evolving product design and product engineering support systems or infrastructures. Such infrastructures, by facilitating the organisational learning process, enabled those companies to continuously improve both the design of their products and the processes by which those products are manufactured. This systematic approach to "learning from experience", exemplified in the *Kaizen* approach to continuous improvement, has meant that knowledge has become institutionalised in many Japanese firms. According to Zucker (1977), institutionalised knowledge becomes "taken for granted" and is embedded in the group or organisation. His research also suggests that the extent to which knowledge is institutionalised is an important factor in facilitating the persistence of knowledge in organisations.

7.4.3. Conventional product design models

A close examination of conventional idealised models of product design, such as those developed by Pahl & Beitz (1984) -- and embodied in the German VDI 2221 standard for product design -- or by the British Standards Institution (1989), reveals that they only weakly embrace the idea of learning from past experience.

Figure 12: Idealised Product Design Process



The Pahl and Beitz approach to product design focuses on the embodiment phase of design in order to address the issues confronting mechanical engineers at this important stage in the product development process. They present design as a single-track process in which each design begins life as a creative concept which is exploded into a set of alternative representations. There follows the selection of an optimal design and, finally, the detailed design of the product. 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.

Importantly, from the point of view of this discussion, Pahl and Beitz stress that product design should be regarded as a learning process which "should be treated, not statically, but dynamically as a control process in which the information feedback must be repeated until the information content has reached the level at which the optimum solution can be found." They omit, however, to provide their readers with any guidance as to how this learning process can be facilitated to help firms cope with the demands and pressures of actual product design in an industrial setting.

The British Standards Institution's BS7000: Guide to Managing Product Design, in contrast, provides relatively detailed guidance on managing product design at corporate and project levels, as well as on managing the design activity itself. At corporate level, for example, the British standard stipulates that all plans, including business, product and resource plans, should be monitored and controlled in a disciplined fashion during their implementation. It further suggests the need to investigate the success of the plans and whether the objectives were appropriate. However, in making it the responsibility of senior management to ensure there is a procedure for such evaluation, BS7000 goes no further than to suggest that the results of such an evaluation should be "communicated . . . to all concerned".

Significantly, BS7000 comes closest to embracing the notion that past design experience is a resource which should be utilised when it specifies procedures for managing the design activity itself. Here it states, among others, that:

- The design manager should plan the availability of historical information, archives and design know how;
- An evaluation of the progress of the design project should be made in order to reveal areas where improvement can be made for the next project design venture;
- Design managers should ensure that the required changes and necessary corrective actions are taken and are effective.

The author acknowledges that such guidelines can contribute to improving the overall management of the product design process. However, it is his belief that far more emphasis should have been placed upon the need for firms to develop formal architectures for identifying, capturing and exploiting corporate knowledge and "wisdom" so that they are able to continuously improve and to learn across development projects. Failure to do so means that, even where models such as the one presented in Figure 12 are adopted, U.K.

electronics firms will still find it difficult to improve either their product design capabilities or their overall competitive performance.

7.4.4. Storing and retrieving design knowledge

Larson and Christensen (1993) examine the problem of information storage from the point of view of information sharing across individuals in a group. They are particularly concerned with the ways in which information which exists either in a person's memory or in some other external store is shared and with the problems of access (direct vs indirect) to relevant information. Where information retrieval is concerned, Larson and Christensen report that groups in which problem-relevant information is shared prior to discussion are likely to do a better job of retrieving that information than groups in which such information is unshared. They also report that shared information is more likely to be retrieved than unshared information.

It is generally the case in the electronics engineering environment, however, that design knowledge spans many areas of specialisation. Furthermore, it is usually stored in people's heads, in engineering log books, in CAD/CAE databases and in project management reports. In other words, it is stored in a *distributed* fashion which makes company wide access to product information only possible through the use of common storage standards and common access methods. Given its fragmentary and sometimes unquantified nature, the storage and retrieval of such knowledge in a manner which supports effective sharing can be extremely difficult. This problem is compounded by the fact that knowledge is often embedded in individuals who hoard that knowledge ("knowledge is power"). Engeström *et al* (1990) describe a clinic administrator who hoarded knowledge by protecting his network of personal contacts in other departments and by solving problems without explaining the rationale to his subordinates.

The merging of data and information to produce a uniform company knowledge base in such circumstances is extremely difficult. Significantly, however, a large proportion of current product design activities are manual activities and designs are essentially paper-based. Hence, if computer support tools are to be successfully integrated with existing systems, one must be able to interface to existing methods and archive formats in order to ensure that simple linkages are created between people, manual methods, paper documentation and computers. Two ways of achieving this, and thus of overcoming the kinds of knowledge storage and retrieval problems described earlier in this chapter, are:

- Using an electronic product book system as a direct replacement for relational databases and paper-based textual archives (Bennett and Culverhouse, 1994);
- Facilitating knowledge capture and reuse within the engineering project management processes.

Electronic books are not new (for example Egan *et al*, 1994; Favela *et al*, 1994), but to be useful in an engineering context they must be structured so as to simplify human readability. The author and his colleague (Bennett and Culverhouse, 1994) chose the book metaphor because it represents an approach to human communication which has evolved over many centuries and which is immediately familiar to a majority of all adults who have received a formal education. By adhering to the book structure and by fixing the position of certain categories of design information within certain chapters of a book, design engineers can be more certain of efficiently locating the design information they require.

7.5. Conclusions

The supporting infrastructure of design has been described as the totality of supporting functions which allow the design activity to take place. It includes provision of technology support in the form of appropriate IT hardware and software aimed at facilitating day-to-day administrative activities (wordprocessing, spreadsheets) and routine inter-personnel communication (email). In order to operate effectively, designers need to be supplied with computer based services which will enable them to cooperate across both departmental and geographic boundaries.

The infrastructure also embodies a variety of organisational and cultural elements. The importance of corporate culture in product design is highlighted by the "aggressive" approach to product design adopted by many Japanese electronics firms.

Given the need for electronics firms to retain hard won knowledge and wisdom, the research has indicated that it is important that they establish Human Resource policies which focus upon minimising the turnover of engineering and design staff. This may be accomplished through the implementation of appropriate reward and recognition systems and by ensuring that key product design staff are educated and trained on an ongoing basis.

The ability of a firm to learn faster than its competitors is increasingly being seen as a major source of competitive advantage. In contrast to Japanese practice, however, few U.K. or European electronics firms appear to have implemented such learning capabilities, preferring instead to "reinvent the wheel" from project to project. There are numerous problems associated with the effective reuse of design knowledge and wisdom, not least the widespread failure by engineering management to grasp the importance of enforcing a thorough approach to product design documentation as a mechanism for capturing design knowledge and "wisdom."

Having examined the Manage, Operate and Support components of an electronics design capability, the author will next present a set of requirements for a company-led methodology the objective of which is to enable an electronics SME to create a resilient product design capability.

Chapter 8.

Requirements for a Methodology Enabling the Specification of Electronics Design Capabilities in SMEs

There remains considerable concern in the U.K. regarding the capacity of SMEs to respond to the new technological and competitive challenges described in Chapter 3. On both a national and a global basis, larger firms are now demanding increased quality, faster turnaround and greater flexibility from SMEs in their supply chain and Lefebvre *et al* (1990) note that SMEs are vulnerable to these challenges in a variety of ways. For example, they lack qualified personnel, they have problems finding adequate capital financing and they lack technological sophistication.

In order to survive, however, SMEs must dramatically improve the manner in which they carry out the entire spectrum of their business activities. In particular, recent advances in computer hardware and software, the need to compete in both domestic and global markets and increasing labour costs are requiring SMEs to focus on methods which will help them improve their time to market capabilities, reduce manufacturing costs, improve productivity and increase product and service quality.

This chapter describes the requirements for a methodology which will enable electronics firms, of whatever size, to specify a flexible design capability. It proposes that such a methodology must use a structured approach in order to enable firms to identify appropriate types of design projects (*nature* of design), appropriate numbers of projects (*intensity* of design) and the appropriate *scope* of the design which is undertaken during those projects. The specification further requires that the methodology accomplishes these objectives by allowing firms to consider how electronics product design needs to be managed, how it must be undertaken from an operational perspective and how it must be supported.

8.1. The need for SMEs to adopt a strategic perspective

A consensus has emerged among authors, in recent years, regarding the need for manufacturing companies to plan and execute their business operations from a strategic point of view. Prominent among the writers in this area have been Fine and Hax (1984), Wheelwright and Hayes (1985), Ohmae (1988), Pendlebury (1987) and Hax (1991). Others, notably Hay and Williamson (1991) and Stalk *et al* (1992) discuss strategy in terms of competitive capabilities. Roberts and Meyer (1991) focus on product strategy, Eschenbach and Geistauts (1987) explore the interface between engineering and strategy and Holt (1991) advocates the development of a technology strategy as a means of harmonising engineering effort with corporate objectives and strategies.

Aram and Cowen (1990) caution, however, that smaller firms often avoid planning because "management believes such processes are only suitable for large organisations." This view is supported by a more recent study undertaken in six small manufacturing firms the South West of England (Addy *et al*, 1994). The study revealed that none of the managing directors interviewed carried out any formal strategic planning. In the four most successful firms, however, the study clearly indicated that the managing directors concerned were all "strategic thinkers" and that they were all aggressively driving their businesses forward on the basis of a wholly informal, "gut feel" strategy formulation process.

8.2. The need for SMEs to adopt new technologies

The adoption of advanced, computer-based technologies has been proposed by numerous authors as a prime means of improving the competitive position of firms (Hayes and Wheelwright, 1984; Skinner, 1985), but evidence suggests that smaller firms are lagging behind in this area (Harvey *et al*, 1989). Lefebvre *et al* (1991) conclude that the productivity of small companies can best be achieved by helping them to make better technological decisions and, in particular, to help less innovative and non-innovative companies to see the world as the very innovative ones do.

Meredith (1987) suggests that selective investment at critical points in the production process will be the key factor for small firms, not massive investment in greenfield plants. He observes that the critical point may be in design, as with CAD, in engineering, as with CAE and Computer-Aided Process Planning (CAPP), or in manufacturing, as with CAM and many other technologies. On the other hand, O'Neill and Duker (1986) recommend new strategies that are based upon the latest technological advancement because small firms can no longer depend on business practices that succeeded in the past, given the turbulent and ambiguous business environment they are now facing.

8.2.1. Disadvantages of small firms

While there is no doubt that small firms exhibit a number of characteristics which facilitate the adoption of advanced manufacturing technologies (Lefebvre, 1990; Meredith 1987; Garsombke and Garsombke, 1989), Schroeder *et al* (1989) caution that the relationship between new technology and the ability to compete is not as simple or direct as many managers believe. While the adoption of Advanced Manufacturing Technology (AMT) can offer many advantages, it can also involve firms in a number of unforeseen and potentially debilitating problems because:

- The initial cost of AMT is much higher than that of conventional technologies;
- It often takes time to resolve technical problems and AMT demands more training to use the technology effectively (Jaikumar, 1986);
- The new technologies require workers to be more technically literate as analytical skills supercede motor skills in importance (Voss, 1986).

Other factors inhibiting the adoption of AMT include:

- Lack of capital investment funds;
- Lack of staff to investigate new technology;
- Inaccessibility to assistance;
- Lack of time to investigate new systems;
- Lack of knowledge of available technology.

Each of these issues will now briefly be discussed.

8.2.1.1. Lack of capital investment funds

Smaller industries are very restricted in capital resources, in many instances even for operational needs. In addition they often face barriers limiting their access to financing capital. This severely hampers their ability to engage in modernisation efforts and training programs, and to hire private sources of assistance.

Furthermore, Hayes and Jaikumar (1991) report that the reluctance of many U.S. companies to adopt new technologies may reflect gaps in their capital budgeting processes as much as they do a lack of understanding of the impact they are likely to have.

> *"Many firms mistakenly look upon new technology as an object rather than a means. The companies that are able to exploit the latent capabilities of a new technology most effectively are generally those which adopt it early, continually experiment with it and keep upgrading their skills and equipment as the technology evolves."* (Hayes and Jaikumar, 1991)

8.2.1.2. Lack of staff to investigate new technology

Most of these firms operate with a limited number of personnel, particularly in technical departments -- if they have any at all. Lack of in-house expertise precludes most companies from implementing measures directed at the rationalisation of processes, product optimization, and quality control. Sheridan (1992) notes, for example, that the primary obstacles to a more rapid adoption of CIM technologies in the United States are lack of necessary funding and a lack of in-house technical expertise.

Management expertise is also a necessity, particularly in the areas of planning, marketing, finance, human relations, and accounting. Often, many of these companies lack systems for determining their true process costs, an essential requirement for implementing cost-recovery efforts.

8.2.1.3. Inaccessibility to assistance

Accessibility to sources of assistance is also limited. Vendors, a main source of assistance for many companies, tend to assign higher priority to firms with larger sales potential and to areas with a high density of companies (thereby excluding many rural manufacturers).

Barriers also exist to direct contact with their customers, who, given the suitable circumstances, can frequently aid in product design, development and optimization, and marketing.

8.2.1.4. Lack of time to investigate new systems

Characteristically, SMEs operate with a day-to-day agenda in which "firefighting" plays a major part (Culverhouse *et al*, 1991). Time limitations significantly impair these firms' abilities to engage in evaluating and improving their operations.

8.2.1.5. Lack of knowledge of available technology

The author's fieldwork in the U.K. indicates that there continues to be a widespread lack of knowledge of available technologies among senior management in SMEs. Here "technology" is taken to include more than just the hardware objects used or created by industrial or commercial organisations. Zeleny (1986) states that any technology has a set of clearly identifiable components:

- **Hardware** -- the *means* for carrying out the tasks to achieve objectives or goals;
- **Software** -- the set of rules, guidelines and algorithms necessary for using the hardware; the *know how* of how to carry out the tasks to achieve goals or pursue objectives;
- **Brainware** -- the purpose, the application and the justification of the hardware and software deployment; the *know what* and *know why* of technology;
- **Technology support network** -- the complete network of physical, informational and socio-economic relationships which support the proper use and functioning of a given technology towards the stated goals and objectives.

In particular, there appears to be a critical lack of understanding among SME management personnel of design and engineering best practice as well as of a whole range of management tools and techniques.

8.2.2. Vendor led approaches

The design automation systems selection, acquisition and implementation process ideally consists of some or all of the following tasks (Teicholtz, 1985):

- Carry out feasibility study;
- Draw up detailed requirements specification;
- Write the invitation to tender (ITT);
- Receive ITT documents from vendors ;
- Draw up a shortlist;
- Finalise the contract to purchase the system;
- Order the system;
- Install the system and carry out acceptance tests;
- Train staff;
- Maintain the system.

While this traditional approach to CAD implementation would, in theory, enable management to make decisions based upon a careful consideration of all relevant information, it is extremely technical in its orientation, and usually fails to take human and organisational factors into account (Harrow, 1983). Its effectiveness is also undermined by the existence of a strong predisposition, in Western managerial culture, to adopt cost reduction methods of assessing the advantages of new technology. Such methods view the benefits of technology in terms of cost reductions to be achieved in the short-term (Farhamood *et al*, 1990).

In reality, managers rarely adhere closely to the process outlined above because they know that many important decisions on new technology occur *after* its implementation (Currie, 1989). In such circumstances, Currie maintains that CAD introduction becomes an "act of faith" rather than the end result of a careful selection, acquisition and implementation process. Such *ad hoc* approaches are particularly dangerous for smaller electronics companies which, as discussed earlier in this chapter, usually lack the breadth of expertise and experience in making decisions in this complex area.

Implementing an advanced CAD or CAE system carries risks which need to be understood and managed, principal among which is the risk of selecting inappropriate technology. Vendors of design automation equipment, supported by the technical press, often apply strong commercial pressures to adopt new technology. According to the Engineering Industry Training Board (1988), in such circumstances companies may risk becoming heavily dependent upon the vendors when attempting to define their design capability requirements and may commit themselves to a project without properly understanding its purpose, its needs and viability, or its relevance to their environment.

One of the consequences of adopting such a piecemeal approach to design automation implementation has been that firms have tended to optimise design function sub-systems, such as PCB or product enclosure design, at the expense of the totality of the product design operation. As a consequence, many firms mistakenly see the *automation system* as the *solution* (Booth, 1990), a view which is reinforced by the tendency of electronics design automation vendors to sell their hardware and software systems as "solutions to your problem". This perspective adversely affects budget decisions since it readily justifies purchases of hardware and software while tending, at the same time, to be less generous in the allocation of time and money to the development of new standards and practices or supporting user training and development.

8.3. The need for a methodology

From an product design perspective, the consequence of not investing in new methods and technologies is likely to be a degraded design capability which is unable to cope with changes in the nature, intensity and scope of design. Indeed, it is clear that many U.K. electronics firms are now burdened with wholly inappropriate design systems.

There is, therefore, a requirement for an affordable and accessible methodology which will help electronics companies to define *for themselves* product design capabilities which are robust and which support their wider business objectives. Such a company-led technique would be particularly useful to SMEs which usually lack the internal expertise required to make informed decisions in this highly complex area. They generally have only limited financial resources with which to "buy in" the expensive consultancy expertise they would need to specify a robust design capability of the kind described above.

The methodology should be based on "best practice" so that firms avoid repeating the mistakes made by others. In addition to providing an affordable means for firms to regularly evaluate and improve their design operations, the application of a company-led methodology would also help to create far greater ownership of and commitment to the implemented design automation solutions (Maull and Hughes, 1992; Maull *et al*, 1990).

As indicated earlier in this thesis, however, there is currently no accessible and affordable methodology which can be used to help electronics firms of whatever size both to adopt a more formal strategic approach to the creation of their design capabilities and to overcome their current reliance on design automation vendors. Such a methodology would need to use a structured approach in order to enable firms to develop a resilient design capability which encompasses the required technological, organisational and infrastructural dimensions.

Within the context of the Manage, Operate and Support framework presented earlier in this thesis, this would be accomplished by considering the nature of current and future design projects (*nature* of design), the numbers of projects expected to be undertaken (*intensity* of design) and the *scope* of the design which is to be carried out during those projects.

8.4. Requirements for the methodology

According to Maull *et al* (1990), any methodology must specify two main characteristics:

> *"First, it must identify the salient variables to be taken into account, thus dimensionalising the problem. Second, it has to order these variables or dimensions to enable the user to progress in an orderly and understandable way from an initial to a new situation."*

It follows, therefore, that the primary characteristics of a design capability methodology tailored to the needs of electronics firms are, firstly, that it should focus on developing a set of capabilities able to respond to a variety of anticipated needs rather than on the creation of a "single point" solution and, secondly, from a content perspective, that it should address the dimensions of context (Maull *et al*, 1990) within which the design activities are situated.

Furthermore, the methodology must be:

- Theoretically sound;
- Practical and useful for SMEs;
- Written in a language SMEs can understand.

The remaining sections of this chapter describe the *process* and *content* issues which are required of the design capability methodology.

8.4.1. Process aspects of the methodology

Tranfield and Smith (1988) have identified nine elements which are key to a successful implementation methodology. They include:

- Business driven – the one and only reason for investing in new technologies is to improve the competitiveness of the company;
- Back–to–basics rethink – the implementation of new technology usually involves step–function change which, in turn, requires a fundamental analysis of the business situation and a reappraisal of business objectives;
- Top management driven – the best way to achieve step–function change is top down;
- Front end–back end – business and managerial issues are best considered at the "front end" of the change process rather than being the tail on the technological dog.

For the purposes of this thesis, however, the author proposes that four fundamental principles must underpin the *process* aspects of the design capability methodology. First, the role of management, in particular the Managing Director, is crucial to success. Second, the full involvement of company personnel is essential if success is to be achieved. Third, the fact that the identification and evaluation of appropriate strategies is rarely an algorithmic process highlights the importance of consensus–building. Finally, the methodology must adopt a structured approach to the specification of electronics design capabilities. That approach must be sufficiently flexible, however, to enable the firm to make repeated, future use of the methodology without the need to undertake the *entire* process on each occasion.

8.4.1.1. The role and responsibility of management

Companies which have achieved dramatic improvements in their competitive position have clearly demonstrated that management plays a key role in the improvement process. Many respected commentators go further and place the responsibility firmly on the Managing Director to have the necessary vision, to exercise leadership, secure consensus among the management team and obtain the full support of company personnel in undertaking the actions necessary to achieve and maintain competitiveness.

8.4.1.2. Harnessing individual creativity

People are by far the most important resource in any manufacturing business. Senior management need to harness the creativity of their staff by involving them fully in any improvement process. Their knowledge and expertise is required to secure the best solutions and to ensure that the individuals involved accept, own and commit to the solutions generated.

8.4.1.3. Solutions are rarely algorithmic

The identification of appropriate actions in many manufacturing situations is rarely algorithmic. Determining what ought to be done in a particular situation often requires the judgement and experience of a number of people each contributing their ideas and understanding.

8.4.1.4. The value of a structured approach

The complexities of modern manufacturing operations and the uncertainties inherent in today's highly competitive markets requires that a large number of options need to be evaluated. To ensure that the full implications of each option are considered and important aspects are not overlooked, a well structured approach is required. The approach needs to be easily understood and must make best use of valuable senior management time.

8.4.2. The content of the methodology

From a *content* perspective, the methodology must adopt a structured approach to design capability building which, by providing participants with a set of best practice tools and techniques, will enable them rapidly to progress from strategy creation to action planning.

Following on from the work reported in the preceding chapters, the requirements necessary to support the management of design, the operational aspects of product design and the supporting infrastructure are now considered. In terms of design process management, specific requirements are identified which will enable the strategic importance of design to be reflected in management of the design process. For example, the need to manage larger and more complex design activities, design for manufacture (DFM), geographic dispersion of design teams, communication issues, monitoring progress and so on.

It should be noted that the requirements have not been derived exclusively from SMEs. They have emerged from the author's investigations into the shortcomings of existing CAD tools, developments in international standards, evidence of actual CAD tools usage and from the investigation into international electronics design best practice.

8.4.2.1. The management of electronics design

For electronics firms, design is a strategic activity. The methodology should therefore help members of the senior management team to regard their product and manufacturing process design activities as a source of competitive advantage. Where appropriate, they must be helped to develop a process which contributes to the delivery of a stream of new products rapidly and predictably. This can only happen successfully, however, after careful consideration has been given to where the company will be in several years and to the kinds of products it intends to develop.

The methodology should discourage firms from viewing design as a black box operation from which new products magically emerge. Electronics product design is a process which must be managed and continually improved, both in order to reduce time to market and to eliminate waste and make better use of company resources. It is not, however, a process which should be micro-managed. The methodology should therefore guide firms in the adoption of enlightened human resource management policies which encourage, for example, the use of multi-disciplinary, cross-functional teams and the devolution of decision-making down to lower levels in the organisation.

8.4.2.2. Operational aspects of electronics design

As described in Chapter 6, the operational aspects of design are classed as those activities which are directly concerned with satisfying the requirements of the internal or external customer. For the purpose of this thesis, these activities are referred to as Generate Product Concepts, Generate Product Solutions, Develop Product and Validate Product.

Despite the existence of a variety of views on the underlying nature of product design – Rzevski (1990) differentiates, for example, between approaches which are predominantly concerned with the management of design and those which seek to understand *how* designers design – the methodology, in developing a resilient design capability, should provide firms with guidance on structuring the product design process.

More fundamentally, it should ensure that greater effort is devoted to the planning and product definition stages of the process rather than to the later design and prototype stages. It should also provide companies with a carefully chosen and well presented set of methods, tools and techniques which, because they represent industry Best Practice, will enable them to make significant improvements both to their overall responsiveness and to the quality and reliability of their products.

Methods such as CE, for example, recognise that the design and manufacture of electronics products requires the application of the knowledge and skills of a wide variety of people, from industrial designers to personnel from marketing, product design, purchasing and inventory control, as well as from customer and supplier companies. Tools such as QFD and DFMA are widely used in a CE context.

8.4.2.3. Support for the electronics design process

At an organisational level, the research has revealed that electronics firms need to create new organisational structures and cultures which can more effectively support their product design activities.

The methodology should thus provide firms with guidance in the establishment of supporting infrastructures for electronics design. Such infrastructures comprise the totality of supporting functions which enable the design activity to take place, including technology support in the form of appropriate IT hardware and software aimed at facilitating day–to–day administrative activities (wordprocessing, spreadsheets) and routine inter–personnel communication (email). They also embodies a variety of organisational and cultural elements, the most significant of which have been described in Chapter 7 of this thesis.

8.5. Conclusions

This chapter has proposed that a design capability methodology must adopt a structured approach which will enable firms to identify appropriate types of design projects (*nature* of design), appropriate numbers of projects (*intensity* of design) and the appropriate *scope* of the design which is undertaken during those projects.

Furthermore, the methodology should accomplish these objectives by allowing firms to consider how electronics product design needs to be managed, how design must be undertaken from an operational perspective and how it must be supported from an organisational and infrastructural perspective.

From a *process* perspective, the methodology must embody four fundamental principles. First, the role of management, in particular the Managing Director, is crucial to success. Second, the full involvement of company personnel is essential if success is to be achieved. Third, the fact that the identification and evaluation of appropriate strategies is rarely an algorithmic process highlights the importance of consensus–building. Finally, the methodology must adopt a structured approach to the specification of electronics design capabilities.

From a *content* perspective, the methodology must provide participants with a set of best practice tools and techniques which will enable them rapidly to progress from company mission, through design strategy to planning the implementation of a resilient design capability. Such a capability must encompass the organisation's knowledge and skills, managerial systems, physical systems and values and, where appropriate, it should also extend beyond the enterprise to embrace customer and supplier companies.

The following chapter of this thesis presents an outline description of the design capability methodology.

Chapter 9.

The Design Capability Methodology

This chapter presents an outline description of a company-driven methodology for specifying resilient electronics design capabilities. The design capability methodology (named *AGILITY* and presented in full in Volume 2 of this thesis) utilises well proven tools and techniques to guide companies through the process of creating a resilient electronics design capability - from the development of an appropriate mission statement to the identification of appropriate design system solutions which can readily be translated into action plans for improvement. In so doing, the methodology seeks to ensure that key skills are transferred to company personnel.

The improvement process embodied in the methodology is the product of 6 man-years of development. Detailed examination of the electronics design process in a number of leading international electronics companies demonstrated that there was a pattern for success which could, in theory, be followed by any company wishing to achieve similar success.

9.1. Top management commitment

The achievement of lasting change in any organisation requires commitment right from the top (Tranfield and Smith, 1988) and it is a key aspect of the methodology that it seeks to empower design management by insisting that the managers themselves, with appropriate assistance from a facilitator, make the critical decisions affecting the future of their businesses and control the overall improvement process.

According to Twiss and Goodridge (1989), the challenge for management is to bring about change in an organic fashion and with minimum of disruption. To do this they must formulate a strategy for introducing change based upon:

- A clear understanding of the technical and organisational objectives -- where they want to be eventually;

- A time scale and plan for achieving these objectives -- how quickly they can get there;
- A phased plan for introducing specific technical and organisational changes and training for their achievement.

The methodology seeks to achieve the first two of these objectives while, at the same time, recognising that the creation of the right environment for the generation and implementation of technical change is dependent upon a number of interrelated elements. According to Twiss and Goodridge (1989) these include:

- Corporate culture;
- The process of strategy formulation and dissemination;
- The organisational structure;
- Managerial information and control systems;
- The attitudes, motivations and contributions of individuals.

9.1.1. Avoidance of vendor-led solutions

This methodology differs markedly from the approaches adopted by some consultancy organisations which attempt to "lock" clients into costly and potentially open-ended relationships. In such circumstances, company personnel are usually not included in the process of devising solutions to their own problems, nor do contracting consultants generally attempt to develop the skills of client staff or pass on their knowledge and expertise. As a result, lack of client ownership of, and hence commitment to, an implemented solution is almost inevitable.

The methodology has been developed independently of any hardware or software vendor. It's impartiality in this respect ensures that the solutions developed are appropriate to the client company - and not to the vendors and consultants who provide the service.

9.2. Process

The methodology achieves results by involving company personnel, at all levels, in the process of specifying the necessary improvements to the firm's product design capability. It is sufficiently flexible, however, to enable the firm to make repeated, future use of appropriate components (individual workshops, for example) when specific product design capability improvements are warranted.

At all times the company retains ownership and control so that the actions identified are fully supported and are more likely to be implemented successfully. The methodology makes extensive use of workshops throughout the design capability specification activity. It also requires that participants undertake a series of preliminary activities prior to taking part in each workshop and it provides a number of toolkits and techniques to help participants to successfully complete those activities. Each component of the methodology will be described in greater detail in Section 9.2.1.

The presence of a facilitator with wide design, manufacturing and consultancy experience also helps to ensure that the improvement process is handled competently and with sensitivity.

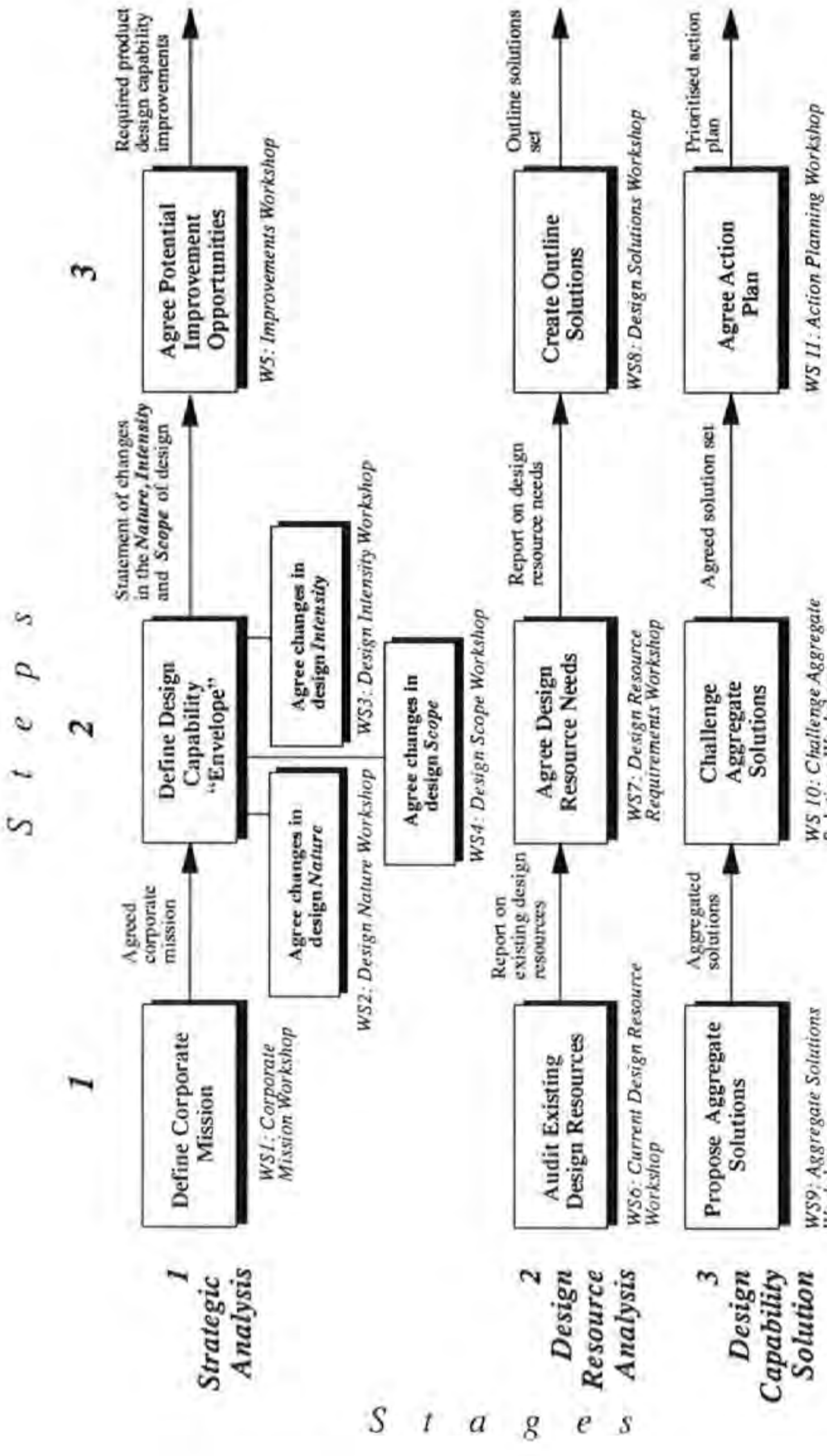
9.2.1. How the methodology is applied

9.2.1.1. Workshops

Workshops are used throughout the methodology to generate contributions, to make decisions and agree actions. Because many of the decisions which participants will need to make are not algorithmic, the most effective actions can usually only be determined by generating a wide range of contributions from the individuals involved. Involvement is vitally important for another reason – without it there can be no ownership and commitment to the solutions generated.

To facilitate this process, workshops are conducted in a non-critical, "egoless" atmosphere in which all present, regardless of status, feel they have a valid contribution to make to corporate revitalisation.

Figure 14: Overview of the Design Capability Methodology



9.2.1.2. Preliminary Activities

The process of applying the methodology is made more productive and effective by the assignment of carefully tailored Preliminary Activities (PAs) to be completed by participants prior to each workshop session.

These PAs include:

- Creation of a Mission Statement;
- Modelling the current design process;
- Identifying potential changes in the *nature* and *intensity* of the firm's design activities and in the *scope* of its products;
- Carrying out an assessment of current design resources.

9.2.1.3. Toolkits

Toolkits provide detailed instructions on carrying out the preliminary activities. The methodology includes toolkits to assist participants in creating a Mission Statement, for example, and for undertaking product portfolio analysis during PA 2 (Customer and Market Evaluation). The set of 10 toolkits is provided in Appendix 2.

Where required, assistance in using the toolkits is provided by the facilitation team who will have considerable experience of applying the techniques in a wide variety of environments.

9.2.1.4. Techniques

A variety of techniques are available which would enable participants to derive maximum benefit from the workshops and preliminary activities. They include Structured Brainstorming, Affinity Diagramming and the use of Prioritisation Matrices (Brassard, 1989). The Structured Brainstorming technique may be found in Appendix 3.

9.3. Content of the methodology

Figure 13 presents an overview of the methodology, showing each of the steps involved in the methodology's three stages: Strategic Analysis, Design Resource Analysis and Design Capability Solution. Each stage of the methodology will be described in the remaining sections of this chapter.

9.3.1. Strategic Analysis

Strategic Analysis is a crucial first step in specifying an electronics company's flexible product design capability. As indicated in Figure 14, the primary output from this stage is a set of product design capability improvement opportunities. Depending upon the current level and quality of the Company's product design, such improvements could be extremely wide ranging.

They might, for example, involve radical changes in the way product design is managed and organised. They might also reveal a requirement to provide design engineers with enhanced design automation support or to provide members of multi-disciplinary teams with electronic means of communicating with each other. Improved engineering staff training and the introduction of more enlightened reward and recognition systems might also be called for.

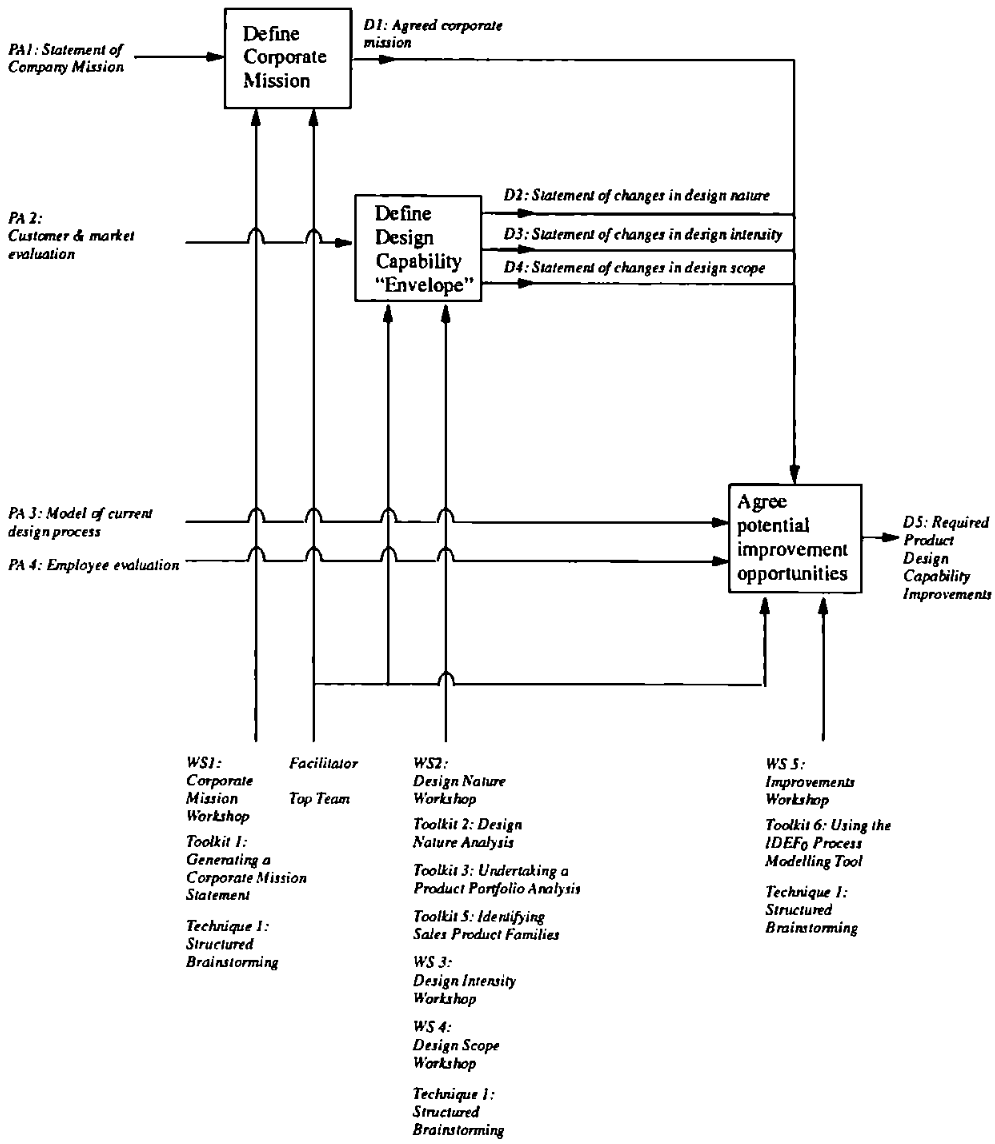
Furthermore, analysis of market trends and competitor product performance will undoubtedly highlight opportunities for improving the Company's product profile. This may involve eliminating various underperforming products and replacing them with a set of innovative products involving new technologies and materials and taking into account broader considerations of customer service, lifestyle and the need for recycling. Such products will represent the platforms the Company will require to create product families which possess the necessary competitive characteristics to enable them to win in the marketplace.

9.3.1.1. Step 1 - Defining a corporate mission

One important strategic factor to be grasped in this context, and one which is strongly advocated by the majority of successful electronics manufacturing companies, is the corporate requirement for a commonly understood mission which, at the same time, permits the firm to retain sufficient flexibility to exploit tactical opportunities.

An essential first step in the process of Strategic Analysis must, therefore, be the development of a clear, unambiguous statement of corporate mission. For those companies which have no mission statement, it will be necessary to start from first principles. Where such a statement already exists, it may be necessary to undergo a process of redefinition to ensure the corporate mission statement "fits" with the future aims and goals of the organisation.

Figure 14: The Strategic Analysis Process



NOTE: Feedback occurs throughout the methodology but, for the purposes of clarity on the diagrams, feedback loops have not been included.

9.3.1.2. Step 2 - Defining the design capability "envelope"

The process of establishing the boundaries of the design capability "envelope" requires the firm to undertake a detailed examination of its customers, markets and competitors in order to establish the impact that developments in these areas will have upon the firm's overall product portfolio and on its product design capability.

Step 2 of the Strategic Analysis process requires the involvement of personnel from customer and supplier companies during the various workshops. Their presence is designed to provide the client company with detailed input on a variety of key issues, including:

- Current product performance;
- Current product functionality;
- Quality;
- Future product and process technology directions;
- Market demand;
- Ability of suppliers to contribute to the firm's design process;
- Changes taking place in the firm's supplier network and
- Supplier relationship problems.

The outputs from Step 2 are a series of statements which will help the firm to define a set of product and design process improvement opportunities. These, in turn, will reflect the anticipated nature, intensity and scope of the firm's design activities.

The creation of a design capability "envelope" is accomplished through three tasks. These are:

Task 1 – Agree changes in the *nature* of design;

Task 2 – Agree changes in the *intensity* of design;

Task 3 – Agree changes in the *scope* of design.

9.3.1.2.1. Task 1 - Agree changes in the *nature* of design

As indicated in Chapter 3 of this thesis, electronics product design can encompass a wide spectrum of activities, from major new product introduction (Strategic Design) through to small-scale incremental improvement (Repeat Design).

The identification of changes in the *nature* of design requires the Sales/Marketing Director to undertake an analysis of the firm's customers and its overall marketplace in order to focus the company's attention on such issues as:

- Any developments in customer product upgrade or new product introduction plans which will have a significant impact upon the firm's own product or manufacturing process technologies;
- The emergence of new component or process technologies whose use might provide significant benefits to the firm, for example in terms of reduced cost, improved product performance or ease of manufacture;
- The emergence of potential new markets for the firm's products;
- The performance in the marketplace of the firm's current portfolio of products.

For example, achieving the required level of improvement to a particular product might only be achievable using digital instead of analogue technologies or, as in the case of cellular telephones, it might require the adoption of microwave techniques.

The output from Task 1, a statement of anticipated changes in the *nature* of design activities the firm will be required to undertake, is fed into Step 3 (Agree Potential Improvement Opportunities) where it is used to help workshop participants to agree a set of product design capability improvements.

9.3.1.2.2. Task 2 – Agree changes in the *intensity* of design

There can be little doubt that competitive pressures are forcing many U.K. electronics firms to undertake far more design projects than they have carried out in the past.

For example, a firm might decide to enter a fast moving, highly competitive niche market which will involve it in high volume production for the first time. The demands of such a market would undoubtedly force the firm to continuously improve and extend its product families in order to satisfy changing customer requirements. However, greater *intensity* of design has obvious implications for a company's ability concurrently to manage and control multiple projects – particularly with regard to minimising the risks involved in product design.

The identification of changes in the *intensity* of design requires the client firm to attempt to estimate the likely increase in the amount of design it undertakes.

The output from this step, a statement of anticipated changes in the *intensity* of its design activities, is fed into Step 3 (Agree Potential Improvement Opportunities) where it is used to help workshop participants to agree a set of product design capability improvements.

9.3.1.2.3. Task 3 - Agree changes in the *scope* of design

In some markets, electronics firms must anticipate changes in the lifestyles and aspirations of their customers, sometimes even before the customers themselves are aware of those changes.

A cellular telephone company might find, for example, that it needs to pay significantly more attention to designing the user interface on its latest product because that product is specifically aimed at enhancing customer lifestyles and satisfying their aspirations. However, the identified improvements might also require the firm to adopt Design for Manufacture and Assembly (DFMA) techniques or even a Design for Disposal (DFD) approach where it is supplying its products to the German market.

In order to identify changes in the scope of its design activities, therefore, the firm must carefully to examine developments in its marketplace in such areas as product safety, product liability, packaging and pollution control as well as in the whole area of human lifestyle.

The output from this task, a statement of anticipated changes in the *scope* of design activities the firm will be required to undertake, is fed into Step 3 (Agree Potential Improvement Opportunities) where it is used to help workshop participants to agree a set of product design capability improvements.

9.3.1.3. Step 3 - Agree potential improvement opportunities

The company must identify opportunities for improving the effectiveness of its design operations and for building upon its existing strengths and competences in product design and development. Such opportunities exist on a number of different dimensions.

These include:

- The *products* themselves;
- The overall *management* of the product design process, including structure and accountability;
- The *operational* activities involved in actually designing electronics products, including systems and processes;
- The infrastructural or *support* activities necessary to ensure effective utilisation of both human and technological resources, including people and culture.

Here the senior management team must consider the evidence derived from a variety of sources. These are:

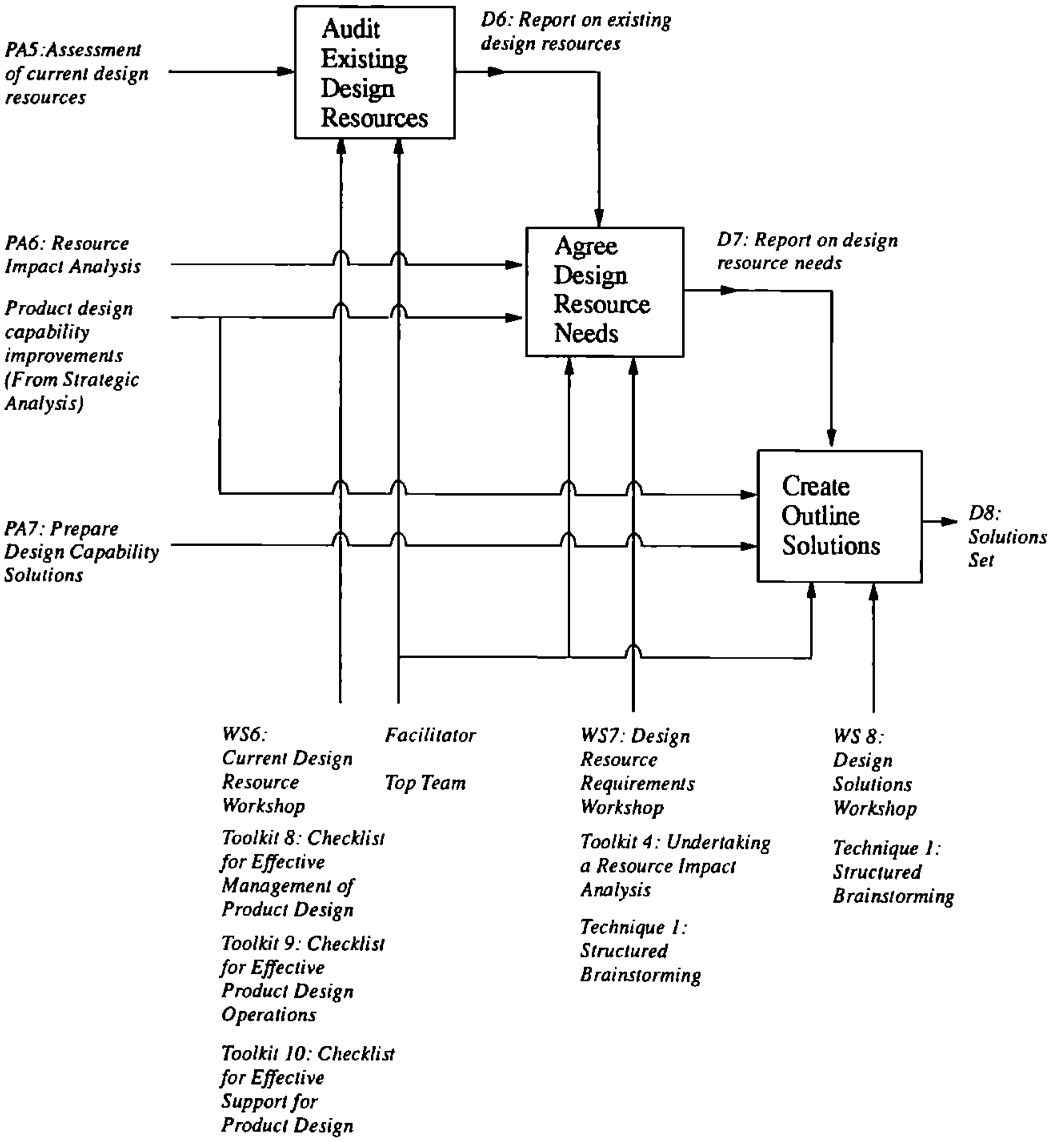
- The outputs of Step 2 described above, namely statements of changes in the *nature*, *intensity* and *scope* of design;
- The results of a process modelling Preliminary Activity (PA) whose objective was to provide a clear understanding of the firm's current product design activities. The modelling should have been undertaken using an appropriate process modelling technique;
- The results of an employee survey designed to elicit staff views on the way the company is organised and managed and the way in which product design is carried out.

The results of this analysis may lead the senior management team to revisit the Mission Statement created in Step 1 and to refine it in light of any new product or market directions which have been agreed.

9.3.2. Design Resource Analysis

In Strategic Analysis the design capability "envelope" was defined and a variety of improvement opportunities were identified along the Manage, Operate and Support dimensions of the company's design activities. Quite rightly, no consideration was given at that time as to whether or not, or indeed, how the improvements might be achieved. Design Resource Analysis is concerned with **how** design resources can be adjusted and more fully utilised to achieve the required improvements. The process of analysing design resources is illustrated in Figure 15.

Figure 15: The Design Resource Analysis Process



NOTE: Feedback occurs throughout the methodology but, for the purposes of clarity on the diagrams, feedback loops have not been included.

9.3.2.1. Step 1 - Audit existing design resources

An essential first step in this process is a thorough audit of existing electronics design resources and capabilities. The audit should be conducted along the Manage, Operate and Support dimensions as described in Chapters 5, 6 and 7 of this thesis and should examine resource issues related to, for example:

- The control of product design and the minimisation of risk;
- Current hardware and software in use throughout the product design process;
- Resources devoted to process design;
- Design infrastructure;
- IT support for inter-personnel communications and for administrative tasks;
- Human resource management.

In order to undertake the audit of existing design resources, participants are asked to undertake the Current Design Resource Workshop (Workshop 6).

9.3.2.2. Step 2 - Agree design resource needs

Having successfully undertaken Step 1, the firm is now in a position to make an informed assessment of how specific product design resources affect each sales product family's performance and how those resources will need to be adjusted in order to meet the product design capability improvements identified in the Strategic Analysis stage of the methodology.

In order to reach agreement on product design resource needs, participants are asked to undertake the Design Resource Requirements Workshop (Workshop 7). Selected participants will have completed the Resource Impact Analysis preliminary activity (PA 6) prior to attending the workshop.

The workshop provides a forum in which participants can consider such questions as:

- If the volume of design is going to increase, do we need to buy more hardware and/or software or do we subcontract design work?

- If we need to apply Concurrent Engineering techniques to our design process, what do we need to do with regard to training?
- If we are going to start designing more innovative products than we have in the past, where are the ideas going to come from? Do we need to hire in more suitably qualified people or can existing staff do the job if they are given appropriate training? What are the implications for the company's overall culture?

9.3.2.3. Step 3 - Create outline solutions

Given that there are usually many ways in which improvements can be effected to the way individual product families are designed, a decision must be made regarding the most appropriate resources to change in order to achieve the required results. In practice such decisions are rarely algorithmic. They require the imagination and creative contributions of relevant company personnel to generate and evaluate alternate solutions.

Workshop 8, the Design Solutions Workshop, is used to provide a forum to secure these contributions and, for each product family, to determine which solution to adopt.

9.3.3. Design Capability Solution

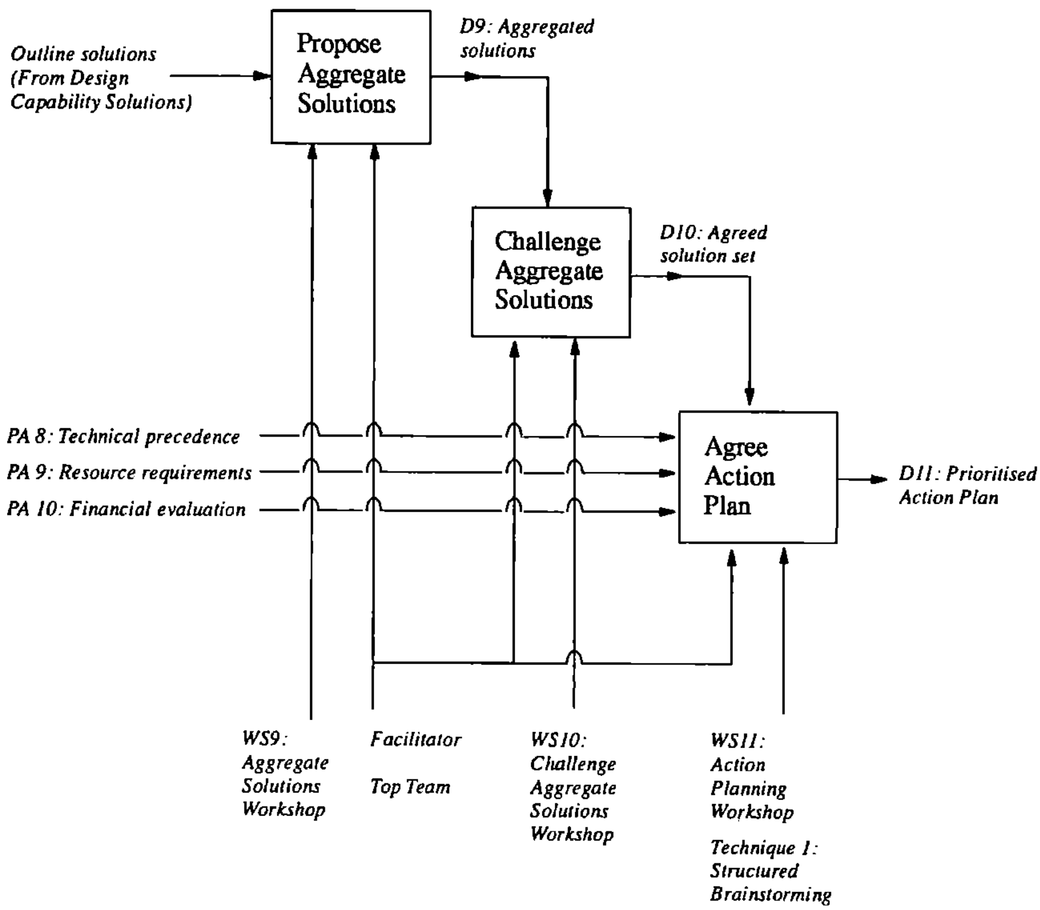
The various individual design capability solutions must be brought together into an overall plan for creating a resilient product design capability. The process of creating a design capability solution is illustrated in Figure 16.

9.3.3.1. Step 1 - Propose aggregate solutions

The solutions which emerge from the Design Resource Analysis process will relate to individual actions with respect to specific resources. For example, there may be several instances where there is a requirement for the use of DFMA and DFD techniques, for the purchase of a more sophisticated design automation system and for the realignment of company human resource management policies to take account of the more demanding job requirements.

Hence, the development of a *company-wide* solution requires some aggregation of solutions to take place. This aggregation is necessary for two reasons. Firstly, because certain actions might not be justified on the basis of their affect on one product family alone but may be worthwhile as part of an improvement affecting many families. Secondly, by amalgamating individual solutions an overall solution might be identified which makes better use of the available resources. This step is accomplished in Workshop 9, the Aggregate Solutions Workshop.

Figure 16: Creating a Design Capability Solution



NOTE: Feedback occurs throughout the methodology but, for the purposes of clarity on the diagrams, feedback loops have not been included.

9.3.3.2. Step 2 - Challenge aggregate solutions

Having assembled related solutions into aggregate solutions, these must be subjected to a rigorous challenge before the firm moves on to create an action plan for improvement. The process of challenging solutions occurs in Workshop 10, the Challenge Aggregate Solutions Workshop. Among other issues, participants should consider those economic, social and technical factors which might have a bearing upon the viability of the design capability solutions.

Challenging solutions is essential for two reasons. First, the process of amalgamating solutions to develop the tracks may in itself have brought into question the Company's capacity to implement them. Secondly, both individual solutions and solution tracks need to be re-examined to eliminate or reconcile conflicts, avoid duplication and provide a realistic and achievable agenda for improvement.

In effect, this process represents the Top Team's last opportunity to assess the solutions before they are incorporated in the client firm's product design strategy and action objectives. The result of challenging solutions is to agree a set of product design capability options which the manufacturing team own and commit to.

9.3.3.3. Step 3 - Agree action plan

Action planning is concerned with identifying and agreeing priorities on specific actions in line with the previously established design capability options.

In most manufacturing situations a large number of actions may be feasible to achieve a desired end, however the process of deciding amongst alternatives cannot be prescribed. Because it is vital to secure ownership and commitment to any solutions, contributions must be sought from those who control and use resources in order to ensure that the selected actions are effective. The necessary contributions are secured through Top Team participation in Workshop 11, the Action Planning Workshop.

Having assembled individual design solutions into a set of agreed capability options, priorities must now be agreed and assigned to specific actions. In order to establish priorities each action identified should be assessed against the following criteria:

- Technical Precedence – what must be done before an action can be undertaken;
- Resources required to implement an action – for example, financial, equipment, materials and manpower.
- The value of taking action to the success and profitability of the company;

In this way a prioritised list of feasible and desirable actions can be agreed which will transform the company's product design performance. Without proper consideration of all of these issues, inappropriate actions might be adopted which would not utilise design resources effectively and which would be unlikely to produce the desired competitive improvements.

9.3.3.3.1. Technical precedence

In order to financially justify actions and identify priorities the full consequences in terms of the availability of resources and their cost must be determined.

The full resource implications can only be assessed if the tasks which need to be undertaken before the required actions can be carried out are identified. Each design capability option must therefore be examined carefully to determine what tasks, if any, must be undertaken prior to its implementation.

This activity is undertaken in PA 7: Technical Precedence and the results are presented to the participants in Workshop 11, the Action Planning Workshop.

9.3.3.3.2. Resource requirements

An important consideration in establishing priorities is to identify the resources required and their availability. Without such consideration actions might be agreed without the means to implement them or that one particular resource, for example, a CAD system or an analogue design engineer might be allocated more jobs than they can reasonably cope with.

This activity is undertaken in PA 8: Resource Requirements and the results are presented to the participants in Workshop 11, the Action Planning Workshop.

9.3.3.3.3. Value to the company

In addition to resource availability, the cost associated with implementing a particular action must be considered in order to assess the economic feasibility of undertaking it. It makes little sense to undertake an action if the benefits which arise from it do not provide an acceptable return on the capital employed or, in the worst case, are far less than the cost of implementing the action.

This activity is undertaken in PA 9: Financial Evaluation and the results are presented to the participants in Workshop 11, the Action Planning Workshop.

Careful consideration of these issues will enable participants to establish a *Prioritised Action Plan*. This, in turn, will enable product design resources to be deployed effectively to secure the greatest benefit to the business.

9.4. Conclusion

A methodology has been presented which adopts a company-led approach to the specification of resilient electronics product design capabilities. The methodology draws extensively upon the lessons of international electronics design best practice - particularly in its insistence that senior management should demonstrate ownership of and commitment to the change process - and uses well proven tools and techniques to guide companies through the process of specifying such capabilities.

The approach presented in the methodology is a considerable improvement over existing in-company or consultancy-led approaches, the latter of which tend to "lock" clients into costly and potentially open-ended relationships. Users are not generally involved in devising solutions to their own problems, nor do contracting consultants devote much effort to developing the skills and knowledge of client staff. Lack of client ownership of and commitment to the implemented solution is almost inevitable.

However, by using a documented methodology a company will have a record of its progress through the various stages and can return to the process as necessary without additional costs. Furthermore, the use of proven techniques in the methodology reduces the risk of failure, prescribed deliverables help gain management commitment and guidelines ensure uniformity of application by providing auditability and assisting in the transference of skills.

From a *process* perspective, the methodology makes extensive use of workshops throughout the design capability specification activity. It also requires that participants undertake a series of preliminary activities prior to taking part in each workshop and it provides a number of toolkits and techniques to help participants to successfully complete those activities.

Where *content* is concerned, the methodology has three stages - Strategic Analysis, Design Resource Analysis and Design Capability Solution - each of which has a number of steps and, in the case of the "Define Design Capability Envelope" step, a variety of tasks.

In Strategic Analysis the design capability "envelope" is defined and a variety of improvement opportunities are identified along the Manage, Operate and Support dimensions of the company's design activities. Design Resource Analysis is concerned with how design resources can be adjusted and more fully utilised to achieve the required improvements. Finally, Design Capability Solution brings together the various individual design capability solutions into an overall plan for creating a resilient product design capability.

Chapter 10.

Conclusions

The work has provided a new approach to specifying electronics design capabilities which will enable electronics SMEs to implement good design practices in their businesses and to support those practices with appropriate design software tools. Such a "best practice" methodology will enable firms to avoid repeating the mistakes made by others, and it will provide an affordable means for firms to regularly evaluate and improve their design operations.

The research has provided a company-driven process methodology which, for the first time, will help U.K. electronics companies to define *for themselves* product design capabilities which are resilient to changes in their respective business environments and which support their wider business objectives. There is currently no such methodology available in a form which is both accessible and affordable to SMEs. Nor is such a methodology available even for use by *large* electronics firms.

The term "company-driven" denotes an approach in which senior management of the company set the agenda for specifying the flexible product design capability and then drive forward the process of creating such a specification. Such a top down approach would ultimately guarantee the commitment of all senior managerial participants to the specified solution.

While the methodology aims to facilitate the creation of product design capabilities in electronics SMEs, it should be equally useful for both medium and large U.K. firms, despite the gulf in organisational, human and technological resources which lies between the smaller and the larger enterprises.

The work has provided an introduction for future work to further refine and develop the methodology, particularly when longitudinal data is available on the extent of its effectiveness in creating resilient design capabilities and further evidence is accumulated regarding its usefulness and efficiency in operation.

10.1. Capabilities and strategic choices

Operating effectively in today's buyer's market is not straightforward, and a growing body of literature suggests that the ability to create and then to capitalise upon a number of "core" capabilities has become one of the most important competitive attributes for manufacturing firms in the 1990s.

From the point of view of product design, the need for a capabilities-based approach has been driven by the very real difficulties firms experience in attempting to predict future markets for their products. For example, a firm may experience severe problems if, having committed resources to the purchase and installation of a design automation system, it is subsequently discovered that the system is incapable of meeting the requirements of a changed marketplace. In particular, there is a requirement for electronics firms to create and develop the ability to cope with three dimensions of design instability, namely changes in the *nature*, *intensity* and *scope* of product design activities.

Unpredictability of demand and competitive pressures means that companies must make strategic choices which allow them to anticipate, with a reasonable degree of certainty, the direction their businesses will take in the future. The hierarchical nature of the design capability methodology, in which each stage sets requirements for the following stage, ensures that all solutions developed fit into the overall business strategy and ensures the integration and cohesiveness of the system.

10.2. Electronics design best practice

The research has shown that in today's highly competitive "buyers' market", not only are many electronics firms being compelled to undertake increasing numbers of design projects, they are also under pressure to design and manufacture innovative products for their OEM customers and, in many cases, to create products which match the lifestyle and aesthetic requirements of millions of increasingly discerning end-users.

In such circumstances, the effective design of electronics products requires that firms should create design capabilities which integrate three interrelated components, namely:

- The essential managerial aspects of product design (such as project management and risk minimisation);
- The "core" or operational resources (such as design automation hardware and software) and activities;
- The supporting infrastructure (including the provision of technology support for routine administrative activities and inter-personnel communications, as well as the enactment of policies and procedures aimed at bringing about the alignment of individual goals with organisational objectives).

From a management perspective, the design of electronics products must be regarded as a highly complex, strategic activity which should be actively supported by senior executives and effectively managed and controlled at corporate, project and design activity levels.

At an operational level, firms must pay close attention to those activities involved in the design both of the product and the process used in its manufacture. Furthermore, engineers should adopt appropriate methods, tools and techniques during the process of product design.

Finally, firms must pay careful attention to the development of a supporting infrastructure for product design. In order to operate effectively, designers need to be supplied with computer based services which will enable them to cooperate across both departmental and geographic boundaries. The issue of corporate culture must be addressed in order to encourage a more "aggressive" approach to product design and, given the need for electronics firms to retain hard won knowledge and wisdom, Human Resource policies must be established which focus upon minimising the turnover of engineering and design staff.

Crucially, also, U.K. and European electronics firms need to adopt an organisational learning approach in order to avoid "reinventing the wheel" from project to project.

10.3. Requirements for a design capability methodology

What electronics SMEs currently lack is a "roadmap" which, by providing a sound process, will reduce the risk involved in creating their own product design capabilities.

A design capability methodology must adopt a structured approach in order to enable firms to identify appropriate types of design projects (*nature* of design), appropriate numbers of projects (*intensity* of design) and the appropriate *scope* of the design which is undertaken during those projects.

The methodology must accomplishes these objectives by allowing firms to consider how electronics product design needs to be managed, how design must be undertaken from an operational perspective and how it must be supported from an organisational and infrastructural perspective.

From a *process* perspective, the methodology should embody four fundamental principles. First, the role of management, in particular the Managing Director, is crucial to success. Second, the full involvement of company personnel is essential if success is to be achieved. Third, the fact that the identification and evaluation of appropriate strategies is rarely an algorithmic process highlights the importance of consensus-building. Finally, the methodology must adopt a structured approach to the specification of electronics design capabilities.

From a *content* perspective, the methodology should provide participants with a set of best practice tools and techniques which will enable them rapidly to progress from strategy creation to action planning.

10.4. The design capability methodology

The process of specifying a flexible electronics design capability must be a team effort which draws upon a wide range of skills, knowledge and expertise. The methodology-based approach provides a way of managing the large number of issues that arise in such circumstances. It avoids mistakes which have been made by previous, essentially *ad hoc*, approaches and makes available techniques which have been found to be successful.

Therefore the approach which forms the basis of the author's methodology is one which concentrates upon the development of a structured, methodical process for constructing a design capability during which various activities are specified in order to build up the information required for decision making. Senior managers are obliged, for example, to define an improvement opportunity "envelope" with which the company can move forward and the methodology explicitly ties the design capability to this future "vision" rather than to the current situation.

The process therefore ensures that the right questions are asked and provides tools and techniques to help at various stages of the analysis. It also ensures that important issues are dealt with and that the required information relating to the business context of electronics design is articulated. Furthermore, the design capability methodology seeks to enlist the skills and expertise of the participants in a way which can be applied to many different company types. The mechanisms which are used to bring this about are a series of preliminary activities and workshops - orchestrated by a facilitator who guides and manages the entire process.

This company-driven approach is believed to be the only feasible one for use in the rapidly changing electronics industry since it enables the companies themselves to determine which issues were important for their businesses and, using these issues as a baseline, would devise the most suitable means for achieving their goals. Such a structured approach would avoid some of the pitfalls inherent in the methods adopted by design automation vendors.

10.5. Contribution of the work

The work has provided a framework for the company-driven specification of electronics design capabilities and a tool for the specification of the design capability itself which considerably improves on current practice. Indeed there is currently no design capability building methodology available in a form which is both accessible and affordable to SMEs. Nor is there any evidence of the existence of such a methodology even for use by *large* electronics firms. It has also enhanced our understanding of international electronics design practice, from both the technological and managerial perspectives.

The company-driven approach has been extended beyond the piecemeal specification of "single point" solutions to product design problems and now embraces the definition of product design capabilities which are robust and which support firms' wider business objectives. An approach has been developed which will enable electronics firms to move, in a structured fashion, from the development of a mission statement through to the identification of appropriate design system solutions which can readily be translated into action plans for improvement.

Hence, for the first time, the Managing Director of a small electronics company can, with appropriate facilitation, go through the process of implementing best design practices in his business and of supporting those practices with appropriate design software tools. The approach advocated here will enable the MD to avoid repeating the mistakes made by others and it will also provide an affordable means whereby his firm can regularly evaluate and improve its design operations.

Furthermore, this approach will make it considerably easier for the MD to gain the ownership and commitment of staff at all levels in the company and, in contrast to many existing consultancy approaches, will leave the company substantially in control of its own product design operations.

While the methodology aims to facilitate the creation of product design capabilities in electronics SMEs, it is nevertheless the author's belief that such a methodology would be equally useful for both medium and large U.K. firms, despite the gulf in organisational, human and technological resources which lies between the smaller and the larger enterprises.

10.6. Future work

This work provides a first step in design capability building which engages future users of that capability in determining their objectives and requirements for the system.

Work is required to further refine and develop the methodology derived by applying it in various types of electronics company. A series of studies is required to test and validate the methodology in live company environments. It is the author's view that only after this has been done can meaningful changes be made to the structure and content of the methodology, as well as to the ways in which it is delivered.

Further experience will also lead to the development of the role of the facilitator in mediating between often competing and conflicting personal, political, resource and business interests. The control of meetings in which strongly felt convictions and animosities come to light and the brokering of useful consensus among participants is a challenge which requires skills and techniques which must be identified and refined.

There is also scope for future work to create software tools which would support both the delivery of the design capability methodology and would assist in embedding an organisational learning approach within the context of project management.

At one level, a software tool could be developed which simply computerised the various steps within the methodology, thereby enabling the participants, for example, to enter numerical or textual data into the computer during the various preliminary activities. The software would then present the evidence, in a suitable format, to the Top Team to help them in their decision making and problem solving activities.

From an organisational learning perspective, aside from post-project audits whose aim is to learn from past success and avoid past mistakes (Turner, 1993), current approaches to project management do not explicitly address the need for knowledge to be recorded during the technological innovation process so that it can be reused to improve the effectiveness of future projects. Indeed, the author has found little evidence of any work which has sought to apply the principles of organisational learning to project management, particularly with regard to the management of technological innovation projects in SMEs.

There is therefore considerable scope for research to develop a computer-based project management tool which will help SMEs to capture and reuse project knowledge and experience.

Specifically, the tool could:

- Provide a means of recording and storing the information generated during each project;
- Assist the users to analyse project management experiences and to develop an action plan for dealing with such situations more effectively should they recur;
- Provide users with a reference and information retrieval system.

The major research challenge would lie in producing tools and techniques which facilitate continuous management and product/service improvement through the reuse of prior knowledge and experience but which are, at the same time, practical and easy for SME management to apply to their businesses. The work would also need to ensure that the tools and techniques embody existing good project management practice, that they interface with existing project management software and that they deliver a good payback in relation to the data input effort required.

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Appendices

Appendix 1.	Case Study Question Set
Appendix 2.	U.K. and Mainland European Case Study Companies
Appendix 3.	U.S. and Far East Case Study Companies
Appendix 4.	Publications
Appendix 5.	Examples of data collected during visits to U.K., European and Japanese electronics companies

Appendix 1

Case Study Question Set

COMPANY STRATEGY:

1. What are the main elements of the company's strategy and what is design's position within that strategy?

2. What is the extent of influence of design over the company's short- and long-term financial position?

3. To what extent are designers made aware, when they are working on a new product, of the expected impact that product will have on the company's fortunes? How is this done?

4. How is product success defined?

5. Of major product introductions over the last few years, how many have been failures? Was design a critical factor in that outcome? If not, what was the major determinant of failure? What is your attitude to failure?

6. What is the current market share held by each product?

7. Who are the company's main competitors?

8. How does the company compete?

    - *Low cost*
    - *Superior quality*
    - *Product functionality*
    - *Delivery performance*
    - *Mix of several of the above*

9. What are the company's investment intentions regarding computer-based design tools?

10. Does the company recognise the need for concurrent/simultaneous engineering? If so, to what extent has the approach been adopted and what impact has its introduction had on organisation structure, management roles and management responsibilities?

11. Does the company use such techniques as continuous improvement programmes and corrective action teams? If so, are findings from these activities fed back to design?

12. Does the company have an integration strategy which will ultimately link all its business activities? If so, how far has it been implemented and what have been the major implementation issues and problems?

13. How is company effectiveness measured?

    - *Percentage products delivered on time*
    - *Customer complaints about delivery, quality etc*
    - *Inventory levels*
    - *Internal rates of scrap/rework*
    - *Throughput time*
    - *Warranty costs*

14. What ways are you looking at to drive down factors like product introduction cycle time, manufacturing cycle time and supplier lead times? Circle the relevant category and for those selected, indicate how this is being done.

- *Design and test*
- *Customer order handling*
- *Equipment set-up/changeover*
- *Batch processing time*
- *Delay/queue time*
- *Other*

15. What standards are adhered to? Is up-to-date information regarding UK and international standards made available?

- *What databases are in use?*
- *Database type*
- *Nature of information stored*
- *Kind of data held against part numbers and components*
- *Method of storage of product design information*

16. How are projects managed?

17. What kind of project management errors have occurred? Examples, if possible.

- *Action that should have been taken was not*
- *Action taken when it should not have been*
- *Solving the wrong problem due to badly defined strategy*
- *Action defines the right problem but solution not used*

ELECTRONICS DESIGN:

1. How is the front end of the design process handled?

    - *Handling quotations*
    - *Estimating*
    - *Tendering*

2. Do you agree that current design tools are merely providing "point solution" support for electronics engineering? If so, why?

3. To what extent is the design function integrated with other computer-aided parts of the organisation? If any integration exists, how is it accomplished and to what ends?

4. What range of experience do design team members have? How much do less experienced people rely on their more experienced colleagues for guidance and advice?

5. Is the design environment/company culture conducive to effective communication of technical and managerial information and decisions?

6. In regards conceptual design, are proposed concepts formally evaluated against technical and economic criteria and risks assessed? If so, how is this done?

7. At what stage in the design process is a testability assessment carried out?

8. What kinds of testability procedures/tools are used? How are they used? Which is the most effective?

    - *Peer design reviews*
    - *Manual checklist/scorecard techniques (rating an electronic system on a number of key testability features)*
    - *Algorithmic testability measurement (controlability & observability) using CAE tools*
    - *Other*

9. At what stage in the design process is fault simulation carried out?

10. What fault simulation techniques, if any, are employed by the company's design engineers? If none, why?

11. Are there formal rules for feeding back up-to-date user experience information back to designers?

12. Is it felt necessary to keep designers and production engineers in touch with latest advances in materials and manufacturing technology? In the case of designers, if this is not the case is it because they are not encouraged to explore new/different avenues in their work?

13. How is the company's engineering change control (ECC) policy implemented? Is implementation effective? What are the main problem areas?

14. Production engineering -- first or last?

15. How much company information exists only in the heads of employees? If the amount is significant, how is it felt this affects company resilience?

16. Design staff turnover (approx. per year)?

17. Have any new CAD/CAE systems been introduced recently? If so, what system implementation procedure was used?

- *Feasibility study*
- *Develop detailed specifications*
- *Contact vendors*
- *Visit existing CAD/CAE installations*
- *Recommend vendor/system to senior management*

18. How was the social system of the company modified in order to facilitate the new CAD/CAE system introduction?

- *Technical elements*
- *Social elements*

ELECTRONICS MANUFACTURE:

1. What philosophy is used to guide the operations of the manufacturing plant i.e. JIT, MRP, MRPII, OPT etc?

2. How is the chosen approach implemented with regard to:

   - *Runners*
   - *Repeaters (irregular runners)*
   - *Strangers*

3. Does the plant use a cell-based approach to manufacture? If not, which approach is used and why?

4. What types of process technologies and equipment are in use? Have they been developed in-house or bought in?

5. For each of the main types of production equipment in use:

   - *How long has each been in use?*
   - *What have been the main difficulties associated with their operation?*
   - *How have these difficulties been overcome?*
   - *Are there any links to CAD/CAE equipment?*

6. What is the extent of production participation in the product development process? How is such participation achieved and what input is provided? What impact does this have on manufacturing in terms of engineering change, yield, reject and scrap rates etc?

7. What are the principal manufacturing issues which need to be dealt with in regards each of the company's products?

8. What production volumes are you achieving per period?

9. How do the company's product prototypes and production models differ from one another? How is process design carried out in the company? How does this activity differ from process planning?

10. What types of manufacturing test are employed and how are they carried out? What kinds of production problems has the company experienced which can be directly attributed to errors in design? How often do these problems occur and how are they dealt with?

11. What are the critical paths/bottlenecks in production?

12. Do the products incorporate some new material (ceramics, injection-moulded thermoplastics) which have been, or are currently, the cause of production problems? Have they been overcome? If so, how?

13. What is the company quality policy and how is it carried out in practice (SPC, QC circles, TQM, continuous improvement)?

14. How is product manufacturing information stored, retrieved, represented? What kinds of information are stored? What others could usefully be stored for use by designers?

15. How much company manufacturing information exists only in the heads of employees? If large amounts, what impact could this have on company resilience?

16. Key manufacturing staff turnover (approx. per year)?

17. For each of the following, please indicate:

- *What you are currently achieving*
- *What you are aiming for*
- *What the issues are*
- *What the problems are*
- *Why they are problems*
- *What the solutions to the problems are*

18.

Manufacturing leadtime	Short	Significant
Product quality	Acceptable	High
Delivery performance	Poor	High
Manufacturing flexibility	Low	High
Manufacturing cost	Low	High
Capacity utilisation	Low	High

19. Extent of use of Artificial Intelligence/Knowledge-based Systems?

SUPPLEMENTARY QUESTIONS

Company Strategy

1. Sharp Corporation has an industrial engineer on the main board of the company, Ricoh has a graphics designer and Matsushita's head of design and advertising is a board member. Does your company have similar representation? Why? Why not?

2. Government/industry synergy in relation to investment in design automation. How does this work?

3. Kennichi Ohmae (McKinsey) says that many Japanese companies continue to respond to Korean (low-end) and German (high-end) competition using the approach that served them well in the past i.e. compete on price (even when they don't have to).

   - *Would you agree that this is what happens?*
   - *Do you think that such a knee-jerk response makes it difficult for Japanese companies to follow the German route?*
   - *How do you respond to such competition?*

4. How would you describe your strategic management style? Why have you adopted such an approach?

   - *Orders & specifications?*
   - *Objectives, strategies, policies with loose day-to-day control?*

5. We understand that Japanese companies devote a lot of resources to the early stages of product development in order to speed up later stages. Is this true in the case of your company? What would the percentages be for early vs later?

6. Do you use a "parallel processing" approach to product development whereby the majority of effort goes into an innovative and desired solution but where a safer solution is designed in parallel from the "technology shelf" to be used if the innovative idea doesn't work out?

7. With regard to integration with other functions:

   - *What level of collaboration occurs between your company and its suppliers?*
   - *Is production used as a source of product development ideas?*
   - *To what extent do product engineers receive feedback from users and after-sales service for the development and improvement of products?*

WA = harmony; AMAE = sense of depending on each other; HONNE = witholding of true feelings in order to harmonise; NOTE: WA is generated by long periods of HONNE but, for that to happen, there must be strong sense of AMAE. These cultural elements are very Japanese and difficult to bring across to the West.

8. How critical are WA, HONNE and AMAE to the success of your product development process?

9. Do you share the view of the Ricoh Corporation that user's requirements have taken over as the major dictator of product capability and that it is now necessary to input consumer lifestyle into the product? If so, how do you go about doing this?

   - *Make technology more intelligent*
   - *Make it more flexible for users from different cultural backgrounds*

- *Consider social context of products*
- *Use social scientists to work along side product designers*

10. Group technology approach?

11. What is the dominant competitive factor currently driving your business?

12. Do you make extensive use of outside suppliers to create more flexibility in product development and production? If so, how does this affect the design process?

13. What percentage of turnover is devoted to R & D (now and in the past)?

14. Would you agree that new, radical product development and incremental improvement of existing products don't coexist well in the same organisation? If so, how do you deal with this issue? For example:

    - *Do you reate separate ventures with separate resources for the creation of each new product?*

15. What structures for product development do you use? For example:

    - *Multi-functional teams.*
    - *Suppliers involved early in the product development process.*
    - *"Ideas handling" systems for stimulating ideas and innovations.*

16. What percentage of resources is typically devoted to pre-development stages in product lifecycle?

17. What level of importance is given to marketing early on in the product development cycle. If high, why? What activities do they undertake?

18. Do companies only develop a few new products per year by plan or default?

19. What proportion of development effort is non-added value and what does it consist of?

20. Where do the new product ideas come from and do these sources have a high success rate?

21. What management information is used: a) to manage with and b) to make investment decisions?

22. Who is driving the investment decisions?

23. What are the perceived major problems?

24. What are your criteria for replacement of design management tools (DMT)?

25. How do you think you manage change?

26. The corporate learning process:

    - *Does the company learn from its mistakes?*
    - *How is this corporate learning process set up?*
    - *How does it work? How much is computerised, how much left to people to carry out (e.g. through personnel movement from position to position)?*
    - *If knowledge = a developing understanding of what is being investigated:*
    - *What kinds of knowledge are being generated?*
    - *How is the knowledge used?*

- *Where does it come from?*
- *What form is the knowledge in?*
- *Why is the knowledge generated?*

27. NOTE: Organisational learning plays a crucial role in Japanese companies. Japanese managers view their organisations as learning social systems within the context of which out of date wisdom is "unlearned" and knowledge of successful projects is systematically processed and transferred into other projects. More general success patterns are disseminated throughout the company as "corporate wisdom."

28. Is the corporate knowledge base used in a positive way?

29. NOTE: In the West, recording mistakes, failure may reflect badly on the individuals involved. May cause them to withold the information.

30. Do you have the infrastructure necessary for introducing advanced design capabilities?

31. Do you agree that innovation is a "numbers game" which depends on irrational people? Japanese people are not known for being irrational.

32. "Product developers should know what they want, piece together a strategy and go to R&D for the missing elements." Is this what happens in your company?

33. If it is true that small and medium size companies are better able to innovate than larger ones, as a large corporation what do you do to encourage and stimulate innovation?

34. We understand that in order to reduce time to market, Japanese companies have devoted a lot of attention to managing new product introduction. How ius this done in your company?

35. Do you have a policy to move your product profiles towards European ones i.e. competing in the product style/image & quality innovation areas traditionally thought to be the European strengths?

36. (MYTH) Japanese not thought to be good at innovation; group emphasis stifles creativity? How do they get around this (supposed) drawback? Explore also:

    - *Group processes*
    - *Culture*
    - *Value systems*
    - *Style*

Electronics Design

37. Do you bid for projects? If so, how much of the product is actually designed at that stage? What success rate do you have (e.g. one UK company said it had a 1:20 bid hit rate)?

38. How are supplier relationships developed and maintained?

39. How do you select EDA tools?

40. How does production/marketing specification get translated into development specs?

41. Do you record failures as well as successes? If so, tell us of the most important ones. How do you distinguish between a failed and a successful design?

42. How do you manage change?

43. Do you attempt to estimate the degree of uncertainty involved in the development of a particular product? If so, what criteria do you use? Do you regard this exercise as important?

44. What aspects of corporate knowledge is encapsulated in design support tools, and what is left to people?

45. At what stage in the decision making process do you look at partitioning? At what level in the company is it decided, for example, to implement something in software instead of hardware?

46. Do your designers object to having their work criticised and corrected by fellow designers? How is such a review process carried out?

47. NOTE: Cite Phil's story of an American engineer working for a Japanese company who submitted his design for scrutiny and was told by his colleagues that, barring a few problems, it was essentially OK. When he sent the design to Japan it came back having been ripped to shreds. The American engineer was devastated. The Japanese engineers were only doing to him what they routinely do amongst themselves.

48. Do you do a lot of reverse engineering of competitor products in order to take the risk out of product development?

49. Do you use computer-based simulation? All done manually? Do your engineers feel at ease using CAD and simulation tools? Do they have time to practice using such tools?

50. What are the main sources of ideas for new products?

51. In regards non-added value activities i.e. clerical/admin tasks that most engineers have to perform, do you have ways of finding out what your engineers are doing i.e. any measures of engineers' time?

52. Do your designers prefer to start afresh every time because it allows them to re-think what they are doing and because it also allows them to have more confidence that the eventual outcome will meet requirements?

53. Organisational styles & management culture? Free flow of information between employees? Does style/culture affect toolset requirements? Can toolsets smooth out the variety of organisational styles? (Japanese formality as barrier to easy communication)

54. If you want to determine whether a project is under control, how do you do it? Iterations after release to manufacture?

55. Do you adopt the approach of keeping your employees, particularly those who are involved in developing new product concepts, under a lot of stress? If so, how do you justify that?

Appendix 2

U.K. and Mainland European Case Study Companies

Outline Details of the 18 Case Study Companies				
Org	**Sector Type**	**Turn-over £M**	**New designs per period**	**Production volumes per period**
1	PCB manufacture	600	1000 ECNs /month	8000 boards per week;1000 different boards per week
2	PCB contract work	3	4 per day	300,000 sq ft of board per year
3	Automotive electronics	1,307	6 new; 6 revisions/year	50K - 100K per product
4	Aerospace	601	2 per year	1500 per year: 750 systems, 750 boards
5	Telecoms, analog products, support tools, research	N/A	N/A	N/A
6	Programmable controllers	44	1/year new, 2/year upgrade, 3/year fault correction	750 units/week
7	Sailboat and power boat instruments	5	4/5 improvements to existing products/ year	200-3000 per year
8	Defence C^3I systems	20	20 new boards per year; 3 - 5 reworks/board	100 off for boards; 5-10 whole systems
9	Electronic/ electromechanical devices	5	10-12 per year	100-200K
10	Consumer electronics products	100	1/year new; 25-30 derived models	35 PCBs per month across 40 TV models; 11 main board chassis each; 350,000 TV sets
11	IC product design and fabrication	42	5/year new	500 total wafer starts per week. 10 million devices per year
12	High volume capacitor design and fabrication	15	2/year new	80K per week
13	Transactional electronics	200	2/3 per year product support; 2/3 strategic development; 30/40 major changes	10K-100K per year

Case Study Company Details (Contd)

Org	Sector Type	Turn-over £M	New designs per period	Production volumes per period
14	Consumer electronics	6,400	3/4 year new; 3/4 year adaptations; 50 redesigns	Company unwilling to reveal this information
15	Automotive electronics	178	15-20/year new; 2/year redesigns; 10-15 per year changes due to design faults	Low volumes on each of a wide range of products
16	Radar systems	---	80 new PCB designs/year	1-10/year
17	Defence electronics	9,805	30-40/year new; no information on reworks	1/year-240/month
18	Hybrid circuits	1.5	3/month new; 3/month redesigns	100 - 1000

Appendix 3

U.S. and Far East Case Study Companies

Outline descriptions of U.S. Companies

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.

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.

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.

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.

Outline descriptions of Japanese case study companies

Toshiba

The following employees from Toshiba's head office in Tokyo participated in the research:

- Dr. Okio Yoshida, Senior Manager, Planning, Technology Planning and Coordination Division
- Mr. Akira Kuwahara, Vice President & General Manager, Technology Planning & Coordination Division

Toshiba -- Fuchu Works

The following employees at Toshiba's Fuchu works participated in the research:

- Mr. Toshiyuki Matsushita, Specialist, Engineering Automation Systems Development Group, Engineering Administration & Information Systems Department
- Mr. Tadao Ichikawa, Senior Manager, Engineering Administration and Information Systems Department
- Mr. Tsutomu Sakamoto, Manager, Microelectronics Technology Group, Engineering Administration and Information Systems Department
- Mr. Shuji Tatebe, Specialist, Software Engineering Development Group, Engineering Administration and Information Systems Department

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**

Toshiba -- Ome Works

The following employees at Toshiba's Ome works participated in the research:

- Mr. Ginzo Yamazaki, Senior Manager, Engineering Administration & Factory Information Systems Dept.
- Mr. Shinji Nishibe, Senior Manager, ASIC Engineering Dept.
- Mr. Kouji Yoshizaki, Senior Manager, Engineering Productivity Development Centre, Technical Planning & Coordination Division (Head Office)

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**

  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

Sony Semiconductor Division -- Atsugi Technology Centre

The following Sony Semiconductors employees participated in the research:

- Mr. Hajime Yagi, Senior General Manager, ULSI R & D Group
- Mr. Tadahiko Nakamura, General Manager, CAD Dept., Semiconductor Group
- Mr. Yasuo Hayashi, Manager, R & D Strategic Planning Dept., Semiconductor Group
- Mr. Akira Kojima, Deputy General Manager, Production Technology Division, Semiconductor Group
- Mr. Tadaharu Tsuyuki, General Manager, Information Systems Div., Semiconductor Group

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.

Fujitsu Mainframe Division -- Kawasaki

The following Fujitsu employees participated in the research:

- Mr. Kazuyuki Tsunezumi, Associate General Manager, Computer Systems Group (Overseas Project)
- Mr. Kazuyuki Shimizu, General Manager, Processor Development Division, Technology Development Group (responsible for technology development, circuits & CAD)
- Mr. Masaaki Nagamine, General Manager, Production Technology Division, Information Processing Administration Group (Mr. Shibayama's boss)
- Mr. Susumu Tomioka, General Manager, Engineering Support Division, Information Processing Administration Group (CAD systems operations)
- Mr. Hirofumi Hamamura, Manager, Design Automation Development Dept., Advanced Technology Development Group
- Mr. Takeshi Shibayama, Manager, Production Engineering Dept., Production Technology Division, Information Processing Administration Group (responsible for manufacturing technology development)
- Mr. Toshiyuki Sakai, Manager, Computer Aided Engineering Dept., Engineering Support Div., Information Processing Administration Group (reports to Mr. Tomioka)

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.

Outline descriptions of Korean case study companies

Samsung

The following Samsung employees participated in the research:

- Mr. Jeong-Ok Park, Senior Executive Managing Director & Chief Technology Officer, Office of the Executive Staff, The Samsung Group
- Mr. Moon S. Song, Executive Director, Information & Systems Business, R & D Centre, Suwon (has since been promoted to office of Executive Staff)
- Mr. Jin Koo Kim, Executive Director, General Manager, ASIC Bochun Laboratory, Semiconductor Business
- Mr. Il-Hwan Kim, Senior Manager, R & D Management Dept., R & D Centre, Consumer Electronics Business
- Mr. Sea-Lim Jung, Manager, CIM Business Dept., Electronics Design Automation Team, International Division of Samsung Group
- Mr. Jun-Ho Jang, Manager of Information Systems, Office of the Executive Staff, the Samsung Group

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 it electronics interests.

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.

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.

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 4

Publications

The following pages show the author's publications relevant to this work.

Presented at the First International Conference on Concurrent Engineering and Design Automation (CEEDA '91), Bournemouth, U.K., March 26th - 28th 1991, pp 60 - 67

SPECIFICATION OF A DESIGNERS' TOOLBOX FOR ELECTRONICS DESIGN

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INTRODUCTION

The needs of survival in the electronics marketplace have ensured that old mass production strategies derived from notions of economies of scale are being discarded. The new imperatives of flexibility, reduced design cycle time, reduced time to market for new products and reduced order cycle time to customers for existing products have imposed significantly heavier design loads on engineers. They have also resulted in increased design task complexity as companies have been forced to address manufacturing, test, service and even aesthetic requirements early in the product design process.

Unfortunately, these pressures, coupled with the perverse way in which many organisations currently structure their design–to–manufacture operations [1, 2], have resulted in the adoption of product development practices which are almost guaranteed to produce unmanufacturable designs. The Electronics Designers' Toolbox (EDT) Project will address these critical issues by functionally specifying the next generation computer–based toolset capable of fully supporting the process of electronics product design in an integrated manufacturing environment.

Thus far, we have established a base line for our work by quantifying electronics design–to–manufacture practice in a number of leading UK and Continental European companies, as well as in a variety of smaller UK electronics firms. In general, our eighteen case study visits have 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 document control.

In addition, most companies in the study focus largely on producing products which perform a function at an acceptable standard of cost. They seldom think in terms of design for low inventories, for example, for minimum number of parts/processes or for high yield. Few of the case study companies take a strategic view of product design. This impression was reinforced by the fact that, in some cases, designers appeared indifferent to component costs while, in others, they were ill–informed regarding the wider impact of their work on corporate fortunes.

The visits also confirmed the fact that existing, computer-based support tools only provide "point solutions" to specific bottlenecks in the product design process. Nevertheless, it is clear that most features of the design-to-manufacture path are well covered by CAD vendors and that, where gaps do exist, vendors are devoting considerable resources to filling them.

Certain critical areas of the design-to-manufacture cycle are not well covered at the moment, however, and it is in these areas, in addition to the development of a strategic framework for electronics design, that we feel we can make a real contribution. Two of those areas involve making substantial enhancements to the design process at the requirements specification stage and the provision of extensive, high quality manufacturing information support for the designer.

This paper presents a preliminary report on the findings of the eighteen case study visits and provides representative examples both of product development successes and of problems encountered by a number of the companies visited. It also examines how these companies currently manage and control their product development processes together with the extent and nature of computer support tool usage and manufacturing information feedback to designers.

The paper follows a traditional "linear-analytic" structure in which we:

- **examine the problems associated with current generation electronics design toolsets**
- **state our research questions and describe our methodology**
- **outline and discuss our case study findings**
- **report on future research directions for the project**

PROBLEMS WITH CURRENT ELECTRONICS DESIGN TOOLSETS

John [3] 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, John cites authors [4, 5] who criticise current CAD systems for their poor support of planning, synthesis, evaluation, conceptual thinking, decision-making and aesthetic judgement.

Our own research in this area [6] 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. We have discovered that, while computer-support tools are becoming increasingly powerful, their implementation at customer sites is often poor.

In general, CAD/CAE systems didn't have top-management support in the companies we visited, nor did they have the same high profile as Computer-aided Production Management (CAPM) systems, for example. Analog design remains an area of critical concern given the growing awareness of the need for mixed-mode chips, but the absence of appropriate design tools continues to make this a difficult task.

Work designed to alleviate design tool support shortcomings has been proposed by the ESPRIT Microelectronics Work Programme [7]. 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 interesting work has been carried out by SERC's Rutherford Appleton Laboratory ECAD Project [8], 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 PCB design. Mentor Graphics is market leader in IC design with such tools as Quicksim, Quickgrade and Quickfault while Racal 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 [9].

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.

Long term Issues

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, the provision of high quality support for the design management process together with accompanying "best practice" design methodologies.

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 and 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.

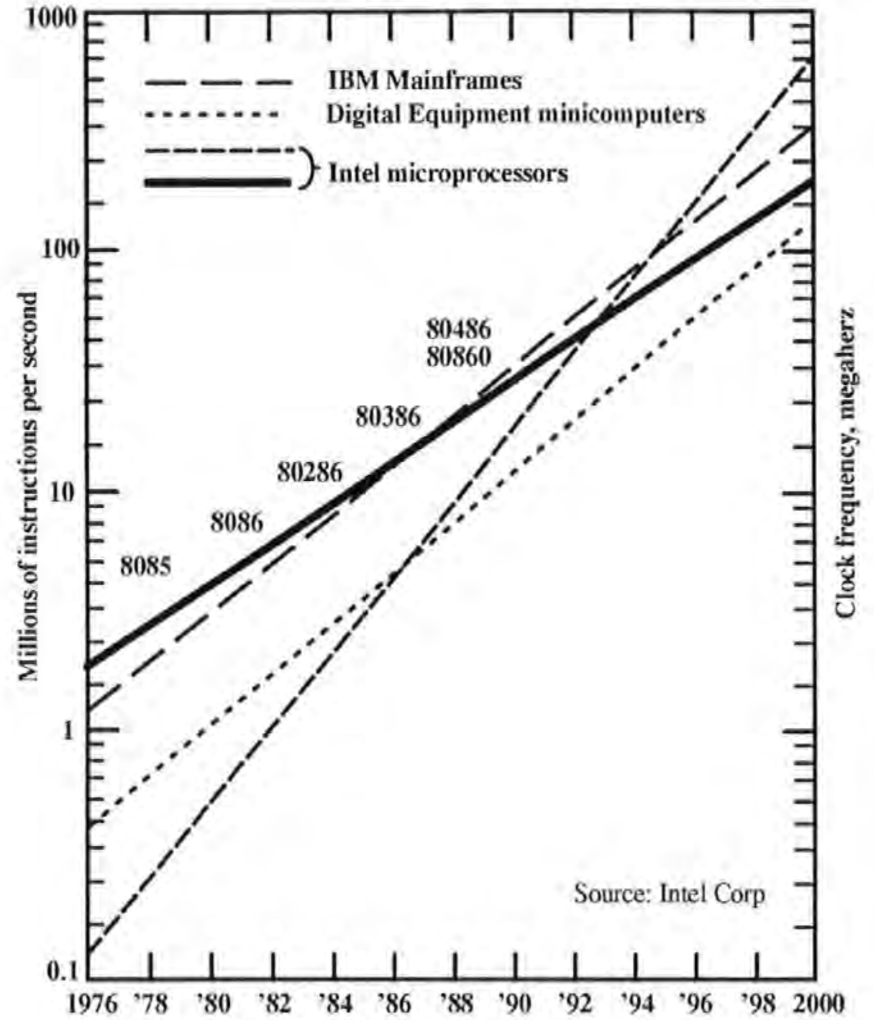

FIG 1: Predicted levels of computing power

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. 1 above. Although specific solutions exist at present, these are not cost effective for all companies.

Speed versus accuracy and circuit complexity: These parameters bear a reciprocal relationship to one another, whether in functional or behavioural simulation, layout or test simulation. The speed of simulation is proportional to the detail required to be simulated. Behavioural level simulators can simulate system function at a rate, per node in the circuit network, similar to device level simulators used for modelling analog functions.

The complexity of the circuit modelled, in terms of number of circuit nodes is also of concern. For example, the simulation of a 2,000 gate logic circuit through 0.1 ms of simulation time takes about 10 minutes computer time [10]. With gate counts of 100,000 being used in current circuit designs, simulation tools must offer improvements in speed or design times will become prohibitively long.

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 [11].

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" [15], which could have unfortunate business implications for the company.

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."

THE ELECTRONICS DESIGNERS' TOOLBOX PROJECT

The Electronics Designers' Toolbox Project is concerned with developments in engineering on a 5 to 10 year horizon. Having established the future technological and organisational context within which the toolset will be positioned, we intend to focus on providing electronics designers, working in a team-based environment, with comprehensive support for all aspects of the electronics product development cycle. Our work will also identify all the required functions of the toolset as well as its inputs and outputs, human computer interfaces, hardware and software platforms and performance and reliability characteristics.

On the individual designer level, such an approach would comprise elements of human computer interface, applications software, engineering data management, databases and communications. It will also incorporate design and manufacturing data, information and knowledge together with the often considerable engineering "wisdom" derived from years of product development experience.

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. Our specification will, therefore, look beyond the individual designer and embrace also the department, company and external business environment in which the design activity takes place.

RESEARCH QUESTIONS

We have focused on gaining 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 which was continuously refined as the case study visits progressed. Interviewees have been 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.

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 customer and supplier development. In view of the fact that our work is concerned with future generation electronics design toolsets, we also attempted to uncover evidence of awareness of emerging technologies (production and non-production), use of new materials other than silicon and appreciation of environmental concerns in light of their possible impact on the design and manufacturing processes.

Information was also 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**
- **Risk assessment at conceptual design stage**
- **Simulation techniques/software used**
- **Engineering change control policies**
- **Design/production interfaces**
- **Component policies**
- **Standards**
- **Impact of different manufacturing approaches (JIT,OPT,MRPII) on the design function**

As far as possible the team has sought to highlight problem areas though we were also interested in uncovering examples of engineering design "best practice."

RESEARCH METHODOLOGY

All the research information was collected through a lengthy semi-structured interview, usually lasting between 3 and 6 hours, carried out at each of the eighteen organisations listed in Table 1.

The companies we 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 research team who, together, questioned up to four design and production managers at a time. In only two cases have Managing Directors been available for questioning.

TABLE 1 Outline details of the eighteen case study companies

Org	Sector Type	Turnover £M	New designs per period	Production volumes per period
1	PCB manufacture	600	1000 ECNs /month	8000 boards per week;1000 different boards per week
2	PCB contract work	3	4 per day	300,000 sq ft of board per year
3	Automotive electronics	1,307	6 new; 6 revisions/year	50K - 100K per product
4	Aerospace	601	2 per year	1500 per year: 750 systems, 750 boards
5	Telecoms, analog products, support tools, research	N/A	N/A	N/A
6	Programmable controllers	44	1/year new, 2/year upgrade, 3/year fault correction	750 units/week
7	Sailboat and power boat instruments	5	4/5 improvements to existing products/ year	200-3000 per year
8	Defence C^3I systems	20	20 new boards per year; 3 - 5 reworks/board	100 off for boards; 5-10 whole systems

TABLE 1 (Contd)

Org	Sector Type	Turn-over £M	New designs per period	Production volumes per period
9	Electronic/electromechanical devices	5	10–12 per year	100–200K
10	Consumer electronics products	100	1/year new; 25–30 derived models	35 PCBs per month across 40 TV models; 11 main board chassis each; 350,000 TV sets
11	IC product design and fabrication	42	5/year new	500 total wafer starts per week. 10 million devices per year
12	High volume capacitor design and fabrication	15	2/year new	80K per week
13	Transactional electronics	200	2/3 per year product support; 2/3 strategic development; 30/40 major changes	10K–100K per year
14	Consumer electronics	6,400	3/4 year new; 3/4 year adaptations; 50 redesigns	Company unwilling to reveal this information
15	Automotive electronics	178	15–20/year new; 2/year redesigns; 10–15 per year changes due to design faults	Low volumes on each of a wide range of products
16	Radar systems	---	80 new PCB designs/year	1–10/year

TABLE 1 (Contd)				
Org	**Sector Type**	**Turn-over £M**	**New designs per period**	**Production volumes per period**
17	Defence electronics	9,805	30–40/year new; no information on reworks	1/year–240/month
18	Hybrid circuits	1.5	3/month new; 3/month redesigns	100 - 1000

PRELIMINARY CASE STUDY FINDINGS

Our preliminary evaluation of the design–to–manufacture performance of the case study companies has been carried out using certain United States military [12] and commercial [13, 14] best practices as yardsticks. The performance categories selected for inclusion in this paper 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 authors feel that the lessons which can be learned are sufficiently instructive to justify this approach.

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, did we find that companies were taking 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.

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 [12].

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 authors and, in some instances, we 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 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.

Impact of stress: Periods of stress have an important impact on the way people and organisations process information. Significantly, it is reported by Sherwin [15] that during early phases of stress situations, people's information processing capabilities actually increase as they tune into a situation. It may be, therefore, that controlled levels of tension at work could help to encourage a stimulating and productive design engineering environment.

After a certain stress threshold has been crossed, however, and the quantity and variety of message inputs continues to increase, Sherwin states that the reliability of information processing falls below what it was before the emergence of the stress situation. During times of acute stress, in fact, he notes that the internal transmission of information may collapse altogether.

The adoption of a design–to–product policy grounded in the Concurrent Engineering (CE) approach [16, 17, 18, 19] would go a long way to alleviating the procedural problems [20] which are often caused when designers face such acute time pressures. These include:

- Acceptance of the fact that there is a dearth of important information
- Reluctance to seek the services of specialists
- Reluctance to look beyond his/her first idea
- Over design due to failure to spend time on necessary investigations and calculations
- "Bodging" of last minute changes instead of seeking more structured solutions

Yet only one company out of the eighteen visited could justifiably claim to be successfully putting Concurrent Engineering into practice. In the worst case encountered, the need for CE was simply not accepted by the company's design engineers.

<u>Information Feedback:</u> Best practice dictates that a design policy should not be "set in concrete." It should, in fact, be continuously reviewed an 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. We believe that the establishment of this kind of learning mechanism is vital to product development success though we acknowledge the costs, both financial and human, 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 our 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 [21] 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.

<u>Parts and materials selection</u>

To ensure the uniform application of parts and materials by all design engineers, an Approved Parts List (APL) must be issued at the start of Full-Scale Development (FSD). In addition to providing design engineers with a baseline from which to select parts and materials, the APL 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 [12].

The companies visited demonstrated far more control in the parts and materials selection areas, though here too the authors 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.

Concurrent engineering

Concurrent Engineering (CE) links and extends the product design functions beyond individual departments, beyond the enterprise as a whole, out into the customer and supplier chain [19]. 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 [13].

The application of the CE approach to product development is claimed [13] 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 our view that CE is best applied to the development of innovative (10% - 50% different from previous generation) or strategic (50% – 100% different from previous generation) 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.

We consider the use of CE far less appropriate to the development of variant products (up to 10% different from previous generation). 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.

However, CE principles in dilute form 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.

Table 1 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 we 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.

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, we 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 bid hit 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 CE approach provides marketing engineers with opportunities to suggest product solutions which are impossible to manufacture. In fact, they 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.

These "horror stories" indicate that we have a long way to go in the U.K. electronics industry before we are able to out-perform our Far Eastern competitors. The case study visits have also served to reinforce our view that top management commitment is the *sine qua non* of successful CE implementation, principally because the adoption of such an approach may require major organisational change.

The strategic implications of CE: Concurrent Engineering has important strategic implications and should only be undertaken in the context of the company's long-term strategic goals. In [13] the authors state that CE relies on a number of tools and techniques, including Early Manufacturing Involvement, Quality Function Deployment (QFD) [22], Taguchi Methods [23, 24], Design for Manufacture and Assembly (DFMA) and Statistical Process Control (SPC). However, it is our view that, while effective use of these techniques may represent critical success factors for CE 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 SPC, Taguchi Methods and DFMA. Only one company said it was using QFD (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 (PM) methods. The company, which makes no use of the PM 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 PM were never discussed by the interviewees.

Configuration management

Configuration Management (CM) 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 [14].

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

Only a limited amount of data was collected regarding Configuration Management. Far more was elicited about the Engineering Change Control (ECC) aspects of product development principally because we were more familiar with change control than with the extremely complex aspects of CM. The authors are nevertheless aware of the need to collect more data in this area, particularly with regard to the origins of the change notes and how long it takes the various companies to process their ECNs.

In particular, the case study interviews attempted to identify daily, weekly or monthly levels of ECNs being generated by the various companies as a means of determining the quality of their design-to-manufacture processes. High numbers of change notes could signify that a company is competing in a highly competitive, high tech environment where change is viewed as essential to the overall success of the enterprise. Conversely, such a situation could indicate that changes are being made for their own sake without being driven by the needs of the business. They may also be controlled in an informal manner, with disasterous consequences for parts registration, Bill of Materials (BOM) and, ultimately, company performance in the marketplace.

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 [25] since product design influences every part of the organisation, including manufacturing, marketing, purchasing and technical literature.

An effective 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:

- 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, slow to respond and failed to involve suppliers.

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 pitch.

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 [12].

There is no doubt that all the companies visited placed the issue of Quality Assurance (QA) 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. 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 QA metric information back to design. The existence of closure mechanisms at local level 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 QA problems are rapidly brought to the attention of, and understood by, designers, managers and engineers. Only one company visited had such a system, however, though there was no time during the interview to investigate its capabilities. 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 QA. The result was the recipients just filed the reports away without reading them.

FUTURE RESEARCH DIRECTIONS

During the coming year, our research will take us on a series of visits to leading-edge electronics companies in the United States and the Far East. The data gathered during these visits will enable us to compare and contrast approaches to product development adopted in Europe, the US and the Far East. A report will be produced for circulation to interested parties.

We also plan to investigate CAD linkages to production and test as well as to other relevant product development stages. Linkages to manufacturing planning and control, scheduling and process planning will also be explored. An outline functional specification of the next generation designers' toolset will then be produced.

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WORLD CLASS PERFORMANCE BY DESIGN

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Abstract

This paper reports on work carried out at the Centre for Research in World Class Manufacturing at Polytechnic South West. The authors have been involved in a 3 year, UK Government-funded research project to functionally specifying a next generation "Electronics Designers' Toolbox." The paper presents key findings of a series of in-depth case study interviews with senior design and production staff at eighteen UK and mainland European electronics manufacturing firms, as well as at eight leading U.S., Japanese and Korean electronics companies and research institutes. In particular, it discusses the concepts of "aggressive" and "consequential" design and suggests practical ways in which Western electronics firms, by learning from international "best practice" in this field, can effect major improvements in their design-to-product capabilities.

1. INTRODUCTION

1.1. Time to market challenges

The transition from the pre-1974 seller's market to today's buyer's market[1] has had a significant impact upon the electronics design process. The seller's market featured large quantities of the same product type, long product life cycles and low diversity. In contrast, the buyer's market is characterised by smaller quantities, much shorter product life cycles and greater diversity, with market success determined by a firm's ability to meet or exceed customer requirements.

These changes have forced dramatic reductions in product development times as companies strive to maintain competitiveness by being "first to market". Studies have shown, in fact, that a product with a market lifetime of two years will experience as much as a 12% revenue loss if introduction is delayed by as little as two months and as much as 38% if it is delayed six months[2]. Indeed, one communications equipment manufacturer visited by the authors reported failure costs of getting to market a year late with one of its products to have been "several million" pounds. A six month delay caused by the need to redesign the user interface on another product also cost that firm millions of pounds. Two recent surveys of UK manufacturing attitudes[3,4] reveal, however, that an alarming number of UK manufacturing executives dismiss time to market as a factor in determining market share.

1.2. Design is strategic

These high levels of environmental and technological uncertainty are forcing firms to adopt management approaches which regard design as a strategic, if not ***the*** strategic, priority in their businesses. The symbiotic relationship between strategy and technology -- and thus between strategy and the engineering design process[5] -- has been strengthened by the fact that design choices directly affect such aspects of product development as materials, fabrication methods, assembly methods, inspection and test techniques. In logistics terms, too, product design can provide the electronics manufacturer with the opportunity to manufacture different items in different locations, to employ flexible manufacturing techniques, to make common use of parts and materials, to adapt standard products to special orders or to have final assembly or configuration close to the customer[6].

Our research has shown that the adoption of this view requires the abandonment of short-term, project-based approaches to product design in favour of creating ongoing design capabilities which are robust and which support wider business objectives. Unfortunately, our research has also demonstrated that Western electronics companies have been remarkably slow to recognise the strategic importance of both engineering and industrial design. All too often, design is viewed by senior management as merely of tactical significance and, in investment terms, CAD/CAE systems invariably have a much lower profile than Computer Aided Production Management (CAPM) systems[7], for example.

As the following sections of this paper demonstrate, however, Japanese companies regard design as one of a portfolio of strategic activities[8] and significant resources are devoted both to the development of in-house design automation tools and to the support of "up front" engineering activities.

2. CASE STUDY RESULTS

2.1. Overview

The results of our international study of electronics design practice have been reported in greater detail elsewhere[9,10,11]. In outline the UK and continental European case studies revealed that all the companies participating in the research were successful in getting their respective products to the marketplace in the face of severe competition. However, those successes were overshadowed by clear evidence that they were, in most cases, obtained at considerable cost in product development iterations caused by such factors as lack of rigour in product specification, "over-the-wall" approaches to design and inadequate document control. In particular, only a small minority of companies regarded product design as an activity which had strategic implications for their businesses.

Significantly, neither the U.S. nor the Korean visits undertaken by the authors uncovered any design practices and software tool usage more advanced than those found in the U.K. and Europe. On the contrary, the visits revealed that electronics firms in the U.S. and Korea face the same kinds of problems in effectively managing the product development process as the authors discovered in the U.K. and European companies it visited.

The Japanese company visits to Toshiba, Fujitsu and Sony, on the other hand, demonstrated product design-to-manufacture capabilities which exceeded any the authors had seen elsewhere. From a production engineering point of view, senior managers at one Toshiba plant indicated that their indirect/direct employee ratios currently stood at approximately 80:20. Around 75% of the plant's indirect employees, the majority of whom are engaged in engineering activities away from the shop floor, are qualified at graduate or Masters degree levels.

All the companies provided some insight into future directions for design automation systems, particularly with regard to the manner in which they have developed their own electronics design toolsets, but also through their efforts at integrating commercially available design software into their design processes. They have each had vigorous in-house CAD/CAM/CAE/CIM development programmes in place for a number of years, a trend which is being driven both by high (currently around $30,000 per seat) commercial licensing costs of software for engineering design workstations, and by demographic pressures. Japan's declining birth rate is causing shortages of engineering staff and is forcing electronics companies to automate as much of the design process as possible.

The design automation systems used in all the Japanese companies had achieved a degree of integration with other computer-aided aspects of their operations not witnessed elsewhere in the world. In particular, their toolsets are strongly integrated backwards into manufacture and, additionally, considerable efforts have been made to effect parallel integration of the various design functions with costing, quality, industrial design and management systems. Where gaps are uncovered between the toolsets themselves, Japanese design engineers -- many of whom also have software engineering skills -- are encouraged to write their own "bridging" software.

Of particular relevance for the UK electronics industry, however, is the manner in which the Japanese firms use design to achieve market success. They initially design products in what we have termed an "aggressive" manner in order to create market share or to offer a level of functionality not found in other products. Having achieved these goals, their design capabilities are then deployed "consequentially" to ensure ease of manufacture and high product quality as part of a low cost business strategy. The concepts of aggressive and consequential design will be discussed in the following section of the paper.

2.2. Aggressive and consequential design

As we indicated earlier, success in the electronics market is critically dependent upon being first to market with products which meet or even exceed customer requirements. Our case study work in Japan indicates that achieving this goal requires the establishment of a strategy for creating new markets and extending market share using a combination of aggressive and consequential approaches to product design.

In order to implement such a strategy, electronics engineering management must acknowledge the extreme difficulty of successfully managing a portfolio of product development projects using a "single track" approach. Clearly, 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 been managed in a manner which typically fails to take into account the different levels of engineering risk involved in their respective development.

Our visit to Toshiba, in particular, demonstrated that coping with high risk levels in electronics engineering projects can best be achieved where companies adopt a layered product development approach. In other words, designs should be categorised 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 1 below demonstrates how this approach views designs as *Repeat Orders*, *Variant Designs*, *Innovative Designs* and *Strategic Designs*[12,13].

Our Four Path model of electronics design treats a new product as a *Repeat Order* if there is no (or near zero) new knowledge required to complete it either in design or in manufacturing. Repeat Order designs typically involve no extra design or production effort since the firm is simply building more of the previously designed product. This category of design may involve the company in cost reduction exercises to reduce parts, for example, or in manufacturing process optimisation where those processes impact the design of the product.

A design may be classed as a *Variant*, on the other hand, where between one and twenty percent new knowledge is required either in design or production.Variant designs are the most common category of design and may be achieved through, for example, the extension of an existing product through incremental innovation, the refinement of existing technology usage or through the application of modified manufacturing technology.

An *Innovative Design* requires between twenty and fifty percent new design or production engineering knowledge. Radical new designs may be created by combining features from existing products, by the use of new technology in existing solutions or through the application of new manufacturing technology. Finally, we define *Strategic Designs* as those which require in excess of fifty percent new design and production engineering knowledge. Their development typically involves the development of entirely new basic operating principles.

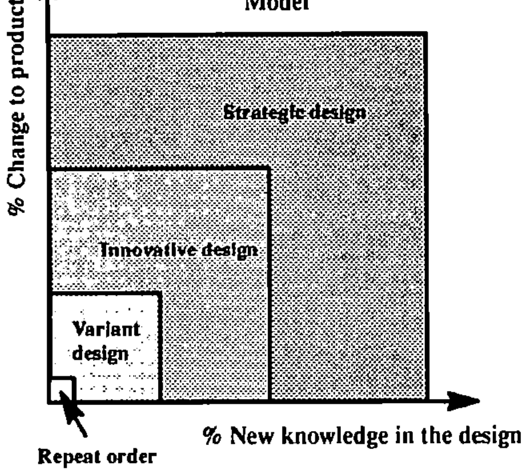

Figure 1: The Four Path Product Design Model

It is important to point out, however, that each of the design paths described above differs from the others in one major way only: the level of risk involved. Strategic and Innovative designs will involve a company in finding solutions to engineering problems it has never previously experienced. Those solutions may well require the adoption of new design techniques, such as Concurrent Engineering or Design for Manufacture and Test, or they may involve the use of unfamiliar materials and manufacturing processes.

Furthermore, different elements of a *single* product may require firms to pursue a variety of design paths. For example, a systems design or a software configured product may contain pre-existing subsections to which new extensions are added. In such circumstances, the existing parts of the product would be classed as "Repeat Order" while the extensions would be viewed as "Variant" or "Innovative."

Adoption of a Four Path strategy would allow UK electronics companies to structure themselves to engage in both aggressive and consequential design. Consequential design focuses on cost reduction and design to product efficiency. In order to excel at this kind of design, companies must be capable of exerting detailed control over their design and manufacturing capabilities whilst, at the same time, making incremental refinements to their products. Aggressive design, on the other hand, demands an ability to respond rapidly to external competitive demands. This may involve the engineering of completely new designs or the use of new technologies in either design or manufacturing. The adoption of a joint aggressive/consequential design strategy would push the company towards a state where it routinely develops creative and innovative products, *in addition to* its "bread and butter" Repeat Orders and Variants.

The manner in which Sony undertook the development of its successful 8mm family of hand-held VCRs, culminating in its latest TR55 product, epitomises this approach and, in the authors' view, may be regarded as a model which should be emulated by UK electronics firms. Indeed, during their visit to Sony, the authors discovered a culture in which "designers have a general tendency to be aggressive." Furthermore, we learned that, working within this kind of design milieu, groups of designers feel "unable to stand still" and are constantly urged to take more risk. On an individual level, we were informed that designers are "aggressive" in their desire to improve their own personalities, their own positions and their own knowledge.

To a greater or lesser extent, all the Japanese companies we visited demonstrated a similar culture and, as part of its "aggressive" approach to product design, each company has created an ongoing design capability which is resilient to change and which supports wider business objectives. The importance of such design infrastructures[14] will be discussed briefly below.

2.3. Design infrastructures

The fact that Toshiba, Fujitsu and Sony each face intense domestic and international competitive pressure means they must maintain a high rate of new product introduction. It was not surprising to discover, therefore, that all three companies undertake considerably more product design than any of the other firms who participated in our research. Less obviously, however,we also found that their success relied on the fact that 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, enable those companies 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.

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 methodologies or guidelines which firms adopt in order to ensure the various design tools are used correctly.
- The management methods used to ensure designs conform to requirements.
- The procedures necessary for identifying, capturing and reusing 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.

In infrastructural terms, it would appear to be a particularly sensible proposition that, just as in Japan[15], organisational learning should play a vital role in the product development strategies of U.K. and European electronics companies. However, our 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 our 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.

While we acknowledge 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.

3. CONCLUSIONS

The comparison of international electronics product design practice undertaken by the authors has revealed a number of key lessons for UK and European electronics companies which can be summarised as follows:

- Design is a strategic activity and must be resourced accordingly. UK electronics companies must support long-term investment in, for example, design automation tools, staff training and the development of company-wide information exchange strategies and capabilities.
- UK electronics companies must adopt approaches to product design which have both "aggressive" and "consequential" dimensions. In practical terms, this implies that firms must have an ongoing product development activity which comprises an appropriate mix of design types. In the absence of such a balanced design portfolio, firms will experience difficulty in pursuing the kind of design strategy mentioned above.

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ELECTRONICS PRODUCT DESIGN BEST PRACTICE -- AN INTERNATIONAL PERSPECTIVE

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INTRODUCTION

The Electronics Designers' Toolbox (EDT) Project is a 3 year UK Government-funded research project, through the ACME Directorate of the Science and Engineering Research Council, the objective of which is to develop a functional specification of a next-generation electronics designers' toolbox. The research has modelled the electronics product design process in a manner which considerably enhances earlier attempts[1,2] at understanding the process of product design. In particular, it extends BS7000: Guide to Managing Product Design by specifying, in greater detail than the more generic British Standard is able to, the activities and tasks necessary for effective design management and actual design of an *electronics* product.

In addition, the understanding of computer-support requirements for advanced electronics product design, gained through development of the design process model, has enabled the authors to begin the development of a functional specification for a next-generation "Electronics Designers' Toolbox" for electronics product design. Although it is not our intention to describe this aspect of our research in detail in this paper, it is sufficient to mention that the functional specification will enable electronics design automation (EDA) vendors to specify the precise functionality of advanced design toolsets. EDA tool users will be able to use an appropriately edited process model to identify the nature and number of design tasks currently being undertaken, as well as to pinpoint their future design task requirements. Once the design tasks have been identified, the design process model will provide toolset users with the means of determining requirements for both EDA tool performance and integration as well as for appropriate product design infrastructures.

In order to establish a base line for this work, the authors have 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 interviews with senior design and production staff at eighteen UK and continental European electronics manufacturing firms. Similar case study visits were undertaken by the authors to eight leading U.S., Japanese and Korean electronics companies and research institutes.

Study Tour Rationale

The project team's earlier research visits[3] had confirmed the view that there were no UK electronics manufacturers able to demonstrate world leadership in both product design and manufacture. Companies were discovered, however, which exhibited *aspects* of "World Class" capability in this field. Hence it was feared that, unless the research team was able to visit acknowledged leaders in the electronics field, we would be forced to work to an inadequate model of electronics manufacture and that, as a consequence, the functional specification for a next generation electronics designers' toolbox we produced would ultimately be of little value to the UK electronics industry.

In order to understand the functional requirements of next generation electronics design automation (EDA) tools, the authors used the study tour to collect data on current design practice, design methodologies and EDA tools used by acknowledged electronics sector market leaders in the United States, Japan and Korea. The companies and research organisations visited are described in outline below.

The remainder of this paper will discuss the research methodology used to carry out the research and will present details of a number of the most significant international case study findings, highlighting differences in both the technological and managerial approaches to electronics product design adopted by the companies visited. The paper will highlight examples of new knowledge discovered through the research visits and will conclude by presenting a number of practical ways in which Western electronics firms, by learning from international "best practice," can effect major improvements in their design-to-product capabilities.

OUTLINE DESCRIPTIONS OF CASE STUDY COMPANIES

The United States

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 enjoying 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 products compete on two main dimensions: time-to-market and 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.

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 (a $1 million U.S. DOD contract), a shared memory 64-256 node machine and a high speed routing chip using 50-100Mhz channels.

It was discovered that the MIT group was not using any advanced tools or techniques for either hardware or software design.

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.

USAF -- Sacramento. The USAF at Sacramento designs radar, air traffic control and weather forecasting equipment, UHF radio and electronic warfare systems. They also maintain existing equipment and reverse engineer obsolete equipment. This USAF site uses traditional manual methods for design and engineering staff have only recently taken delivery of their first integrated CAD system.

Japan

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 four areas: information processing and control systems, energy systems, industrial equipment and printed wiring boards and hybrid functional circuits.

Toshiba -- Ome Works. Toshiba's Ome Works employs a total of 3,700 staff, of which 1,400 are engineers. 700 engineers 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), bringing the total of engineers employed to 2,000.

The main products produced by Toshiba's Ome Works can be grouped into two areas: information processing and control systems and software.

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 and is derived from sales of such products asASICs 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 semiconductors each year, of which 20% are totally new.

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 of 0.5 micron integrated circuit technology.

Korea

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 Hewlett Packard), as well as aerospace and defence products. It is also a major provider of insurance and leisure facilities, both within Korea and elsewhere in the world.

Samsung supports four electronics institutes and a CAE Centre. Nevertheless, while the company invests some 8% of turnover in electronics research it is instructive to note that Samsung derives only 40% of its revenue from manufacturing, of which only 25% comes from its electronics interests.

The research team visited Samsung's colour TV and VTR Divisions at Suwon City, as well as the company's ASIC Research Centre in Seoul.

RESEARCH METHODOLOGY

All the research data was collected through a lengthy semi-structured interview, on many occasions lasting for up to two days, at each of the design sites visited. The interviews were usually conducted by two members of the research team who questioned groups of design and production managers and staff. The authors were able to interview a considerable number of very senior design, R&D and executive staff managers, particularly in Japan and Korea. 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 visits around production facilities.

In order to gain an in-depth understanding of how each currently develops its electronics products, a question set was developed which was continuously refined as the case study visits progressed. Interviewees were all questioned on organisation strategy, the position of design within that strategy and the organisation's overall approach to product development. Such insight could only be gained by talking to Board-level personnel, including the Managing Directors, of the various companies. Particular emphasis was also placed on establishing the methods used to control the product design process.

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 customer and supplier development. During the discussions, some 200 questions were posed to the interviewees. The answers to these questions, which were grouped under the general headings **Corporate Strategy, Electronics Design** and **Electronics Manufacture**, provided a significant input to the development of the authors' design process model as well as their functional specification of a next generation designers' toolbox for electronics design.

KEY ISSUES IN ELECTRONICS DESIGN

Despite the obvious constraints involved in conducting the kind of semi-structured interviews described above, the researchers were able to gather a considerable amount of highly relevant data, particularly in the United States and Japan. The UK/European case study data have since been analysed in light of the results of the US/Far East visits, and a number of key issues emerged which will be discussed under the following headings:

- *Design Process Management*
- *Design-for-manufacture*
- *Concurrent Engineering*

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 authors' 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 authors' 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 and 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 the development schedule. Quality aspects are defined separately.

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 engineers to manage their own work and to achieve the goals set out in the company's business plan. To keep on target, each operational unit has regular discussions on a daily and weekly basis. The entire product development group meets monthly to review progress.

During the design of large mainframe computer systems, for example, Fujitsu's project managers define system performance requirements down to LSI level. Once partitioning of tasks has been undertaken by experienced engineers, who specify precise targets for each task, engineers are then free to implement the design in any manner they choose. Support for this part of the design process may be sought through consultation with colleagues as well as through open access interrogation of Fujitsu's engineering database. Information concerning LSI use/implementation methods is freely circulated among engineers, both verbally and by memo, and tight communication links are maintained between CAD development engineers, technology development engineers and systems design engineers. Formal information exchange takes place between hardware and software development engineers, often through small group meetings, especially when new system functions and architectures are being defined.

As part of the overall product planning to production process, quality, product life cycle and design-for-manufacture knowledge are communicated back from production. Subcontractors, who contribute significantly to Fujitsu's product development success, are taught how to use new technology, for example, and how to reduce costs.

Low staff turnover. While this design management approach superficially may 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. 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 (OJT) systems which rely heavily on the availability of experienced engineering staff to teach preferred engineering techniques to novice engineers, and to pass on design process knowledge. At Fujitsu Mainframe Division, for example, it is estimated to take one year of OJT to turn a graduate recruit into a proficient designer, despite the fact that Japanese engineering undergraduates are not taught how to use CAD/CAE systems at university. However, despite the fact that the company's design review process is based upon previous development experience, with the list of items being reviewed expanded each time they go through the process, it is worth noting that Fujitsu Mainframe Division has not yet succeeded in incorporating their own design process knowledge into its engineering design tools.

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.

In marked contrast to Japanese practice in this area, our 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.

Indeed, a comparison of Japanese OJT and design apprenticeship techniques with UK, European and US practice in this field highlights the fact that the Japanese generally adopt a longer-term view even of personnel recruitment than do their Western competitors. It has been reported elsewhere[4] that Japanese companies have twice as many staff engaged in human resource management as their Western counterparts. They are tasked with training, recruitment of new employees in schools and universities and with facilitating change within the companies themselves.

Design-for-manufacture (DFM)

DFM at Hewlett Packard. While the case studies indicated that many UK and European firms are good at parts and materials selection, they tend to be poor at understanding effect of early parts and materials selection upon final manufacturing costs and constraints. In contrast, the authors 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 correctly resides within the design group.

The tool incorporates knowledge derived from PCB yield curve 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. 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.

Concurrent engineering (CE)

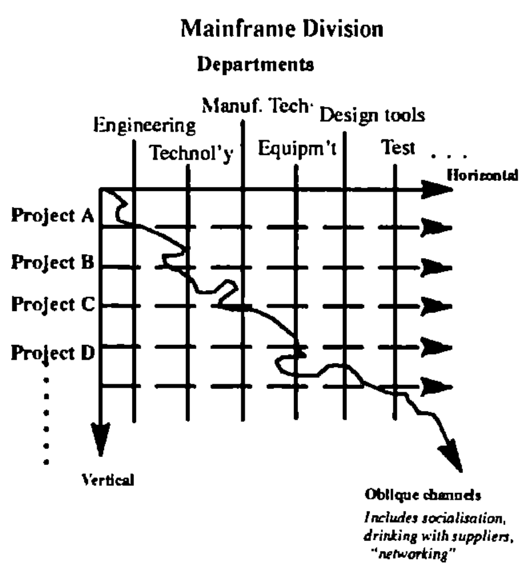
The UK and European companies visited during the research are engaged in the development of only a very small number of entirely new products each year. Since most of their design activities are concerned with making incremental improvements to existing product lines it is perhaps not surprising that we 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[5], 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.

Design for Test (DFT), Design for Manufacture (DFM), Design for Assembly (DFA) are all techniques used, and applied, in various sectors of electronics production engineering in both the UK and the United States. However, few design engineers interviewed in these countries appeared interested in the issues which lie behind such concepts, and even fewer realised that it should be their concern. Further, design appeared to be compartmentalised in many UK, US and Korean companies, with industrial design, product function design and product assembly and test design being done by different groups of people in different parts of a company, with little routine communication between them. In Japan, on the other hand, the case study companies routinely marshal whatever resources are required to accomplish a particular product development goal and, in so doing, place great emphasis on effective communication, both horizontally between small development teams and vertically with regard to strategic product planning.

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. Personal roles also tend to be ambiguous. For example, even though a person may be an engineer, he may act as a manager. On the other hand, since the head of the group is only regarded as a symbol, the manager may be technically inferior to many of the people on his team. In such circumstances, choosing the right "head" is a key consideration since the leader's most important role is considered to be the synchronisation and harmonisation of his staff. Any manager who is weak technically will be provided with the necessary assistance he or she requires.

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 1 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.

Fig 1: Project Management at Fujitsu



"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. At Sony's Semiconductor Division, too, little distinction is made between the various functional responsibilities in a project. They simply organise and coordinate the people and resources required to achieve a particular target.

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 of 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 mainframe deliveries were on time.

To conclude this paper, a number of practical ways in which Western electronics firms, by learning from international "best practice," can significantly improve their design-to-product capabilities will now be presented. The "best practice" lessons have been grouped under three headings, namely **Design methodology**, **Design culture** and **Design automation systems**.

LEARNING FROM INTERNATIONAL BEST PRACTICE

Design methodology

Our case study research has highlighted a patchy appreciation, by many Western companies, of the importance of company-wide design procedures and methodologies. While the Japanese companies visited were particularly effective in organising their design efforts and in developing design methodologies, only a few Western companies appeared to assign any significance to the establishment of corporate design methodologies. In fact, the predominant UK view appeared to be that product design is a "black art" and should be left alone.

With regard to design methodology, we believe that firms should recognise the importance of classifying design projects according to the amount of engineering risk involved, or according to their degree of difficulty. The adoption of such an approach by one UK company would have helped it avoid major cost and time overruns on the development of a strategic product aimed at "leapfrogging" the competition. The problems were caused by a failure to recognise that a considerable amount of R & D work would be required, in addition to the normal product development activities.

The research has also highlighted the importance of ensuring that company design procedures are known and documented, and that their application is reinforced both through technology and through the "social system" of the company.

Design culture

The Japanese company visits left us with the 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. 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.

This culture of design appears to alter the way in which Japanese companies consider electronics product design and manufacture. One Japanese company has found that excellence in design has enabled it to take control of its manufacturing operations to such an extent that the company is now free to invest heavily in engineering support for the earlier phases of design.

A number of the Japanese companies visited have both a top down and a bottom up approach to project initiation. They encourage their (predominantly young) designers to design products they themselves would like to own and, partly as a result of this trend, the focus of their design effort is increasingly becoming concerned with the social and lifestyle context within which the products are being used. The visits also revealed that Japanese electronics firms spend more time developing their product specifications and designing out problems than is customary in the West.

In addition, all engineers in the companies visited have free access to corporate information, including secret information. The lifetime employment system these firms operate means very few employees ever leave, and there is little danger of such information "leaking" to competitors. Such practices differ markedly from those encountered in the West, and particularly in the UK where many engineers are denied access even to component cost information.

Given the complexity of modem electronics products, it is also vital that engineering knowledge and "wisdom" should be retained within the company, in a form which is easy to access and utilise.

Design automation systems

The Japanese companies also provided some insight into future directions for design automation systems, particularly with regard to the manner in which they have developed their own electronics design toolsets, but also through their efforts at integrating commercially available design software into their design processes. The companies have each had vigorous in-house CAD/CAM/CAE/CIM development programmes in place for a number of years, and they have been using this work to extend the boundaries of engineering design. By this we mean that they are moving away from a narrow, merely technological focus in design and are increasingly venturing into design management, the development of design infrastructures, design-for-manufacture and even into aesthetics and lifestyle design.

The design automation systems used in all the Japanese companies demonstrated a degree of integration with other computer-aided aspects of their operations not witnessed elsewhere in the world. In particular, their toolsets are strongly integrated backwards into manufacture and, additionally, considerable efforts have been made to effect parallel integration of the various design functions with costing, quality, industrial design and management systems. Where gaps are uncovered between the toolsets themselves, Japanese design engineers -- many of whom also have software engineering skills -- are encouraged to write their own "bridging" software.

CONCLUSION

It must be emphasised that the conclusions which the authors have drawn from their data relate only to the the results of their case study visits. Although they have attempted to research a good cross-section of the international electronics industry, extrapolation from these results must be undertaken with care.

Our studies have allowed us to investigate design practice and design CAD tool usage in a number of companies around the world. Although the human potential we have observed in each company has been roughly similar, the evidence of good design practice has varied. Many of the UK companies appeared to be preoccupied with getting production perfect, to the detriment of design. Their efforts were considerably hampered, too, by ongoing "civil wars" between the design and production engineering functions.

On the other hand, leading Japanese companies are clearly aware of the wider impact of design on product competitiveness and the authors observed a consistent approach to company management of product design in the companies they visited. It is our view that the leadership shown by the senior staff in these companies has facilitated the development of policies, procedures and practices, without which their design engineers would be unable to continually improve both the quality of their products and the design process itself.

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ELECTRONICS PRODUCT DEVELOPMENT PRACTICE -- EAST VERSUS WEST

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ABSTRACT

This paper reports on industrial best practice in the area of electronics design. It discusses major issues affecting engineering design, based upon evidence obtained during a recent international review of product design and manufacture practice. The case study visits highlighted a considerable number of shortcomings in both the management of the design process and in the computer-based support for that process. They also provided important insights into design-to-manufacture "best practice." The case study data have been analysed, and a "best practice" model of the electronics product design process, here presented in outline, has been produced. The paper presents a number of practical ways in which firms, by learning from international "best practice," can effect major improvements in their design-to-product capabilities.

INTRODUCTION

The needs of survival in the electronics marketplace have ensured that old mass production strategies derived from notions of economies of scale are being discarded. The new imperatives of flexibility, reduced design cycle time, reduced time to market for new products and reduced order cycle time to customers for existing products have imposed significantly heavier design loads on engineers. They have also resulted in increased design task complexity as companies have been forced to address manufacturing, test, service and even aesthetic requirements early in the product design process.

Unfortunately, these pressures, coupled with the perverse way in which many organisations currently structure their design–to–manufacture operations[1,2], have resulted in the adoption of product development practices which are almost guaranteed to produce unmanufacturable designs. The Electronics Designers' Toolbox (EDT) Project, a 3 year UK Government–funded research project through the ACME Directorate of the Science and Engineering Research Council, has addressed these critical issues in two ways. Firstly, the research has modelled the electronics product design process in a manner which considerably enhances earlier attempts[3,4] at understanding the process of product design. In particular, it extends BS7000: Guide to Managing Product Design by specifying, in greater detail than the more generic British Standard is able to, the activities and tasks necessary for effective design management and actual design of an *electronics* product. Secondly, our work has enabled us to functionally specify a next generation "Electronics Designers' Toolbox" for electronics product design.

In detailing the activities, communication processes, project management requirements and documentation standards that an electronics designers toolbox should support, the authors' design process model seeks to ensure that design engineers are able to use their extremely sophisticated and expensive support tools correctly. In the absence of correct toolset usage, we believe that there can never be any certainty that designers will design products which meet customer cost, quality and functionality requirements and which are easy to manufacture and to maintain.

The understanding of computer-support requirements for advanced electronics product design, gained through development of the design process model, has enabled the authors to develop a functional specification of a next-generation CAD toolset. We have discovered that it is rare for Electronics Design Automation (EDA) vendors to apply such a structured approach to the development of their advanced computer support tools. Capability requirements for this kind of software are usually market driven, and time-to-market for each new software release is a critically important consideration. In such circumstances, it is far more common for vendors to receive suggestions for product enhancements, perhaps during a user group meeting, to brainstorm around the ideas and then to proceed with their implementation in software. The few vendors who have attempted to write functional specifications for their products found that the writing of the software was actually completed well before product functionality could be fully specified.

Although it is not our intention to describe this aspect of our research in detail in this paper, it is sufficient to mention that the functional specification, in conjunction with the design process model, will enable vendors to develop advanced electronics designers' toolsets. It will also provide EDA tool users with the ability to use an appropriately edited process model to identify the nature and number of design tasks currently being undertaken, as well as to pinpoint their future design task requirements. Once the design tasks have been identified, the functional specification will provide toolset users with the means of determining requirements for both EDA tool performance and integration as well as for appropriate product design infrastructures.

In order to establish a base-line for this work, the authors have 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 interviews with senior design and production staff at eighteen UK and mainland European electronics manufacturing firms. Similar visits have been undertaken to eight leading U.S., Japanese and Korean electronics companies and research institutes, including Hewlett-Packard, MIT, Toshiba, Sony, Fujitsu and Samsung.

The remainder of this paper will describe a number of the most significant international case study findings, highlighting differences in both the technological and managerial approaches to electronics product development adopted by the companies visited. A "best practice" model of the electronics product design process will be presented in outline, together with a number of practical ways in which Western electronics firms, by learning from international "best practice," can effect major improvements in their design-to-product capabilities.

INTERNATIONAL CASE STUDY FINDINGS -- A REVIEW

In general, the eighteen UK and mainland European case study visits undertaken by the authors revealed that all participating companies were successful in getting their respective products to the marketplace in the face of severe competition. However, those successes were overshadowed by 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" approaches to design and inadequate document control. In addition, most designers in the study focused largely on producing products which perform a function at an acceptable standard of cost. They seldom thought in terms of design for low inventories, for example, for minimum number of parts/processes or for high yield, nor did the companies appear to regard product design as an activity which had strategic implications for their businesses. The visits also confirmed the fact that existing, computer-based support tools only provide "point solutions" to specific bottlenecks in the product design process. Nevertheless, it is clear that where gaps do exist in the design-to-manufacture path vendors are devoting considerable resources to filling them.

Significantly, neither the U.S. nor the Korean visits uncovered any more advanced design practices and software tool usage than those found in the U.K. 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 team discovered in the U.K. and European companies it visited, and which it reported in detail elsewhere[5].

Of the U.S. organisations visited, only Hewlett Packard (HP) 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 paper, 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, the authors discovered that 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 authors had seen elsewhere. In particular, these visits confirmed our 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 are also encouraging 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.

In addition, it was learned that all engineers have free access to to corporate information, including secret information. The lifetime employment system these firms operate means very few employees ever leave, and there is little danger of such information "leaking" to competitors. Such practices differ markedly from those encountered in the West, and particularly in the UK where many engineers are denied access even to component cost information. From a production engineering point of view, senior managers at one Toshiba plant indicated that their indirect/direct employee ratios currently stood at around 80:20, with around 75% of indirect employees being qualified at graduate or Masters Degree levels. In addition, there was considerable evidence to suggest that, in all the Japanese companies visited, extremely well-resourced product and process design support environments have effectively become "factories" supporting well-controlled manufacturing operations.

The Japanese companies also provided some insight into future directions for design automation systems, particularly with regard to the manner in which they have developed their own electronics design toolsets, but also through their efforts at integrating commercially available design software into their design processes. The companies have each had vigorous in-house CAD/CAM/CAE/CIM development programmes in place for a number of years, and they have been using this work to extend the boundaries of engineering design. By this we mean that they are moving away from a narrow, merely technological focus in design and are increasingly venturing into design management, the development of design infrastructures, design-for-manufacture and even into aesthetics and lifestyle design.

This trend to in-house engineering software development is being driven both by high (currently around $30,000 per seat) commercial licensing costs of software for engineering design workstations, and by demographic pressures. Japan's declining birth rate is causing shortages of engineering staff and is forcing electronics companies to automate as much of the design process as possible. For example, Toshiba is currently developing its own new CAD environment. However, despite the fact that the company's JCAD system is scheduled for completion in March 1992, the company already has plans to complete a next-generation CAD system (Super-JCAD) by the end of 1994.

While the current project will allow Toshiba engineers to carry out system simulation for midrange computers, for example, they have been unable to simulate personal computing devices such as hard- and floppy-disk controllers because of the complexity of their LSI functions. This personal equipment simulation capability will be one of the enhancements embodied in the Super-JCAD system. Fujitsu engineers, on the other hand, are using the company's most powerful mainframe products to design the next generation top-of-the-range computers and, since simulation plays such an important part in this process, the company has developed a special logic simulation processor for that purpose.

DETAILED CASE STUDY EVALUATION

Our detailed evaluation of the design-to-manufacture performance of the case study companies has been carried out using certain United States military[6] and commercial[7,8] best practices as yardsticks. 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 authors feel that the lessons which can be learned are sufficiently instructive to justify this approach. The performance categories selected for inclusion in this paper are **Design Process Management**, **Design-for-manufacture** and **Concurrent Engineering**.

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 authors' 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 authors' 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.

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 in this paper, 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 (OJT) systems which rely heavily on the availability of 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 OJT to turn a graduate recruit into a proficient designer, despite the fact that Japanese engineering undergraduates are not generally taught how to use CAD/CAE systems at university. However, despite the fact that the company's design review process is based upon previous development experience, with the list of items being reviewed expanded each time they go through the process, it is worth noting that Fujitsu Mainframe Division has not yet succeeded in incorporating design process knowledge into its engineering design tools.

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.

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. Examples of violated design policies include simulation (when obligatory) not done for lack of time, customers being allowed to effect specification changes on the basis of informal conversations with engineers, product specifications not being checked for consistency and standards being considered last because of pressure to get the product to the marketplace.

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 authors' 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 (FET), 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, our 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. Indeed, a comparison of Japanese OJT and design apprenticeship techniques with UK, European and US practice in this field highlights the fact that the Japanese generally adopt a longer-term view even of personnel recruitment than do their Western competitors. In this regard, it has been reported elsewhere[9] that Japanese companies have twice as many staff engaged in human resource management, working on training, on recruitment of new employees in schools and universities and on facilitating change within the companies themselves, as their Western counterparts.

Design-for-manufacture (DFM)

DFM at Hewlett Packard: 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 authors 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 correctly resides within the design group.

The tool incorporates knowledge derived from PCB yield curve measurements taken over for 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[10]. 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.

Component selection: As mentioned above, several of the UK and European companies visited demonstrated better practice in the area of parts and materials selection, though here too the authors encountered a number of significant 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 defence electronics company which had developed its own computer-based technology selection program. The system offers component lists to the engineer and makes the selection of non-standard or approved components visible on the schematic. Any deviations of this nature are automatically logged and have to be cleared at the appropriate design review.

On the other hand, poor component selection practice was discovered in a company which admitted giving no encouragement to its design engineers to minimise the parts list. Significantly, the activities of a value analysis group actually resulted in increased component numbers as the group 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 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 little authority and that the purchasing department performs only a service function.

Concurrent engineering

The application of the Concurrent Engineering (CE) approach to product development offers significant benefits in terms of reductions in manufacturing startup and preproduction costs, in product development cycles and in the number of engineering changes generated[8]. Nevertheless, it is the authors' view that CE is best applied to the development of innovative (20% - 50% different from previous generation) or strategic (50% - 100% different from previous generation) 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.

We consider the use of CE far less appropriate to the development of variant products (up to 10% different from previous generation). 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. However, CE principles in dilute form 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.

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 we 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.

In one extreme case, the company concerned had experienced a "war of attrition" between design and production, leading to an almost total collapse in confidence of one department for the other. Similarly, though in a different firm, the authors learned that the benefits of having a production engineer involved at the front end of the product development process were not appreciated simply because the company had a culture of "macho manufacturing" in which production took pride in "always managing to make the product somehow." Again, in another of the companies visited, the lack of a formal CE 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. Personal roles also tend to be ambiguous. For example, even though a person may be an engineer, he may act as a manager. On the other hand, since the head of the group is only regarded as a symbol, the manager may be technically inferior to many of the people on his team. In such circumstances, choosing the right "head" is a key consideration since the leader's most important role is considered to be the synchronisation and harmonisation of his staff. Any manager who is technically weak will be provided with the necessary assistance he or she requires.

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 1 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.

"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 2 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 mainframe deliveries were on time.

Fig 1: Project Management at Fujitsu Mainframe Division

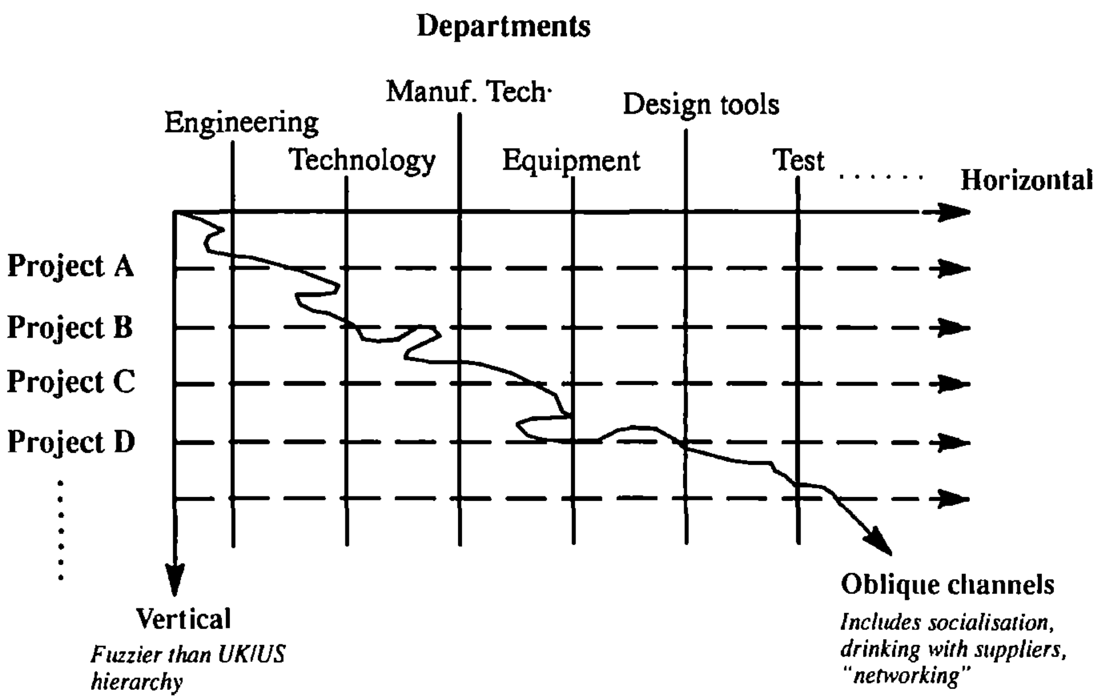
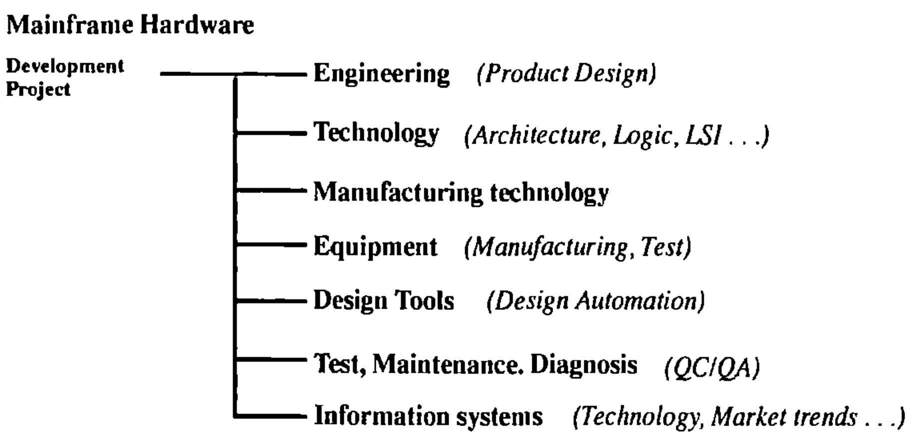


Fig 2: Concurrent Engineering at Fujitsu Mainframe Division



A "best practice" model of the electronics product design process will now be presented in outline, together with a number of practical ways in which Western electronics firms, by learning from international "best practice," can significantly improve their design-to-product capabilities.

ELECTRONICS ENGINEERING DESIGN PROCESS MODEL

Significant differences have been observed between Japanese electronics design practice and the tools and techniques used by electronics manufacturers in the West. This is particularly true with regards to the way people are organised, trained and motivated. It is quite clear, however, that the cultural differences between East and West make it extremely difficult for Japanese engineering design best practice to be imported wholesale and successfully implemented in Western electronics companies. The authors have incorporated a strategy for overcoming this problem within their design process model[11].

Critical to successful use of the model is the recognition that 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.

The design process model 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. The purpose of the gates is **not** to monitor the progress of the project but to provide the company with an opportunity to formally evaluate the evolving product design in a systematic and thoroughly documented manner. Thus, before development is allowed to proceed further, the design must satisfy a set of audit criteria laid down for each release gate. The gates are referred to as:

- *Initial Screen*
- *Preliminary Assessment*
- *Product Definition and Pre-development Business Analysis*
- *Pre-test Review*
- *Pre-production Review*

Within this context, the process model views company information as a series of three **product books**, each holding aspects of the developing product for future reference. Each book has contents, chapters and indices. The fact that appendices are used to track the appropriate chapters ensures 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.

The set of books generated during the project constitute the **Product Encylopedia**. 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.

In other words, Product Book 1 should include a concise rationalisation of the product's purpose, both from the company and the customer viewpoints. Hence 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[12].

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 should also be described.

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

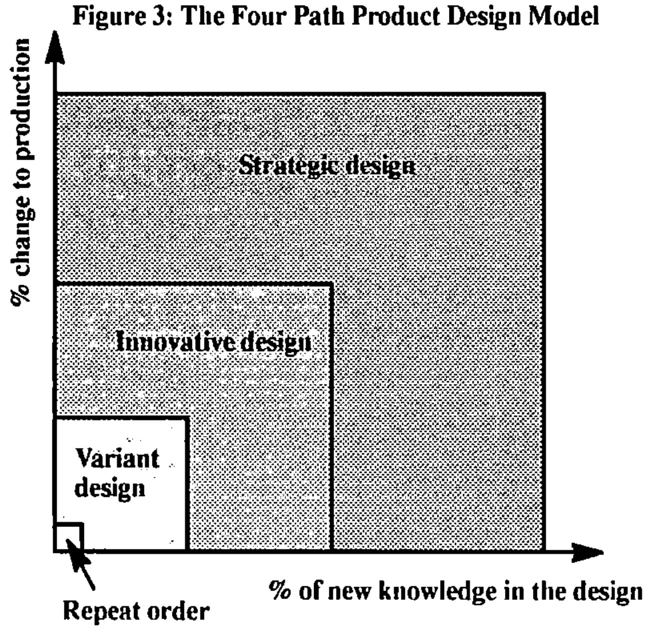
The contents of Product Book 3 must be updated as a result of feedback from field engineering and sales/marketing. Examples of this kind of feedback include field failures, product maintenance problems and customer response, both favourable and unfavourable. Any engineering change notes (ECNs) generated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

Our research has also shown that electronics engineering 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. Clearly, 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.

The authors' design process model addresses this issue by explicitly acknowledging 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 3 below demonstrates how this approach views designs as **Repeat Orders, Variant Designs, Innovative Designs and Strategic Designs.** The design process model also acknowledges that, for the same reasons as those described above, different aspects of the *same* product may require different developmental routes to be taken. For example, a product may require innovative mechanical design, variant software development and repeat order electronics.

In addition, the model supports the cognitive needs of the engineer by forcing creative and analytical activities to be separate phases in a design path. Documentation standards are defined which apply right through from customer contact to production. It is assumed that techniques such as DFM are employed to ensure that information is available from elsewhere in the company at the correct points in the design cycle.

Figure 3: The Four Path Product Design Model



The creation of the design process model has enabled us to begin the development of an electronics design methodology which will address the longer term needs of electronics design teams and will provide the UK electronics manufacturing industry with a "route map," enabling companies to radically improve their design-to-product capabilities. The methodology explicitly seeks, among others, to:

- *Minimise design effort by recognising that a number of different strategies have to be followed according to the novelty of the nascent product*
- *Improve inter-personnel communication within the product design team*
- *Ensure that product specific knowledge is captured and incorporated into the company knowledge base, in a manner that encourages re-use of knowledge in new products.*
- *Recognise that, since human beings are poor at being simultaneously creative and analytical, design activities must be appropriately partitioned to take such cognitive weaknesses into account*

LEARNING FROM INTERNATIONAL BEST PRACTICE

The comparison of international electronics product design practice presented in Table 1 below highlights a number of key lessons for UK and European electronics companies 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.

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.

Table 1: Comparison of international product design practice

Category \ Country	JAPAN	UK/EUROPE	UNITED STATES
DESIGN MANAGEMENT	Matrix organisation in all companies visited; multi-disciplinary team-based approach	Strongly organised along departmental lines; some matrix structures	Strong departmental organisation supported by corporate support groups e.g. DFM
INDIRECT VS DIRECT EMPLOYEE RATIOS	80:20 with 75% of support staff at graduate or Masters degree level	30:70 with 10% graduates	40:60 with 30/40% graduates
TRAINING	Strong philosophy re: training; OJT common; basic design skills acquired through apprenticeships	Very mixed approaches; no apprenticeships for basic skills; some evidence of buying in skills	Very mixed approaches; no apprenticeships for basic skills; tendency to buy in skills and to quickly dismiss staff who don't measure up
DESIGN STAFF TURNOVER	<2%; no key staff turnover	10% - 20%, including key staff	10% - 20%, including key staff
CORPORATE ATTITUDE TO DESIGN	Design regarded as one of a series of strategic activities	Generally design given low priority, especially in regards investment	Mixed response, some took a strategic view, others gave design a lower priority
DESIGN-FOR-MANUFACTURE	DFM is the prevalent approach	Widely varying; some DFM	Widely varying; some DFM
DESIGN TOOLS	2nd or 3rd generation in-house tools; some bought-in	Almost entirely bought-in	Almost entirely bought-in

It must be emphasised, however, that these conclusions have been drawn from the results of our case studies and, although we have attempted to view a cross-section of the electronics industry, extrapolation from these results must be undertaken with care.

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Reusing Company Knowledge and "Wisdom" to Improve the Electronics Design Process

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Abstract

The paper focuses on the concept of individual and group learning as it applies to electronics product design and presents research evidence demonstrating the current state of corporate learning in the international electronics industry. It demonstrates a number of practical ways in which U.K. electronics companies can effect major improvements in their design-to-product capabilities and describes an approach to design process improvement which highlights the key role played by product documentation systems.

Introduction

The socio-technical idea that organisations are organisms which can learn emerged with the development of systems thinking in the 1950s. Since then, much has been written about organisational learning and the "learning company" (for example Pedler *et al*, 1991; Argyris, 1982; Senge, 1990; Akkermans and van Aken, 1991; Dodgson, 1993; Levitt and March, 1988; AMED, 1993; Garvin, 1993), although the terms themselves are only of relatively recent origin. Nevertheless, there appears to be a consensus among these authors that such learning is vital to corporate success. Indeed, the view has been expressed (Stata, 1989) that the rate at which companies learn may become the only sustainable competitive advantage.

The emergence of such a consensus has undoubtedly been influenced by the manner in which successful Japanese firms have fostered and encouraged the creation of new ideas and by the way in which they have devoted themselves to learning at all levels within their organisations (see Imai, 1986; Imai *et al*, 1985; Yamanouchi, 1989; Nonaka, 1991; Bowonder and Miyake, 1993, for example). Hayes *et al* (1988) report, however, that few Western manufacturing companies have been able to measure up to this "new paradigm" of continuous learning and improvement.

Notwithstanding the existence of an extensive body literature on organisational learning, however, few authors writing in the Organisational Studies, Operations Management and Manufacturing fields have attempted to examine the subject from the standpoint of the individual production engineer or product designer or from the multi–disciplinary group perspective. That area of research remains largely the preserve of Social Psychologists (Moreland and Hogg, 1993) who, in their studies of small groups, have long sought to understand the underlying processes involved in, for example, group socialisation, communication, task execution and planning (Argote, 1993).

In the remainder of this paper the authors will focus on the practical knowledge storage and retrieval problems faced by electronics designers, both as individuals and as members of groups. They will present a potential solution to these problems in the form of a design database which is structured in the same way as a book: with chapters, sections, headings, tables of contents and indices. The authors argue that such an "electronic book" would be a more intuitive tool for human designers than many current design automation products because the users' mental model of the database would already have been formed by years of experience reading books.

Problems with reusing design knowledge and wisdom

To be successful at electronic product design, a company must have a thorough understanding of its existing product range, including all product functions and technological limits. In order to achieve such an understanding, firms must be able to archive and retrieve all salient product knowledge. However, it is precisely in this area that most electronics companies are highly vulnerable since their ability to develop such products depends, to a significant extent, upon the availability of "old style" expertise -- otherwise known as "wisdom" or "lore" (Culverhouse and Bennett, 1991). Unfortunately, such distilled long term interpretation of knowledge is usually only retained by the individual. In our experience, such "migratory" (Badaracco, 1991) expertise is rarely, if ever, systematically identified, captured and reused at the company level.

Levitt and March (1988) point out, however, that the availability of knowledge in an organisation is associated with the frequency of use of a routine, the recency of its use and its organisational proximity. They state that recently used and frequently used routines are more easily evoked than those which have been used infrequently. Conversely, organisations have difficulty retrieving relatively old, unused knowledge or skills. There are additional problems associated with current approaches to electronics design knowledge reuse. These include:

- The failure of manual knowledge capture methods to act as an effective feedback mechanism since recipients (other than designers) often tend to file paper documents away and ignore them;

- The failure of designers to record sufficient *contextual* information and knowledge about an evolving design. In an effort to minimise effort and cost, electronics designers typically only provide documentary evidence of their work in the form of a circuit diagram and a description of its function;
- The idiosyncratic and largely unstructured nature of personal engineering log books. This makes it difficult for other designers to interpret and understand the original designer's decision-making processes;
- Failure by engineering management in many firms to grasp the importance of enforcing a thorough approach to product design documentation as a mechanism for capturing design knowledge and "wisdom";
- Poor use of the knowledge storage and recall capabilities of CAD/CAE tools.

Bennett *et al* (1992) reported that a number of large Japanese electronics firms had been able to overcome these problems by evolving product design and product engineering support systems or infrastructures. Such infrastructures, by facilitating the organisational learning process, enabled those companies to continuously improve both the design of their products and the processes by which those products are manufactured. This systematic approach to "learning from experience", exemplified in the *Kaizen* approach to continuous improvement, has meant that knowledge has become institutionalised in many Japanese firms. According to Zucker (1977), institutionalised knowledge becomes "taken for granted" and is embedded in the group or organisation. His research also suggests that the extent to which knowledge is institutionalised is an important factor in facilitating the persistence of knowledge in organisations.

Storing and retrieving design knowledge

Larson and Christensen (1993) examine the problem of information storage from the point of view of information sharing across individuals in a group. They are particularly concerned with the ways in which information which exists either in a person's memory or in some other external store is shared and with the problems of access (direct vs indirect) to relevant information. Where information retrieval is concerned, Larson and Christensen report that groups in which problem-relevant information is shared prior to discussion are likely to do a better job of retrieving that information than groups in which such information is unshared. They also report that shared information is more likely to be retrieved than unshared information.

It is generally the case in the electronics engineering environment, however, that design knowledge spans many areas of specialisation. Furthermore, it is usually stored in people's heads, in engineering log books, in CAD/CAE databases and in project management reports. In other words, it is stored in a *distributed* fashion which makes company wide access to product information only possible through the use of common storage standards and common access methods. Given its fragmentary and usually unquantified nature, the storage and retrieval of such knowledge in a manner which supports effective sharing can be extremely difficult. This problem is compounded by the fact that knowledge is often embedded in individuals who hoard that knowledge ("knowledge is power"). Engeström *et al* (1990) describe a clinic administrator who hoarded knowledge by protecting his network of personal contacts in other departments and by solving problems without explaining the rationale to his subordinates.

The merging of data and information to produce a uniform company knowledge base in such circumstances can become extremely complex. Significantly, however, a large proportion of current engineering design activities are manual activities and designs are essentially paper-based. Hence, if computer support tools are to be successfully integrated with existing systems, one must be able to interface to existing methods and archive formats in order to ensure that simple linkages are created between people, manual methods, paper documentation and computers. To achieve this, and to overcome the kinds of knowledge storage and retrieval problems described earlier in this paper, the authors propose an electronic product book system as a direct replacement for relational databases and paper-based textual archives. Electronic books are not new (for example Egan *et al*, 1994; Favela *et al*, 1994), but to be useful in an engineering context they must be structured so as to simplify human readability.

We have chosen to use the book metaphor because it represents an approach to human communication which has evolved over many centuries and which is immediately familiar to a majority of all adults who have received a formal education. By adhering to the book structure and by fixing the position of certain categories of design information within certain chapters of a book, design engineers can be more certain of efficiently locating the design information they require.

Product books

In the authors' view, company product design information may be viewed as a series of three "electronic" product books, each holding aspects of the developing product for current use or for future reference. Structuring product information and knowledge in this way would allow design engineers to access that information in a familiar fashion. The technique developed here is to use company product books as the engineering database for each product. This results in a combined database which is intuitive for the human user since, in addition to the inclusion in the documentation of more advanced referencing techniques such as hyperlinks and structured browsers, it is structured like a book. 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. We propose that any chapter longer than 5,000 words should 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. This consistency of documentation across both company and product simplifies routine human cross-referencing and filing when information or data is sought on a particular aspect of a product, independent of who is requesting the information. Additional books may 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"). The set of books generated during a product's life constitute a *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. Specifically, Product Book 1 should include a concise rationalisation of the product's purpose, both from the company and the customer viewpoints. It should explicitly include such factors as desired market positioning, target market, desired lifecycle, cost and such high level technical aspects as product variant strategy.

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 describes a product's conceptual design.

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

Conclusions

The authors have examined organisational learning as it applies to individuals and groups engaged in engineering design activities. They have proposed a computer-based solution to the many problems associated with identifying, capturing and sharing vital design knowledge and wisdom. That solution, a series of electronic product books, would allow engineers to access information about the products in a familiar way. It would also make it easier for engineers to remember where specific information is, thereby facilitating navigation around very large engineering databases.

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IMPROVED ELECTRONICS PRODUCT INNOVATION THROUGH THE CREATION OF FLEXIBLE DESIGN CAPABILITIES

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INTRODUCTION

A considerable body of research, for example that of Lefebvre et al (1) and Schmidt (2), indicates that many different factors, including product design, contribute to successful product innovation. The work of Bennett et al (3) in the electronics industry, however, indicates that high levels of environmental and technological uncertainty are forcing firms of all sizes to adopt management approaches which regard engineering design as a strategic, if not **the** strategic, priority in their businesses. The adoption of this view requires the abandonment of short-term, project-focused approaches to product design in favour of design capabilities which are flexible and which support wider business objectives.

What companies, particularly small and medium size manufacturing enterprises (SMMEs), currently lack is a "roadmap" which, by providing a pattern for success, will reduce the amount of risk involved in creating their own product design capabilities. The methodology described in this paper aims to improve the product innovation effectiveness of UK electronics companies by providing firms with such a roadmap. The methodology will give electronics manufacturers the *internal* wherewithal to specify product design capabilities which are resilient to changes in their respective business environments. This has been achieved through the adoption of a user-led approach which builds upon the key lessons derived from the authors' research into international product design best practice.

Specifically, the methodology will enable an electronics firm to:

- *Articulate its business strategy with respect to product design. In order to identify the nature, extent and location of the resilience required, it will be necessary to identify potential changes in the firm's environment by considering such factors as stakeholders, competitors, suppliers and trends in relevant product and manufacturing process technologies;*
- *Map the components of its current design capability onto a template of design tasks -- the "as is" product design template;*
- *Create a set of requirements for its new product design capability -- the "to be" product design template;*
- *Create an overall product design solution which takes into account the management of design, the operational aspects of*

design and the infrastructural or support elements of a design capability. This is accomplished by comparing its "as is" task template with its "to be" set of requirements.

THE NEED FOR FLEXIBILITY IN ELECTRONICS DESIGN

Electronics firms are daily confronted by a marketplace which, according to Kooy (4), is characterised by decreasing product lifecycles and by increasing product diversity, quality requirements, competition, innovation speed, integration and miniaturisation. That marketplace is now irrevocably demand (buyer) rather than supply (seller) driven and the needs of survival have quickly forced firms to abandon the old mass production strategies derived from notions of economies of scale. Operating effectively in a buyer's market is not straightforward, however, and a substantial body of literature, for example, Zelenovic (5) and Gerwin (6), suggests that flexibility has become one of the most important competitive attributes for manufacturing firms in the 1990s. From the point of view of engineering design, Bentley (7) notes that the need for greater flexibility has been driven by the very real difficulties firms experience in attempting to predict future markets for their products.

Following Bonder (8), we have chosen to define flexibility in terms of versatility (a capability to respond to a wide range of scenarios ahead of time, or effecting a rapid modification once a change has occurred) and agility (an ability to side-step a potential source of disadvantage). We believe this is useful when considering the development of a firm's electronics product design capability and it is particularly relevant at the product level where firms are facing changes in three major engineering design dimensions: The *nature* of the designs being undertaken, the *scope* of the designs and the *intensity* of the design activities.

The nature of design

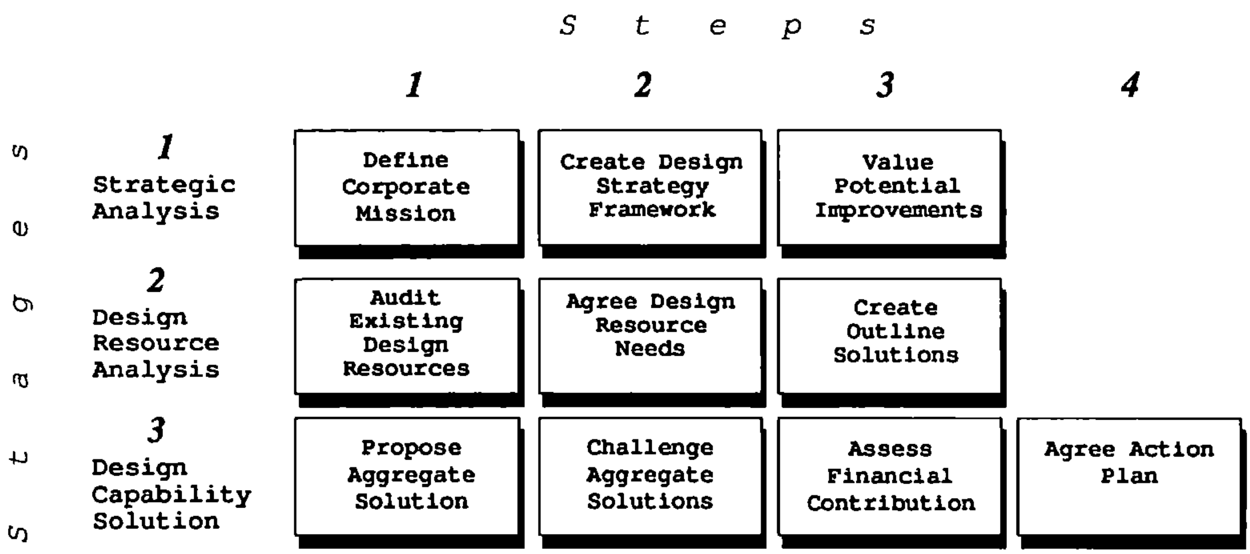
Japanese product design practice, as reported by Buur (9) and Hamel and Prahalad (10), indicates that U.K. electronics firms should adopt product strategies which emphasise the importance of designing across the whole product development spectrum. According to Bennett et al (3), electronics firms should adopt a portfolio approach to design which involves the development of Repeat Order, Variant, Innovative and Strategic designs. Our research indicates, however, that the majority of designs being carried out in the U.K. and European case study firms are of the Repeat Order and Variant variety.

The scope of design

The changes in competitive forces outlined above are forcing electronics companies to think hard about leading their customers in the directions they want to go before those customers know it themselves. This "new paradigm" is extending the scope of design by requiring firms to gain deep insights into the needs, lifestyles and aspirations of today's and tomorrow's customers.

way product design is managed and organised. They might also reveal a requirement to provide design engineers with enhanced design automation support or to provide members of multi-disciplinary teams with electronic means of communicating with each other. Improved engineering staff training and the introduction of more enlightened reward and recognition systems might also be called for.

Figure 1: Methodology Overview



Furthermore, analysis of market trends and competitor product performance will undoubtedly highlight opportunities for improving the Company's product profile. This may involve eliminating various underperforming products and replacing them with a set of innovative products. Such products will represent the platforms the Company will require to create product families which possess the necessary competitive characteristics to enable them to win in the marketplace. Strategic Analysis involves a detailed examination of the Company's customers, markets and competitors in order to establish the impact that developments in these areas will have upon the firm's overall product design and development capability. It also requires the Company to audit its own product design and development environment in order to gain a clear picture of its strengths and weaknesses in this area. The focus for the Strategic Analysis stage is provided by the Corporate Mission Workshop which, by specifying "the business we are in," seeks to provide a clear statement of the Company's purpose and goals.

Design Resource Analysis

Design Resource Analysis starts by auditing product design resources and capabilities. Based on this assessment alternate ways of achieving the required competitive Product Family, as well as of effecting improvements to the management, operational and support aspects of engineering design, are generated and evaluated before selecting the most appropriate solution for further consideration. In the Strategic Analysis stage described earlier, the competitive profiles for each product family were defined and the value to the company of achieving those improvements was identified. Improvement opportunities were also identified in the management, operational and support areas of the Company's design activities. Quite rightly, no consideration was given at that time as to whether or not, or indeed, how the improvements might be achieved. Design Resource Analysis is concerned with **how** design resources can be adjusted and more fully utilised to achieve the required improvements.

Given that there are usually many ways in which improvements can be made a decision must be taken on the most appropriate resource to change to achieve the required results. In practice such decisions are rarely algorithmic. They require the imagination and creative contributions of relevant company personnel to generate and evaluate alternate solutions. A workshop is used to provide a forum to secure these contributions and determine which solution to adopt.

Design Capability Solution

The Design Capability Solution stage of the methodology consists of the following steps:

Step 1: Propose Aggregate Solution

Step 2: Challenge Aggregate Solution

Step 3: Assess Financial Contribution

Step 4: Agree Action Plan

This stage of the methodology brings together the various solutions into an overall plan for creating a flexible product design capability. Having identified individual solutions and assembled related solutions into solution tracks they must be subjected to rigorous challenge before proceeding. Challenging solutions is essential for two reasons. First, the process of amalgamating solutions to develop the tracks may in itself have brought into question the Company's capacity to implement them. Secondly, both individual solutions and solution tracks need to be reexamined to eliminate or reconcile conflicts, avoid duplication and provide a realistic and achievable agenda for improvement. In effect, this process represents the manufacturing team's last opportunity to assess the solutions before they are incorporated in the Company's manufacturing strategy and action objectives.

The aggregate design capability solution is evaluated from a financial point of view in order to ensure that product design resources and capabilities are applied to sales product families which are currently, or are expected to, make a significant financial contribution to the company. Having identified in Strategic Analysis the desired competitive improvements in each product family, in Design Resource Analysis, identified how resources should be deployed to achieve the profile and in Design Capability Solution assembled individual design solutions into solution streams, priorities must be agreed and assigned to specific actions. In order to assign meaningful priorities consideration must be given to three issues; technical precedence - that is, what needs to be done before an action task can be carried out, the resources required to take action and, not least the value of taking action to the success and profitability of the Company.

Conclusions

This paper has presented a user-led process methodology for helping small and medium-size electronics companies to define *for themselves* product design capabilities which are robust and which support their wider business objectives. The methodology enables firms to implement product design best design practices in their businesses and to support those practices with appropriate design software tools. It provides an affordable means for SMMEs to regularly evaluate and improve their design operations and it will help to create far greater ownership of and commitment to the implemented design automation solutions.

The work presented in this paper is the result of research undertaken during the Electronics Designers' Toolbox (EDT) project, a three-year project, funded by the ACME Directorate of the Science and Engineering Council (SERC), to specify the functionality of a next-generation designers' toolset for electronics design.

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Appendix 6

Examples of data collected during visits to U.K., European and Japanese electronics companies

COMMERCIAL IN CONFIDENCE

ELECTRONICS DESIGNERS TOOLBOX PROJECT

COMPANY 6

Document reference number: EDT/ORG/006

Document issue number: 007

Date of issue: August 31, 1990

Prepared by: Jan Bennett and Phil Culverhouse

1. COMPANY PROFILE

1.1. Type of business:

Four companies in Organisation 6 group. Few links between them. The main link is a group parts numbering scheme to allow group manufacturing. Could allow group purchasing but not implemented.

1.2. Major product types:

Programmable controllers (multi-loop control)

820 Instrument: RFI problems; heat problems; totally unmanufacturable; will die at the end of 1990. Organisation 6 have the world's last supply of static RAM for use in this instrument. The development and production of this product was useful because it humbled the design engineers.

818 Instrument: Most popular model; is s/ware configurable. Have standard instrumentation configured by s/ware. This instrument was the first where CE approach was used throughout the design phase. But the product is 3.5 years old, it is seeing more competition and needs upgrading.

The 818 has 30,000 possible hardware variants: 3 possible display boards, 5 possible power supplies (1 basic p/s but 5 output options), 3 basic comms possibilities, 151 possible output options.

Not designed for cell-based manufacture.

818R Instrument: Replacement for 818 model. Will be totally SMD and will only go through 7 processes giving reduced processing and handling time. It's a micro-board without physical comms. Cost reduction and redesign of the 818 model.

828 Instrument: Replacement for model 820. The order code is horrendously complex (so many possible variations) so they will need to have a computer in the line. The employee won't see the order code at all since the computer will merely take the next code off the stack and tell her which bits to put together.

The first 60 828s will be demo models and will be given to select customers. In June they'll go to pilot production. Essentially to allow them to refine the production process.

SMD on both sides. Very high packing density.

Designed for cell-based approach.

1.3. Personnel:

1.3.1. Administration:

1.3.2. Design:

1.3.3. Production:

1.3.4. Test:

1.4. Turnover:

£44 million (1989)

1.5. Competitive dimensions: (Cost, quality, reliability)

Highest quality, best support (tailoring product to customer by Organisation 6), highest functionality. Most expensive.

1.6. Level of competition:

1.7. Main competitors:

West, UK

1.8. Types of computer support tools: (Design & manufacture)

1.8.1. Electronics design:

PCB

1.8.2. Mechanical design:

1.8.3. Manufacture:

1.9. New designs/period:

Two major instruments involving 20/30 PCBs/year. Cost reduction is main effort here.

1.10. Production volumes/year:

Shipping 750 units/week.

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:

60% on some product lines.

3. MANAGEMENT PROCEDURES

3.1. Design review procedure: (Concept to prod.)

Design guidelines are now at revision 7 and being continually revised as they learn new lessons. As far as possible they have been implemented in the Visula rule base.

Marketing and senior engineering staff meet to discuss and evaluate opportunity prior to Project Management Team (PMT) being formed.

Currently have BS5750 part 2. Working to implement part 1 by the end of Nov. 1990. They are operating it but do not quite have complete document issue control.

Wish procedures to be simple and easy to remember.

3.1.1. Description of signoff stages: (Incl. adherence)

Have sequential series of signoffs (called gates). See document entitled "Product Lifecycle -- Phases and Transitions." Not adhered to rigidly since at present design freeze stage is flexible. The release gates approach is an idealised one but by December they intend to have a fully operational gate process in time for the replacement for the 818 model instrument.

Currently use issue control to track design modifications:

a. Designs are alpha-controlled (A,B . . . Z etc)

b. Approved designs are alphanumeric (A1, B etc)

c. Pre-production/production are numeric (1,2 etc)

So, rev A1 would refer to an approved design whose drawings are in the design approval file.

Use issue control system written in DBase III -- very happy with this.

3.1.2. Problem areas/iterations:

As they practice simultaneous engineering, they appear to have few problems with design iterations. They also use prototyping in Design to check prior to production.

But they would like to have a properly maintained project file that held details from engineering log books together with subsequent decisions. This would help to smoot customer problem resolution and improve resilience of company to engineering staff turnover. (Make it easy for engineers to keep an electronic log of major project problems).

3.1.3. Standards adhered to:

BS5750 Part 2

Have got company internal workmanship standards.

Over past two years they have been installing a formal quality system like BS5750. Has been beneficial but it's only regarded as a foundation.

Have created a quality manual in a way that best suited their business needs. No outside consultants. No Crosby's or other gurus. Departmental managers wrote their ownprocedures, not the quality department. Three activities in the company:

Business 1	Business 2	Business 3
(Distribution & Service) maintenance & service	(Discrete prods) BS5750 part 2 At the moment BS5750 part 2 is only being applied to the manufacturing side. Later they will apply it to Business 1 and BS5750 part 1 to engineering design in Business 2.	(Systems) e.g. control systems for cable making line at BICC

Quality group has 4 groups:

Design: getting quality designed into the product; helping designers by giving them problem solving tools and techniques

Manufacture: 2 QA engineers in UNit 1 (PCB Assy) and in instruments

Vendor: now have 4 inspectors who are engaged in proactive work with suppliers; go out with the buyers; used to have a traditional goods inwards inspection system 4 years ago

Systems: one person investigates quality system itself to make sure BS5750 system fits together

Concerned with development of quality culture in the company.

Inspection has surface look at incoming components. Problems come with custom parts or older parts which are sourced in low volumes from local companies who have come to rely on the company's inspection procedures. With largest PCB supplier they are working to get quality up so no inwards inspection is required.

Have got company internal workmanship standards. Also have QITs, regular quality group in Unit 1. Are using SPC as a tool. Quality manager has training budget but it tends to get chopped when orders aren't coming in.

System for getting quality information back from the myriads of QA measurements isn't clear. There are lost of detailed closure mechanisms at local level which mean that relevant information is not getting back to people who may benefit from such knowledge. ECN problem investigation is the mainstay which ensures that knowledge about bigger problems does get back up the line.

Could see benefit of being able to filter these issues and turn them into design requirements.

BS5750 framework has helped to generate quality information but it hasn't helped to encapsulate knowledge for future design.

3.2. Simultaneous engineering: (Yes/no & degree of success)

Yes. Seems very successful. 3 years ago they were manufacturing a product which had a 300% reject rate. Change to CE was almost all manufacturing led.

Use of this approach preceded current MD's arrival at the company. Current Production Manager came to the company in 1984, but they only began using CE in 1985 when work started on the 818 instrument. Philosophy: "Let's get right what we're going to build tomorrow." Must use knowledge of what can be improved in manufacturing processes + understanding of needs of new products; may need to redesign production processes.

Example of CE at work in the company: getting into SMT resulted in the introduction of a lot of other processes e.g. cropmatic tool for cropping leads which were too long, pick and place (entirely new), autoinsertion of axial and DIL.

Manufacturing engineers were learning re: SMT and were using that knowledge to influence design. That knowledge resides in the production department.

They also have a CE approach to test and have been using ATE since 1980.

Have matrix organisation with projects being run by PMTs. However, company is organised into design and manufacturing and thus team consists of members of all relevant areas. Layout of purpose built factory encourages communications between staff. All communications need to go through production. Has paid dividends.

PMT comprises: Project manager + members of

a. Instrumentation

b. Systems

c. Production Engineering

d. Purchasing

e. QA

f. Marketing

PMTs are set up right at the beginning of of a project, and comprises staff from Engineering, Manufacturing and Marketing. Once design actually starts they bring in Quality, Test etc. Staff are there to totally represent their department's interests by identifying issues which need to be solved.

They meet weekly in minuted meetings. Problems picked up as they occur, minutes also circulated to Engineering Director.

Chief Engineers of Instrumentation and Systems are responsible for support tools and training of personnel. Team leaders responsible for technical excellence.

In re: 818R model, they are consurrently developing processes to cope with increased flexibility requirements of the new product. Flexibility is the main issue coupled with low lead times through assembly. Some boards run at 100/week, others run at 1/3 months.

In re: design for test, they are trying to get a suggestions list for system test before design starts in earnest. The suggestions list is derived from experience, look ahead and cost reduction suggestions. At instrument level, they discuss instrument capability and are able to get DFT incorporated into the manufacturing spec.

For the 900 series of instruments (first dual input type of instrument), need to calibrate both inputs simultaneously to save time. But, because of accuracy required for settling time, calibration will take 12 minutes. The 818 model take half that time.

Company culture:

a. Has few offices

b. Encourages creativity

c. PMTs have 100% attendance (report achievements, high level requirements and targets)

Projects claimed to be well estimated (time/cost). But do have s/ware slippages. Three months on current project.

Staff turnover: 10% - 15% out of 50 engineers.

3.3. Engineering Change Control:

See ECN procedure document.

Use Problem Review Request (PRR) to control revision requests. A formal system of feedback requiring any engineering change note (ECN) to have a PRR number handles problems and opportunities. At start of ECN, changes are required to have completion dates associated with them, all agree and get signed off. Ensures that checks are completed.

ECC system is partly automated. Computer-based system developed in-house (Dbase 3) to track ECCs. Powerful tool. Staff have confidence in it.

PRR statistics: (See ECN System output graphs)

Total PRR's in Week 16 (of April 16)

a. total now open 138

b. total closed 55

c. new entry PRRs 65

d. closed by change 35

ECN punctuality vs forecast (in average days late):

. Week 4 (January 22) 50
. Week 8 (February 19) 80
. Week 12 (March 19) 35
. Week 16 (April 16) 32

Have an ECC committee meeting each Friday at 8:30 during which all change requests are reviewed and assigned to appropiate department for action. Wednesday each week is the cut-off day for any change requests.

New products become ECN controlled when they reach alphanumeric issue status. Progress on investigations into changes is also reported.

4. NEW TECHNOLOGIES/MATERIALS

Component engineering committee (set up 18 months ago) looks at what to do in future (realised they weren't preparing themselves for tomorrow), today, in production and in re: yesterday (maintenance). By way of e.g. one of their new designs is using a component with size 0603 which is half the current size. The committee was tasked with preparing a manufacturing and equipment buying strategy. In the past they would have bumped into the problem and would have simply reated to it.

In re: PCB technology they are pushing PCB fab techniques. For one product they require 4 thou" grid and 4 thou" track for inner layers on 6/8 layer boards. Currently only NEC in Japan is offering this. They are exploring UK/European suppliers. UK ones cannot offer this pitch.

They are looking for second generation SMT equipment which will give them higher component densities on 818R boards.

Drive to miniaturisation will force them into TAB, chip-on-board, multi- chip modules, TAB grid arrays, 3d stack modules.

Interconnection: what is future of interconnection?

Panel displays: exclusively use flourescent in-line panel displays. Some are pushed to s-o-a.

Moulded circuit boards are being used by U.S. Organisation 6. ICI does it in the UK.

Mechanical components: silicon rubber in keyboards, flexible material (how do you measure quality?), membrane keyboards.

5. DESIGN METHODOLOGY (Engineering practice between sign-off)

5.1. IDEF0 validation: (Comments/diagram)

5.1.1. Diagram identifiers:

CAMI.EAP, Company A, Design Functional Module. Nodes COMPA/A23, COMPA/A232, COMPA/A2321.

5.1.2. Comments:

Technical Director thought that IDEF0 diagrams for design were idealised since, in reality, design did not work in such a smooth progression. He suggested two box diagrams:

a. Design specification (simultateous engineering), including manufacturing requirements and test strategy.

b. Solve problems identified above.

Design is the creation of change so IDEF not sensible.

5.2. System:

All process design done using common sense. No need felt for simulation. They are constrained in where they can physically position machines in the plant.

SMT placement process is traditionally regarded as a single process. In reality it can be split into adhesive and paste. The two requirements are significantly different in terms of flexibility. But contractors are only buying one type of machine.

5.3. Hardware:

Manual design, except ASICs (hybrids???)

Products used to be entirely analog. Shifted away from this to analog periphery and digital (uP & ASIC) core. PCB layout done using RACAL VISULA layout tools.

Redac kit bought in to allow constrained layouts. Circuits and mechanical are all designed manually.

PCB manufacture contracted out. Contractor also has prototyping shop, allowing most prototypes to be risk evaluated for prospective volume run.

Do have modem links to PCB supplier. Gerber format so it's just a case of transmitting an ASCII file over the phone line. The supplier has imported the company's design and quality rules into his CAD system.

Do perform prototype development since designs are mixed analog/digital. But get most designs right first time for volume.

Most recent problem was RFI so board had to be re-laid out.

They have postprocessing for Dynapert and bed-of-nails configuration.

PCB versions poorly tracked at present. Will be using Apollo version control software this year (DSEE).

Implications of CFM for design: expansion of role of manufacturing to design area to help them understand what production is doing. 4 key areas in which they can improve their design for CFM:

a. design for high yield

b. design for minimum number of processes

c. design for standard component/processes

d. design for set–up and batch sizes (need slick setups so they have to reduce variations on any one board + any one product)

Designers aren't expected to come up with all the answers on this. Issues are kept very general.

5.4. Software:

Use CASE tools which fit neatly into BS5750 documentation standards requirements.

5.5. Problems:

They have a design problem with power supplies which are occasionally dying for no apparent reason. The incidence is so low that it is difficult to get sufficient evidence of the problem to pinpoint its cause.

Faults per period arising from design errors:

a. Hardware: 2/3 per year e.g. overstressing of components on power supplies

b. Firmware: 6/year max. Firmware bugs deminish with maturity of the product

c. Component batch: 3/4 per year

6. MANUFACTURING METHODOLOGY

6.1. IDEF0 validation: (Comments/diagram)

6.1.1. Diagram identifiers:

6.1.2. Comments:

None elicited.

6.2. Shopfloor practice: (JIT/MRP etc)

Have their own version of bespoke (??) for stock/inventory. MRP and CFM/JIT practiced. Have multi-location stock control for shop floor.

Continuous flow manufacture:

Practice continuous flow management (their own version of IBM's CFM). Already do DFM and DFT, now they are working on design for CFM.

5 people are responsible for implementing CFM from within production.. They report to a steering committee comprising senior manufacturing management. They are working to 6month, 1 year and 5 year timeframes in re: what manufacturing should look like. Once every three months they review progress in re: timescales.

Use matrix management. CFM development people report to steering committee. Work on CFM 25% of their time.

CFM project has 4 main areas:

a. material supply

b. production flow

c. systems integrity (ensuring that whatever is done in manufacturing in a physical sense is manifasted in a high degree of integrity on the computer system (Wang).

d. human factors

They are focusing on different areas of the factory

e.g. they target an area of material flow and, instead of kitting they have moved to kanban. Later they will go to direct delivery to the line. So far they have worked on material flow in 2 or 3 areas and have installed the first production flow line.In terms of moving to CFM environment, 2 drivers:

a. reducing the materials pipeline

b. improving lead times of product to customers. At the moment this is 4 weeks. Depending on the product they want to get this down to 2 weeks in 6 months time. In next 2/3 years they want to get it down to 1 week.

Implications for design: expansion of role of manufacturing to design area to help them understand what production is doing. 4 key areas in which they can improve their design for CFM:

a. design for high yield

b. design for minimum number of processes

c. design for standard component/processes

d. design for set-up and batch sizes (need slick setups so they have to reduce variations on any one board + any one product)

CFM issues include test and production engineering. Certain types of test are associated with low yield.

In re: the new 818R model, they are involved in a 818 model cost reduction and redesign exercise. How to reduce component and manufacturing costs. Design engineers aren't aware of total manufacturing costs. They must look at high yield SMT for this model. One board is totally SMD except for 3 components (used to be 50-50). They are tasked to find SMD replacements for those 3 non-SMD components.

Those new components may cost 6p vs 4p for conventional component. Engineers were only looking at materials costs, not overall cost of manufacture.

The 818 line: Because the 818 instrument has so many different hardware variants, they need to be able to make the final hardware choice as late as possible in the instrument build (in the case of the 820, that choice was made at PCB build stage).

Targets were set at the outset of the 818 project (which weren't written down) e.g. no soldering on the production line, all sexing to be done using plug-ins, fault-finding at board level only with any faults being returned to experts for repair, single build standard for each module.

The line itself uses kanban technique. Green card on bin for when bin still has parts, red when it needs replenishing (storeman replaces bin). No attempt is made to kit the instruments.

Unit 1 (PCB assembly): CFM approach. Don't issue kits from stores. Mass download of components for a week's production. Semi-autoinsertion also uses CFM. All SMT stock is held in this area. No dedication to a particular board.

Problems with wave soldering: turbulent wave, omega wave. They have to manually tape over the slots on the board to prevent solder going up through the slots. Are working on this problem but no solution at present.

Have auto-assembly cell for axial and DIL components which has 2 ACI machines. Stuff between 80,000 and 90,000 components. Real placement rate = 5secs/component.

Use Dynapert MPS 500 2-head pick and place machine. Has 160 carriers. Set up is a major issue here and they try to constrain designers in terms of numbers of components. Set up is a major source of quality errors. For the 818 model, they are able to build the board without changing the setup.

Semi-automatic cell using 6 (soon to be 7 because of capacity problems) Lynx Laserlight machines. Claimed to be "brilliant." CFM binning with 2 bin system. Try to plan process so any given machine can do as many boards as possible.

Do have a certain amount of offline manual insertion for things which have to be put on after autoinsertion and cleaning but try to keep this to a minimum. 5 years ago they had 100 girls doing this. Now there are between 6 and 10.

Testing using bed of nails, end to end testing, in-circuit + functional. CFM used throughout.

6.3. Production test: (What they do)

HP test, both functional and bed-of-nails.

They have adopted a number of different approaches. They wanted to do incircuit test on every circuit board to ensure every component would function in practice, so they introduced functional test. But they didn't choose the right functional test equipment. Chose Mars Gazelle. Mars pulled out leaving them with an unsupported piece of test equipment.

They also wanted to be able to do a complete test of the assembled product. Developed an in-house system called PLATE (Production Line Automatic Test Equipment). They decided to take a system like that away from production engineering and grow the test department.

The 818 line: Warm up racks are used as the first place a failure can occur. Testing to see if displays are showing any obvious output errors e.g. strange symbols etc.

After warm up rack, instrument goes into automatic tester (PLATE 1). They have three stations. The test equipment also configures the instrument. ATE stations are networked. Download configuration data from main computer which knows the 'live' orders. Only need to enter 'movement order number' into test system which then interrogates main computer for the relevant test spec.

Instruments are interrogated for which boards are inside, results are compared. Test station checks it can download full customer configuration. It then goes into full test according to the instrument spec. If everything is OK, the instrument is commonly configured for 'soak' but this is going to be done away with because it doesn't identify process failures.

The only feature which soak highlights is display problems. If they could automatically test displays, they could get rid of the need for soak.

Out of soak into automatic insulation test. The isolation of input and output in the instruments is extremely important.

Labels are only printed at the end of the line for those instruments which have passed. No failed instruments can be boxed. Any failures go to failure analysis.

A manual inspection is carried out after the functional testing. Two types of rear covers are then on the instrument, instruments are labelled, accessories are added and the whole lot goes into a plastic bag and into a box. The whole of this process takes 2.5 minutes.

Main limitation at the moment is test equipment reliability.

At PCB board level, their biggest problem is that engineers don't simulate. Deliberate choice not to do it because the tools they would need are too expensive. So they rely on manual analysis and test stations for simulation of the environment in which the instrument will be used.

Have a PC3000 system which allows them to put instruments through their paces in terms of plotting distrubances on inputs. This gets them past the need to simulate at board level.

Test dept. have to generate their own test vectors (manually) but they are encouraging engineering to given them a minimum set of test vectos.

Whenever they design custom ICs, they feel that the core of the IC can best be tested by manufacturing. Test dept. is concerned with any damage to i/p and o/p buffers due to handling of the device + testing of solder joints down to the board.

Need to stop designers from designing cul-de-sacs in their designs which lead test up a one-way street. They have tried to write guidelines but these aren't followed by designers.

Feedback on component failues done via PRR mechanism.

Instrument/system test done using PLATE1. PLATE2 will take radically different approach. Extremely complicated test software because must take into account all the millions of variants. Organisation 6 responds to a diverse marketplace by making systems as configurable as possible hence the tremendous complexity of PLATE.

When design engineering change the firmware in, say, the 818 model, this has huge implications for the PLATE system which will require substantial modifications to the software (and possibility of introducing more bugs into the system).

The product codefor the 818 model is up to 100 digits long. Just handling the product code is a major problem because the code has to be interpreted into test and calibration parametric values.

PLATE generates fault tickets and analysis of these is done manually. They have yield improvement groups (YIG) to rigorously analyse the fault tickets looking for trends, looking to see whether PLATE benches are showing up regularly. YIG has successfully flagged a number of low level problems which like they are design problems. But there is a robustness problem with PLATE1 itself and it will be replaced with a more robust PLATE2.

PLATE2 will likely be redesigned in a much more dedictaed way to strip out much of its current flexibility.

From instrument test, they have a database collecting fault logging data which is separate from fault ticket analysis and is for the line's benefit.

6.4. Production technology used:

Use Dynapert MPS 500 2-head pick and place machine. Has 160 carriers.

Have auto-assembly cell for axial and DIL components which has 2 ACI machines. Stuff between 80,000 and 90,000 components. Real placement rate = 5secs/component.

Infrared reflow, steam wash, flow soldering, CFCs for cleaning (claimed not to have a high loss within the plant but could not vouch for what the company contracted to dispose of used CFCs did with the chemicals).

Semi-automatic cell using 6 (soon to be 7 because of capacity problems) Lynx Laserlight machines. Claimed to be "brilliant." CFM binning with 2 bin system. Try to plan process so any given machine can do as many boards as possible.

In unit 1 (PCB assy) they use 4 test machines.

Old HP in-circuit tester (bed of nails) which is good for analogue but not for digital. Bought Genrad tester for digital.

Mars Gazelle for end-to-end testing of PCBs. Not used on new boards because is not supported by Mars any more.

New HP in-circuit and functional tester.

6.5. Other production information:

Appraisal units assembled by production prior to sign-off.

Hand assemble all non surface-mount. Dynapert the SMD (replacing it because the machine is 3 years old and cannot handle the smallest components used now. Capacitors now use 0402 (in mm) size).

Also use hybrids for high packing density (they have two standard card frames and all products must fit these thus great pressure on packing density).

90% auto, 10% manual.

Volume: ~1,000/week of 20 - 30 different circuit boards.

In re: quality control they have a resident Taguchi expert (George Bandurek). Parts approval is done by committee.

Process design goes hand-in-hand with with product design. Sometimes it occurs in advance of any product development process, as in the circumstances surrounding their introduction of Surface Mount.

Runners, repeaters, strangers:

Runners (base prods) controlled using CFM/MRP.

Repeaters (specials) comprise single numbers for a customer, manufactured in main area, pushed across to "specials dept." who customise it. Numbers are very small so controlled by manager, materials controlled by MRP because materials change is low.

Strangers (1/2 per year), once they go to numeric issue status they are controlled by CFM/MRP. before that it's a gray area. May not purchase from BOM. Materials etc managed by production engineering. Something may be a stranger because it's an obsolete product -- still in demand but elderly. It will be managed by someone who will drive it on an individual basis.

In re: the 818 model, even when it's replacement is being produced, they will still be producing 300 818s a week.

The concern is not so much how to control strangers, but how to control the move from strangers to repeaters to runners.

Have problems with production yield. If yield is low they can't drive production under CFM.

7. INFORMATION

7.1. Product:

7.1.1. Storage: (Incl. staff turnover & problems)

50 engineers with 10% – 15% turnover/year.

7.1.2. Presentation:

7.1.3. Policy:

MD is very keen on measurements. Have a monthly management review meeting in which managers produce their measurements. Visibility of these measurements has changed company culture but getting production lines to own the measurements has taken time.

Measurements include vandor rating system, overall reject rate of all batches (up or down).

Other examples include:

Measure	1986	1990
No of different components	80	500
No placements/year	2m	15m
No component types	3	20
No different PCBs	13	60
No diff placement progs	16	110
Typical batch size (panels)	50	5
Typical PCB qtys	100- 500 p/week	1 p/month -1000p/week

7.2. Procedures:

7.2.1. Storage:

On paper in file.

7.2.2. Presentation:

Boxed diagrams + written procedures.

7.2.3. Policy:

Adherence to BS5750

7.2.4. Inter-person communication:

Stick-its (3M).

7.3. Manufacturing:

Stored on (Wang) computer. System is fairly flexible.

Have problem with transactions of components out of stores when there is a shortage due to incorrect BOM. Now only one person can record them out.

No good handle on scrap usage.

Information is captured from the shop floor but instead of kitting and downdating from stores, they want to pull material from stores and downdate when the product is shipped. They know from the product code what materials were used.

Instead of recording WIP they record RIP (raw in progress) which includes floor stock + stock in stores. Easier from an accounting p.o.v.

No use of bar codes for WIP tracking purposes.

In process of installing Ethernet. Have a star network with all PCs and terminals hooked to central Wang but not from PC/terminal to PC/terminal.

Visula postprocess is downloaded to floppy for part programs for SMT placement equipment. When Ethernet is installed they will be able to download directly.

7.4. Test:

Record numbers of failures in test. Paper logging system which allows them to guage where they have a test limits problem i.e. failues occurring in resistors and/or capacitors failing when they are good. The logging system gives print- outs of test results, distributions etc.

8. CUSTOMER RELATIONSHIPS

8.1. Specification engineering: (Well constrained/wandering goal-posts)

No information.

8.2. Level of contact:

8.2.1. Joint development/design:

8.2.2. Problems:

9. SUPPLIER RELATIONSHIPS

9.1. Level of contact:

Need to create an environment in the company whereby people who don't usually relate to suppliers get an opportunity to do so (i.e. technical --> technical, quality --> quality).

Many suppliers relate to customer by having a salesman holding all aspects of the relationship on his own. This is a filtering operation and the company has had to tell a number of its suppliers they don't want to see any more salesmen.

CE and suppliers: e.g. membrane switch supplier. In the case of two products (818 and 900 series) they could not have designed and achieved what they have in isolation from the supplier's own development program.

Confidentiality is not perceived as a problem though they may ask supplier to sign confidentiality agreement.

Right person from supplier company will be brough on board almost as soon as pen is put to paper in design of new component. But, if they are dealing with a known mechanical part, no supplier involvement is required at all.

Their next generation instrument enclosure was designed with suppliers being brought on board at concept stage.

9.2. Quality issues:

Need to create an environment in the company whereby people who don't usually relate to suppliers get an opportunity to do so (i.e. technical --> technical, quality --> quality).

9.3. Policy Issues

Biggest issue is too many suppliers. Currently 250. But to put the right level of involvement into each in re: commercial, technical, quality etc they need to have half that number.

Have a program for reducing supplier base. Look at a) degree of duplication in supplier base, b) how closely technical capability matches current/future requirements, c) how well the supplier is on a route to quality ship-to-stock programs, d) ability of supplier to see company as a partner rather than as an advewrsary.

Have subdivided supplier base into 4 groupings:

a. Class 1: technologically and commercially ahead of company i.e. their technology = greater than company's need and no quality education needed

b. Class 2: all of class 1 but company has to educate in some way

c. Class 3: neutral, sitting waiting to be raised up in classification, potentially good

d. Class 4: on the way out

Have removed a number of suppliers in past few months.

Company is moving to broader contacts between itself and its suppliers. In this situation, where knowledge of contractual relationship exists, you have to make intentions much clearer. They are currently drafting a new supplier agreement.

EDI links to suppliers is not really feasible because supplier marketplace is quite unsophisticated. They don't see their customer base talking to them electronically, but several suppliers have had to initiate EDI links with their suppliers. Would like to have it, but can't see it happening within 18 months.

Do have modem links to PCB supplier. Gerber format so it's just a case of transmitting an ASCII file over the phone line. The supplier has imported the company's design and quality rules into his CAD system.

9.4. Other:

All custom components are designed by company. Standard components tend to be very stable. All mechanical parts specifically design for the company.

Their use of kanban, CFM, manufacturing leadtime reduction program has led them to demand more responsiveness from suppliers. Have had to encourage some class 1 suppliers to reduce their lead times. Aim is to increase service level to customers.

In the case of one supplier, they are offering a 50% reduction in time taken to turn around a company-designed component. This has had a dramatic effect on company's lead times.

10. CONFIGURATION MANAGEMENT

10.1. Techniques:

Configure standard product with s/ware specific to customer.

10.2. Problems:

Wish to also configure by reduced component count on customer boards where possible. Loking into this at present.

11. TOOLS: (Usage/problems/support)

11.1. In-house:

Clive Latimer (ex-Mars Electronics) has a matrix scheme for hierarchical analysis of business. Refer to paper entitled "Purpose, Functionality, Structure and Process" (January 1990) for details.

Developing a CIM tool using Unix-386 + OOP graphics for cell control. Under test at customer site. Will be employed in- house when debugged.

PLATE 1 and 2 for complete test of assembled product. There are 7 PLATE systems in use in the UK and 1 in the US.

11.2. Bought in:

Racal Redac for PCB design. Too expensive for panellisation software so they hacked their own. But you have to be very careful as mistakes can be made due to this.

Mars Gazelle for functional test.

COMMERCIAL IN CONFIDENCE

Not to be disclosed without prior permission
from Prof. David Hughes,
Centre for World Class Manufacturing
Polytechnic South West (Plymouth).

ELECTRONICS DESIGNERS TOOLBOX PROJECT

COMPANY 15

Document reference number: EDT/ORG/015

Document issue number: 002

Date of issue: August 31, 1990

Prepared by: Phil Culverhouse and Jan Bennett

1. COMPANY PROFILE

1.1. Type of business:

Automotive electronics. Main customers: Rolls Royce, Opel, BMW etc

1.2. Major product types:

a. **Engine management, power train and chassis control** (ignition control systems, automatic four-wheel drives, automatically controlled differential-lock systems, electronic transmission control)

b. **Car body electronics** (airbag diagnostic and control systems, IR locking systems, trip computers, vehicle conditioning monitoring systems, traffic information systems)

Manufacture 450 products (5 years ago started with 0). This year they started with ABS and Engine management systems.

1.3. Personnel:

1.3.1. Administration:

1.3.2. Design:

240 design engineers.

CAD support group: 17/18 people. 3 in Electronics design, 1 in mechanical design

Development depts have 180 electronics/software engineers, 40 mechanical engineers

Including 1 for system management, 2 for documentation, 9 for prototyping facility

Most design engineers hired in '87/88. Some hired in '83, so some experience in depth. But young engineers aren't being trained to relate to customers, to be aware of costs.

Almost no design staff turnover. Lost 2 out of 240 last year.

1.3.3. Production:

1.3.4. Test:

1.4. Turnover:

£ 178 million; 30% sales increase over previous year (1989 over 1988?)

1.5. Competitive dimensions: (Cost, quality, reliability)

Low cost, superior quality. Difficult to reconcile these two objectives.

Quality, price. Former is a prerequisite, latter provides competitive edge. Recently won a 6 year Opel contract for £ 180 million by assuring customer that prices would be cut each year.

1.6. Level of competition:

Fierce

1.7. Main competitors:

Bosch, NipponDenso, Delco

1.8. Types of computer support tools: (Design & manufacture)

Figure 1. illustrates Organisation 15s current design software usage. It also highlights significant gaps in their design/simulation capabilities.

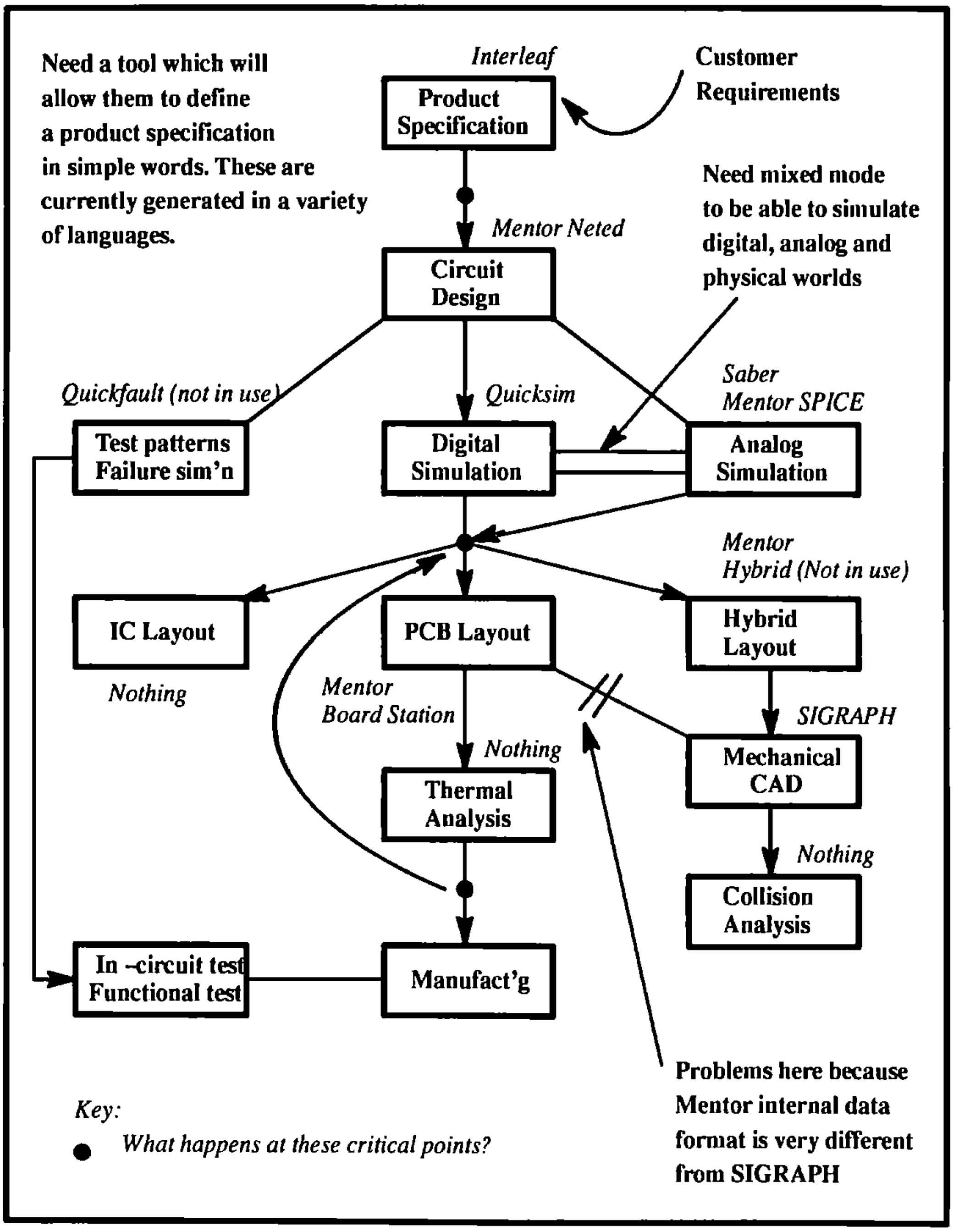


Figure 1. Organisation 15 computer-based support tools

Evaluated Racal Visula, Daisy before choosing Mentor. ZPL might have advised them that other parts of the organisation were using Mentor . .

CST investment intentions:

By 1994 plan to have 90 workstations. 50 for electronics design, 40 for mechanical.

1.1. Successes and failures in product introduction:

1.1.1. Electronics design:

See above

6 Workstations, 7 more on order from Mentor.

1.1.2. Mechanical design:

See above

14 Apollo workstations running in house SIGRAPH system

1.1.3. Manufacture:

See above

1.2. New designs/period:

New designs: 15 – 20 p.a.

Redesigns: 2 p.a.

Changes due to design faults: 10 – 15 p.a. (89% flagged by customers).

17 new product functions in 1987; 15 – 20 in 1990

Product lifecycle: 1.5 – 3 years

Manufacture 450 products (5 years ago started with 0). This year they started with ABS and Engine management systems. Rapid new product development.

1.3. Production volumes/year:

Low volumes on each of a very wide range of products.

2. STRATEGY

2.1. Overall company strategy:

In next 5 years achieve sales of £360 million. Continue high levels of service to customer.

2.2. Position of design within strategy:

Design viewed as strategic but only as one of a portfoilio of strategic activities. 80% of product costs determined at design stage.

Other strategic aspects:

a. Logistics-oriented decentralisation; market orientation, JIT, top-down planning

b. Product lines responsible for assembly, test and repair

c. Team spirit; short decision loops

d. Highly qualified staff; emphasis on training

e. Success-oriented control

f. Customer-related activity

Not appreciated at higher management levels how essential computer-based support tools are. Design is seen as strategic but, at the same time, management questions the need for the expensive Mentor workstations. Why not continue with PCs? No lobby at higher levels.

Designers are kept aware of potential impact of product on company's fortunes by the PMT mechanism. They have close interaction with customers during the product development process so all design engineers are very aware of the cost implications of what they are doing.

Product success defined as satisfaction of customer requirements to the required level of quality and to the right price.

2.3. Product market share:

No information on this.

3. MANAGEMENT PROCEDURES

3.1. Design review procedure: (Concept to prod.)

Figure 2. illustrates the Organisation 15 product development procedure. The process starts approx 2 years before the first product hits the market.

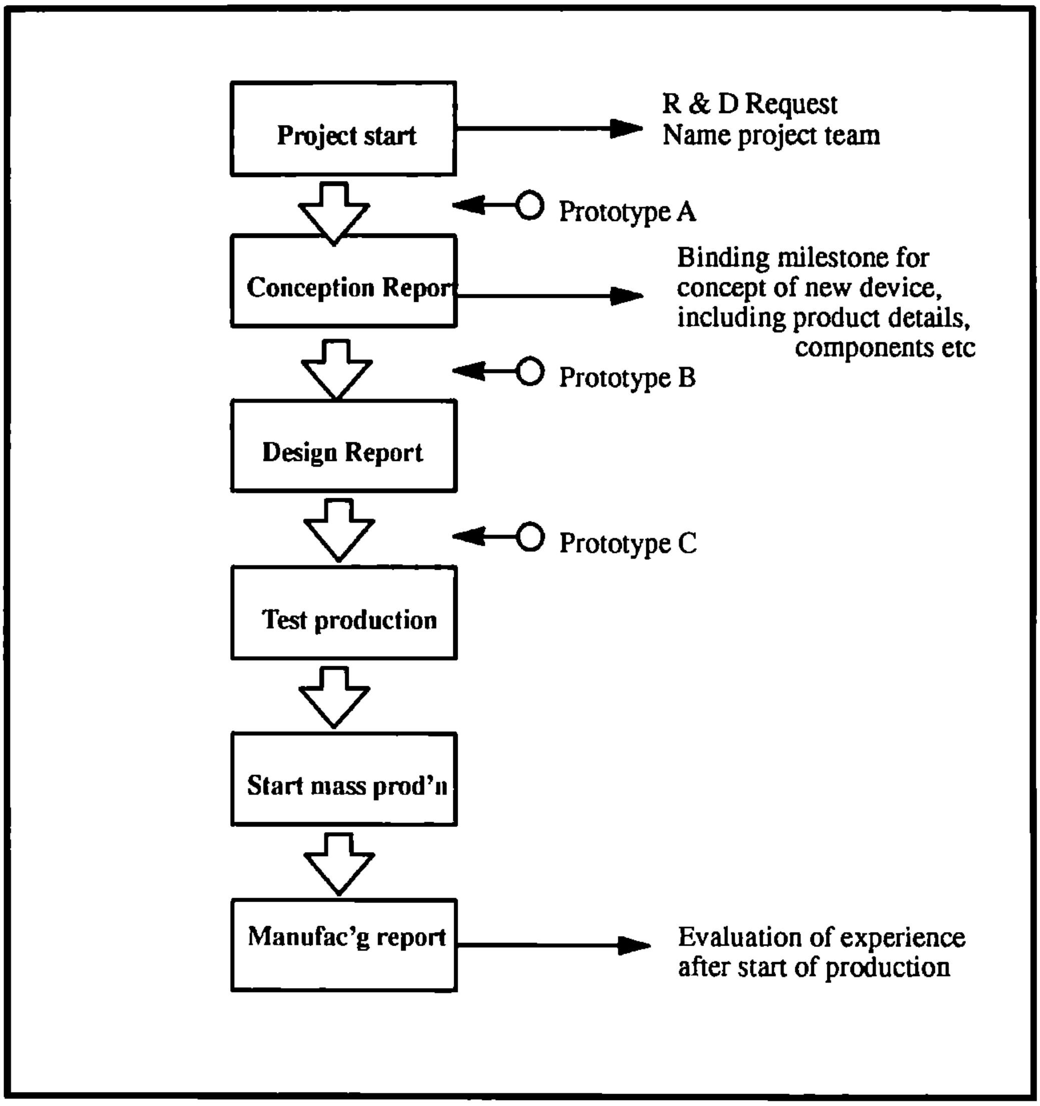


Figure 2. Organisation 15 product development procedure

3.1.1. Description of signoff stages: (Incl. adherence)

a. IDEA

b. spec (just an interleaf published document)

c. concept

d. prototype

e. test

f. redesign

g. series development

h. in car test

i. release

3.1.2. Problem areas/iterations:

Projects are managed using project management methods, but although they have computer-based tools for PM, they aren't used.

customer request -> product specification is not rigorous, just an Interleaf document, but not checked for consistency in any formal way. The function will be explained in simple ords and diagrams. But there is a mapping problem in getting from this to a microprocessor, signal conditioning and watchdog timers, RAM and ROM, in Peter Bahns opinion.

3.1.3. Standards adhered to:

Motor industry standards. BMW standards, Porsche standards, German industrial standards. Some customers use Mil standards, but they don't follow suit.

Standards to be followed are defined in the spec.

3.2. Simultaneous engineering: (Yes/no & degree of success)

Recognise need for CE approach, but although management tried to give the impression they were succeeding hands down, there were still problems. Successful? Probably.

"Not possible" for an engineer to design a product which can't be manufactured.

Hold meetings every two weeks with customers to assess progress of development, but customer is not included in New Product Team (NPT).

NPT can theoretically by-pass procedures, but hasn't happened over last 4 years. Early on in development process, the team meets monthly. Meetings become more frequent later on.

In re. deadline slippage, they usually only experience a one or two week delay depending on the product, the customer and the characteristics of the designer.

They check deadlines every 4 weeks with complete top management.

Same product development team sees product through entire lifecycle. Same team looks after same product family.

Production engineering first.

3.3. Engineering Change Control:

Paper-based but developed in 1979. Out of date. CAD support group charged with re-evaluating configuration management and ECC and with automating it where possible.

Change note peak in first 6 months of product release, mainly due to customer requests for changes.

4. NEW TECHNOLOGIES/MATERIALS

Any new technologies are evaluated, then given to the factory for the process engineers to take on board.

Not looking at 3D hybrids at the moment because of cust and because customers aren't asking for them.

Designers/production engineers kept in touch with advances in materials/process technologies via ZPL (Corporate Production and Logistics) central service. ZPL objectives include know-how transfer, multiple use of technologies, increasing flexibility, synergy across Group divisions. Changing from corporate funded to project funded structure.

Products don't incorporate a lot of new materials/technologies.

ZPL 1: Production

850 people

Technologies and materials (Dr. Eduard Lenz); Electronics Packaging (Wolfhard Frey); Integrated Manufacturing Systems (Dietrich Hoh); Parts Manufacturing; Integrated Production Methods; Engineering Design Methods (Gunther Zintl); Environmental Protection and Technical Safety

ZPL 2: Logistics

Central Logistics; Central Purchasing; Central Information Systems;

ZPL 3 etc

5. DESIGN METHODOLOGY (Engineering practice between sign-off)

5.1. IDEF0 validation: (Comments/diagram)

5.1.1. Diagram identifiers:

5.1.2. Comments:

5.2. System:

5.3. Hardware:

Product design sequence:

a. project start ---> R&D request (2-4 years prior to product)

b. Concept report --> prototype A

c. Design report --> prototype B

d. Test production report --> prototype C

e. Start of mass proudction --> manufacturing report.

This last report is and evaluation of experiences and discharge of project teams' responsibility. **This report is fed back to R&D, some examples are used in training** (possibliy those bits that went well and those that failed?)

Designers restricted to approved list of components. Can't use any they like.

Hold meetings every two weeks with customers to assess progress of development, but customer is not included in New Product Team (NPT).

NPT can theoretically by-pass procedures, but hasn't happened over last 4 years. Early on in development process, the team meets monthly. Meetings become more frequent later on.

In re. deadline slippage, they usually only experience a one or two week delay depending on the product, the customer and the characteristics of the designer.

They check deadlines every 4 weeks with complete top management.

For hybrids, the design and layout is done in-house, the fabrication (substrate and thin-film is contracted out to two suppliers. Other component assembly, laer trim and test is performed in-house again (the wire bonds are physically pulled on samples from each batch).

5.4. Software:

Have problems in the software engineering area. No definitions of interfaces, procedures etc.

Final product configuration is mainly software, although can be partial population of PCBs. They do ensure (proof??) that designers are aware of the impact of this assemlby issue through the PMT structure and a company design rules book.

On the Airbag project a designer within a PMT is responsible for laising with production (*** this signals they do not actually practice concurrent engineering!!!). He/she will have statistics of the assembly process and burn-in monitoring to ensure performance of each individual product.

5.5. Problems:

ECN - on paper, they clammed up when we tried to raied the issues and problems. We heard from Peter Bahn that they had real problems with ECN at present.

Most engineers have one years experience, usually striaght from university. Bahn reckons it takes two to three years to gain enough experience to become useful.

In 1983/84 they got the kernal of their staff, they have full complement in design now, and recuitment will slow down.

A COMPLAINT: Young engineers have no knowledge of **WHAT WE CAN MAKE**, yet they have to handle customers, project management and costings.

An Observation by Peter Bahn:

Young engineers have very limited knowledge, they are poor problem solvers (they have no manufacturing knowledge). In software engineering, there are no concrete DO's and DON'Ts. Organisation 15 only programs in assembler (??? is this corrrect), they don't define interfaces well and their data input/output techniques are poor.

Problems in manufacturing:

The 'A'model is released to production to get problems sorted out, but only good if MENTOR procedures are adhered to. For example: in 1989 a hybrid was designed, the schematic engineer was allowed to make changes to design during the layout phase of the work even in the last few hours upto Gerber output was prepared. Therefore require better engineer discpline..... I am not so sure, the whole point is that the design WAS successful (I presume) and it is credit to the system that it was possible to do this.!!!!!!!

6. MANUFACTURING METHODOLOGY

6.1. IDEF0 validation: (Comments/diagram)

6.1.1. Diagram identifiers:

6.1.2. Comments:

6.2. Shopfloor practice: (JIT/MRP etc)

Production engineering is charged with **evaluating manufacturing machinery early on to assess spread of operating tolerances** (this is cometimes required by customers).

JIT (not fully); logistics principles

But, not delivering directly to production lines. Must go through goods inwards. Statistical inspection (AQL).

Don't have sufficient confidence in supplier quality since volumes aren't there.

Autoinsertion uses cell-based approach. ABS production is line-based. Airbag system assembly is line-based.

Use cells and lines.

Use "A", "B", "C" model approach. "C" is produced as near production standard as possible, but still on separate lins.

Some simulation done to design processes.

6.3. Production test: (What they do)

Figure 3. illustrates the airbag system board assembly and test process. Airbag electronics are 80% diagnostics, 20% crash analysis.

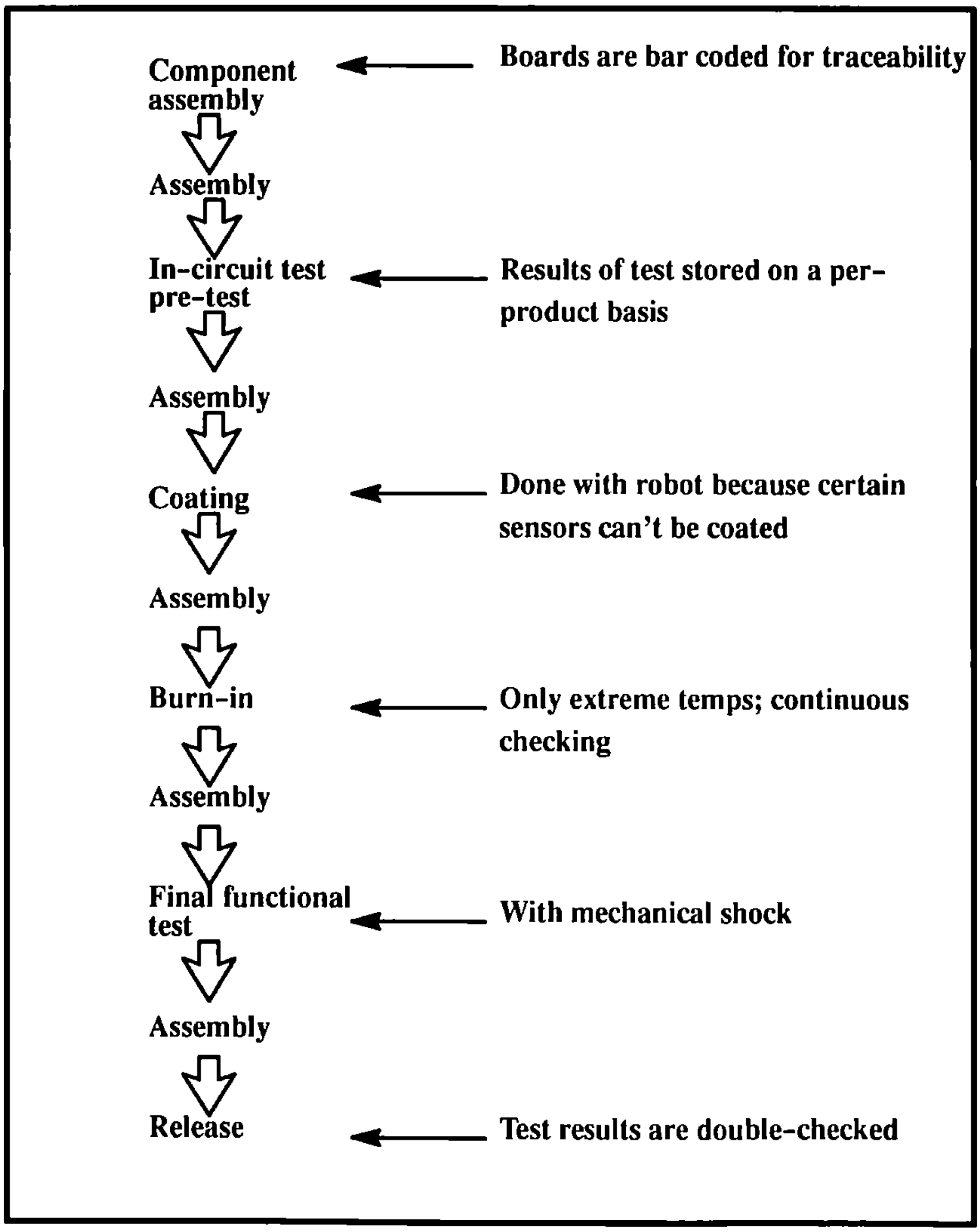


Figure 3. Airbag system board assembly and test process

6.4. Production technology used:

Manufacturing technologies:

a. PCB: SMD, solder paste screen printing, valour phase (mostly) and IR soldering. VP is better than IR because in IR the temperature depends on the mass of the components. Soldering line uses nitrogen atmosphere, so uses less solder because better oxidisation. This means less fluxer is required so they don't have to wash with CFCs.

At the end off the solder line they have 100% manual inspection. If there are problems, the operators can tell line supervisor and line can be stopped (if serious).

b. Hybrid: ceramic substrates

c. Montreal Accord and CFCs. Have a group in Organisation 15 looking at how to avoid washing PCBs. Water is no good for Organisation 15's products because they have relays on board.

d. Fuji machine for assembly of leaded components. Sequence of production process on this machine is not decided by designers. Must be programmed by a programmer using a Fuji-supplied piece of software on the machine.

e. Boards are checked for tolerance using a vision system (mask comparison, simple subtraction)

f. Conformance coating (not for all boards).

SMD production line is run by 1 person. Capacity of 5000 units/hour. Cost £390,000.

70% SMD now. In 1 year they will up that figure to 90%. Remainder will comprise manual insertion of oddly shaped components where costs would be too high to automatically insert.

All PCBs are a standard size. Pads are oval shaped and are specified as such in design rules. Only use multi-layer boards for ABS, otherwise single or double sided.

6.5. Other production information:

On the way to CIM but want to keep people in the production loop to provide flexibility. Don't want an integrated material flow line because must have people to take responsibility for products.

Often faced with capacity problems as customer demands force them to ramp up production from ~8,000 p.m. to ~70,000 p.m. or from 120,000 to 200,000.

A future project is to improve traceability. Air bag system boards carry a bar code. But other products are still tracked by batch.

Use separate prototype lines. These are similar to proper line. "C" prototypes have to be made in as close to the final production environment as possible.

At "A" prototype stage they make a design/layout which is checked by the technology dept.

"Shadowing is a difficult area to cope with. Hard to make rules. But they have strong recommendations which have been worked out in discussions between technology dept and designers. If in doubt, make studies on the machine.

Airbag system line had to have capacity doubled due to recent legislation in the U.S.

Are able to simulate production flow. Problems with downtime etc are recorded on paper to keep track of failures. Supervisors have terminals on their desks enabling them to input this data.

New equipment reliability is documented by the technology department. Their personnel are available to help production.

For process design they use simulation and build up prototypes.

Use Siemens pick and place machine. ABS line is all Siemens kit (HS180 - capable of 0805). Fuji for SMD, axial and radial components, FUJI software also used for PCB placement sequencing.

No links from CAD/CAE to production but this is planned in 1 year's time.

Very few production problems which can be attributed to design errors because of use of PMTs.

Burn-in is a bottleneck.

Key manufacturing staff turnover is nearly zero because Organisation 15 is a young company. Average age of workforce is 28. Big employee hiring in '82/83.

Automatic warehousing. Need to keep stock because of uncertainty of customer demand.

They have just purchased MENTOR (last year), but they already know they have a component accuracy problem, where MENTOR figures make no allowance for manufacturing tolerances on PCBs. **Problem resolved by bareboard visual inspection of drill hoiles/pad positions on goods inward.**

'A' prototype generated by MENTOR is checked by the technology department. Especially for IR reflow shadowing (I guess they only check for vapour phase problems at present). They don't have enough experience (statistics) to convert these in MENTOR rules that Boardstation could automate.

7. QUALITY

Quality assurance: an in-house developed technique developed to enhance 'ownership' of work quality in a DEMMING like fashion.

Training is given on

a. SPC, EMEA, soldering

b. creative design

c. new technologies

7.1. Quality approach used:

TQM for process and product qualification and for series production (?)

SPC

Efficient QA system provides:

a. High innovation rate

b. Customer orientation

c. State-of-the-art technology

d. Effective control systems (Organisation 15 claims to be good at this)

e. Long-term commitment to approved suppliers

7.2. Quality metrics taken:

They have a strong culture of control through measurements e.g. field failure rates. Strong on analysis as well.

a. **Field service:** returned item analysis. Regarded by Organisation 15 as important. Production manager gets reports about this. On one product = 110 ppm returned items.

b. **Process analysis:** FMEA; fault-tree analysis (Ishikawa); tolerance calculations; process simulation.

c. **Process optimisation:** design of experiments

8. INFORMATION

8.1. Product:

8.1.1. Storage: (Incl. staff turnover & problems)

Test results stored on a per product basis.

The magnetic archiving of design data could mean that, in 10 years time, designs may not be able to be read/used by that generation of Mentor software. So paper-based archiving is thought to be the only one which guarantees that designs can be kept for 20 years.

8.1.2. Presentation:

Test data easily available to anyone who wants it.

8.1.3. Policy:

Figure 4 outline Organisation 15's possible future database approach.

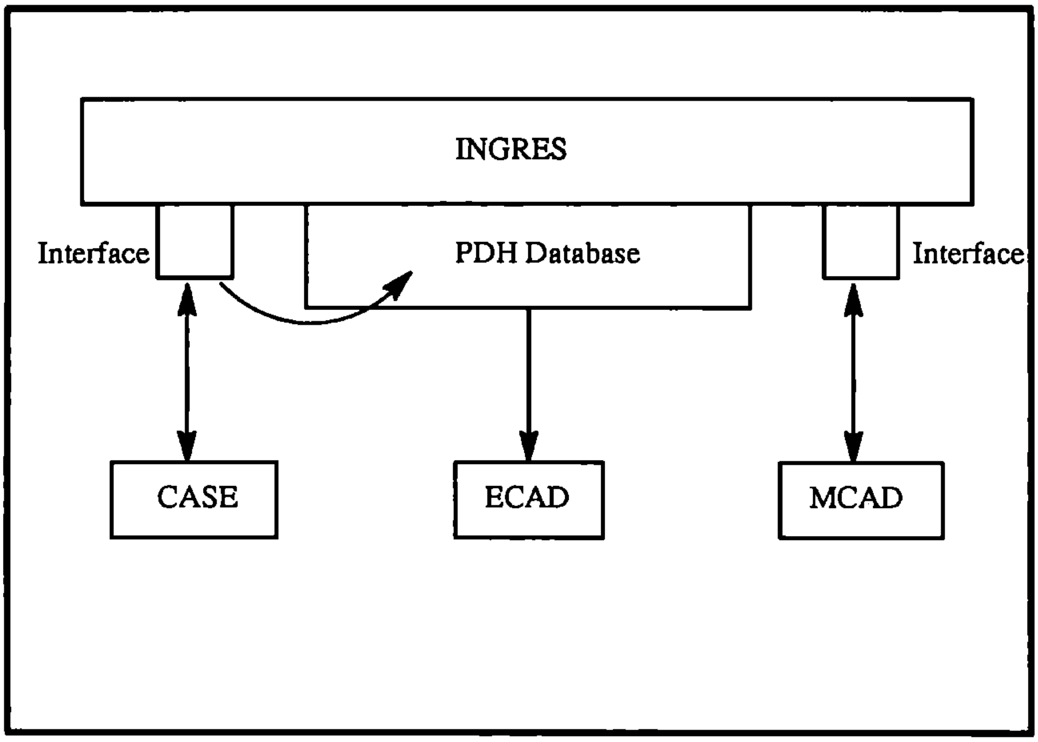


Figure 4: Possible future database approach

8.2. Procedures:

8.2.1. Storage:

8.2.2. Presentation:

In re. formal procedures for feeding back up-to-date user experience information back to the design engineers, PMT mechanism means that engineers have close interaction with customers right through the product lifecycle. This appears to ensure that they get rapid feedback in re. product performance etc.

They measure failures; analyse each returned part.

8.2.3. Policy:

Factory network:

Ethernet in each Organisation 15 building connected up using fibre optic cable.

Also Token Ring network in each building.

Successfully use DEC, Sun, HP, Siemens BS2000 maniframe, 300 PCs on network so have achieved a uniform network for management, production and design information.

Trying to install an Email system based on PCs.

The company is quite new to computers.

9. CUSTOMER RELATIONSHIPS

9.1. Specification engineering: (Well constrained/wandering goal-posts)

9.2. Level of contact:

Close relationships with customers. They inspect production line after production has started.

9.2.1. Joint development/design:

Major problem is cost. They often need to go back to the customer to ask if they **really** need the functionality of the product.

Hold meetings every two weeks with customers to assess progress of development, but customer is not included in New Product Team.

9.2.2. Problems:

10. SUPPLIER RELATIONSHIPS

They distinguish between equipment and parts suppliers.

They are trying to reduce the number of parts suppliers they use.

Trying to shorten the design cycle by including equipment suppliers in overall supplier policy (don't remember details on this).

SMD = on target; test equipment = off target

Suppliers are graded.

Incoming goods inspected.

EDI links in future.

Reduction in supplier base.

Sometimes included in design considerations.

10.1. Level of contact:

10.2. Quality issues:

11. CONFIGURATION MANAGEMENT

11.1. Techniques:

11.2. Problems:

12. TOOLS: (Usage/problems/support)

12.1. In-house:

12.2. Bought in:

Factory network:

a. Ethernet

b. 350 PCs, 7 network servers

c. 25 Apollo workstations on a token ring network

d. 2 Sun workstations for CAD draughting and hybrid layout

e. VAX for storage, quality data

f. Siemens BS2000 mainframe with 100 terminals

g. HP9000 ATE, including in-circuit test

h. Sicomp ATE

i. EDI links to some customers

Had problems with social impact of advanced tool introduction. Moved from PC based Sophisticate system to Mentor workstations. Have had to simplify the Mentor interface for thei engineers.

Other problems anticipated in getting designers to accept the discipline required for effective use of the Mentor software.

CAD Support Group:

They have just purchased MENTOR (last year), but they already know they have a component accuracy problem, where MENTOR figures make no allowance for manufacturing tolerances on PCBs. Problem resolved by bareboard visual inspection of drill hoiles/pad positions on goods inward.

Advises technical and development departments re: CAD/CAE. Provides tools, training and develops libraries.

Use Mentor Version 7/Unix 10.1. Will upgrade to Mentor Version 8 early next year. Problem will be in synchronising software upgrades.

Mentor doesn't have good interface to manufacturing so they are thinking of using some of Organisation 15 (Group) software called STAB for this purpose.

Will order Mentor CASE tools at the end of the year.

Interface between mechanical and electronic worlds is seen as a problem. Looking at IBM's CATIA for 3D modelling and 3D surface models.

Libraries are a serious Mentor failing. Need an overall tool for library generation. Also need tool for documentation management and productionof service user manual.

Not felt necessary to develop and produce their own ICs since it will increasingly be possible to buy ICs on the open market and provide functionality through software.

Recognise need to have component suppliers provide simulation models for their products.

Central service groups (like CAD support) are viewed with suspicion by management because they don't generate sales. Organisation 15 culture.

Organisation 14 central information and service team is mainframe based and appears to be blocking the progress of the CAD team. There is no voice for computers/information at the highest managerial levels in the organisation.

Every time designs are reused, it saves the company £36K on new tooling or £1K on qualifying a new component. Designers should look to see where similar designs have been done in the past. Need institutional memory.

They use SABER for analog simulation, they would like to use mixed mode and allow sotfware simulation and physical functions (mechanical) to be modelled to. They are evaluating QUICKFAULT, but not sure at present.

They have six MENTOR stations (since 1998) and getting seven more soon.

Mechanical CAD is using SIGRAPH (a siemens product - thirteen stations), but some of these are for hybrid layout. They are expecting to acquire HYBRIDSTATION later, to replace some of these.

PCB layout was PC based, but attempting to migrate to MENTOR (obliged to, but time taken to convince middle management and engineers).

Mechanical -> PCB constraints currently only work on PCB profile, component heights will be added later. The problem is that their internal databases are not compatible, they hope IGES 4.0 will solve the problem (wishful thinking?? - no I guess this is an industry must).

SIGRAPH supports 2/3D, solid modelling (CATIA is better according to Peter Bahns), NC tool and flat metal forming.

Most designs are microprocessor based, a few ASICs have been designed (10), but most are contracted out to the Toulouse or other divisions (30/40 designs).

They will be purchasing CASETOOLS from MENTOR, Toulouse already has one station.

Peter Bahn is instituting a programme of work to link the Organisation 15 manufacturing tools to MENTOR.

iA current problem with MENTOR is that each tool has its own library, and effort is required to ensure they link well and contain uptodate information - for example, not every part has a geometry.

They do not have LAI models, and they are not sure of the returns yet.

They would like every IC purchased to have a simulation model (VHDL perhaps)

Still to define CAD milestones and critical paths and so on. Although they have added own checks to NETED written in HLI and PASCAL. They would like on-line checks fo fan-out and the like.

RACAL/VISULA:

Organisation 15 is a RACAL OEM, why did they not choose to use Visula?

a. Poor simulator (Organisation 15 own integrated into Visula system)

b. No common user interface

c. Informix database can be unuseable if tight controls are not adhered to during library creation/update as it is a relational database.

DAISY:

SUN only 386i, they reasoned that logician was not on a stable platform.

Toulouse in 1983 first used CAE2000, then migrated to MENTOR.

Prior to MENTOR, Regensburg had a PC based layout and schematic entry tool called PC Sophisticate, running on Novell network. But no networked library and when library was being edited it was locked from user. Also, package did no on-line checks. They have used this since 1986 and still have eight stations. Still used as standalone tools, but poor version control and security archiving. Also the problems have not been documented (could this be operating problems and bugs?).

MENTOR:

NOTE: Could have a parser that runs over a MENTOR text output when in BOARDSTATION, that automatically generates a report of some kind. Perhaps extracting levels of importance, problems, and poor usage.!!!!!

They have added a set of macros to FABLINK to allow automatic generation of company drawings. These have been added to the menus in FABLINK. Automatically generates layout schematic to internal standards, a parts list, standard referenced parts list (siemens corporate references), and NC drill tapes.

They do not use MENTOR versions, rather they use 'copy tree' as it is more secure.

NOTE: The management is a little afraid of computing technology, there is no direct horizontal link across from design to manufacturing in CAD/CAE. Dr Nessler is the only linkage point.

Kessler and company have no technology knowledge therefore they block technical workstation acquisition, since their viewpoint is from the mainframe central resource angle.

COMMENT by Peter Bahn:

"New and future products cannot be realised without computers, but this is not appreciated by top management. There is still no lobby that ensure the problems are understood. CAD capital investment programme is still regarded as DM200,000 sum wich is not amortised across the products."

It is his task to highlight the differences the PC and MENTOR capabilities.

Future inestment plans are to have 50 MENTOR and 40 SIGRAPH by 1994, amortised over the entire product range, not just funded as an engineering toy.

CONFIDENTIAL

INFORMATION GATHERED DURING VISIT TO TOSHIBA CORPORATION, MARCH 4/5, 1991

Interviews with:

- Dr. Okio Yoshida, Senior Manager, Planning, Technology Planning and Coordination Division
- Mr. Akira Kuwahara, Vice President & General Manager, Technology Planning & Coordination Division

Fig 1: OUTLINE OF TOSHIBA

	Non-consolidated base		Consolidated base
Net sales	$19,373 million		$26,911 million
Employees	70,000		142,000
	Japan	Overseas	
Facilities	25 plants	25 offices	
	12 laboratories	23 plants	*Fiscal year ended March 31, 1990*

- Most Board members have engineering backgrounds.
- Use the Group Executive Technology System (unique to Toshiba in Japan). See Fig. 2 below.

Responsibility of Group and Division Executive, Technology lies in 5 areas:

- R & D
- Product reliability & productivity
- Engineering work efficiency
- Deployment of engineers
- Career development of engineers

The mission of the Corporate Technology Committee is to:

- Plan Corporate R & D strategy
- Allocate Corporate R & D resources
- Manage the Corporate R & D promotion program which includes the Corporate incentive R & D program and the Corporate strategic R & D program
- Coordinate technology transfer
- Promote manufacturing technology
- Protect Toshiba's IPR

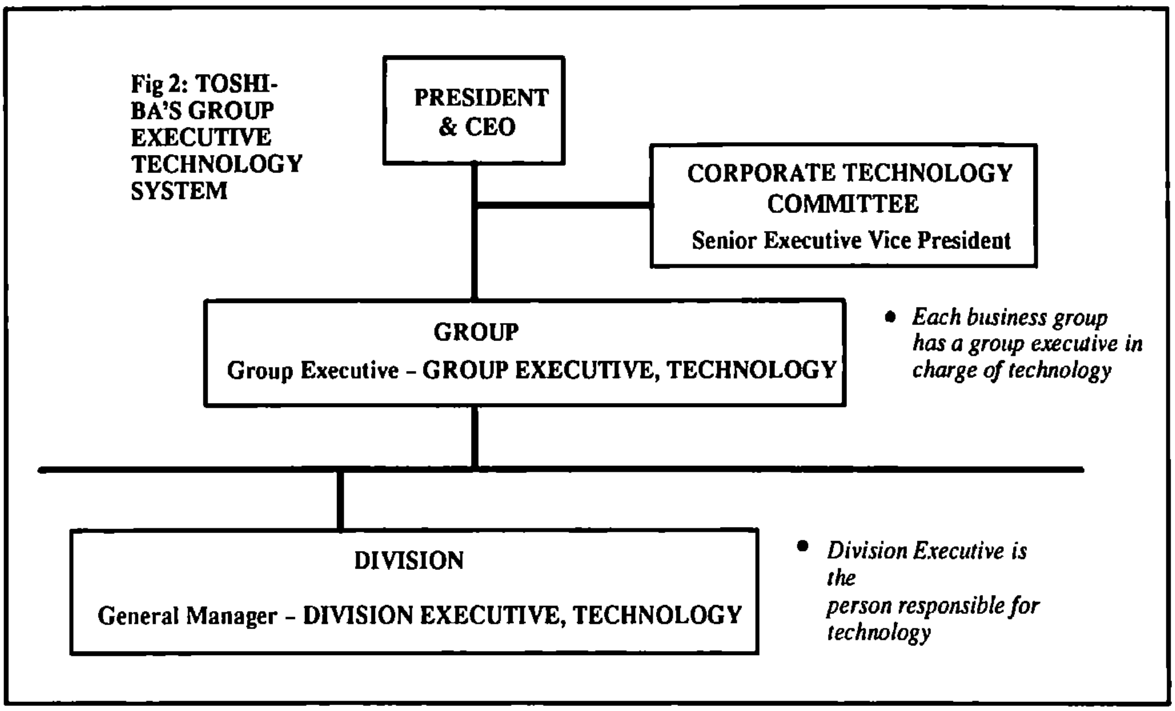


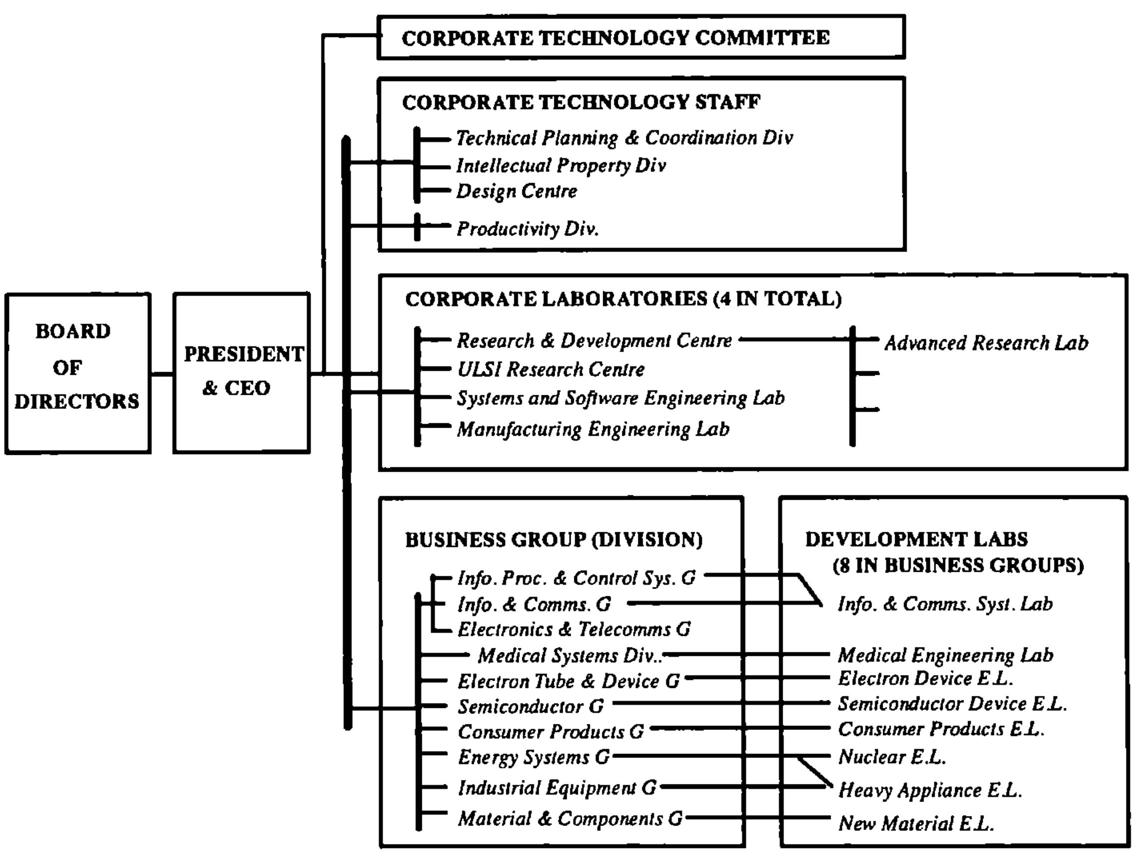
Fig 2: TOSHIBA'S GROUP EXECUTIVE TECHNOLOGY SYSTEM

- From 1980 to 1989 had a strategy to focus on information systems. Known as Project I because it was concerned with information, integration and intelligence (AI to add value to products). Integration issues illustrated by the fact that Toshiba is now selling an air conditioning system using twin fan inverters originally developed in the heavy electronics business.
- Heavy electronics is a fundamental part of their business. Accounted for 22% of Toshiba's business in 1989. Consumer electronic accounted for 22% while Information/Communication Systems & Electronic Devices accounted for 56% of sales in that year. If anything gets the squeeze in the future it will be consumer goods.
- R & D has a three-layer structure: SHORT, MEDIUM, LONG. SHORT & MEDIUM are managed by Group Executive Technology; LONG is managed by corporate R & D labs. SHORT = 1 - 3 years and carried out by operating division. MEDIUM = 3 - 5 years and carried out in development labs, LONG = 5+ years and is carried out in corporate labs.
- Toshiba puts 8.2% of its sales into R & D (£832 million in 1988/1989). 15% of this went into Corporate Fund, 3% went for external contracts and 82% was applied to the operating divisions' funds.
- R & D approach has two tracks: (a) broad goals, (b) stricter planning where areas are considered vital and are chosen to be part of the corporate incentive R & D program.
- R & D people allowed to spend 10% of their time pursuing their own interests.
- Education of engineers also includes education of technology executives themselves. They recently had a 2-day conference for executives/key personnel during which they made a factory tour and discussed issues like "use of computers in factories". They had about 100 attendees. The conference also provided attendees with important opportunities for "jinmyaku" (networking). Toshiba is now selling an air conditioning system using twin fan inverters originally developed in the heavy elec-

tronics business. Air conditioning people benefited from their "pipes" into heavy electronics to transfer the twin fan inverter technology.

- Design, technology and R & D all viewed as strategic activities.
- Emphasis placed on educating, training and nurturing key people.
- Information/learning is regarded as a key issue. Toshiba has an organised approach to learning from mistakes and applying lessons learned.

Fig 3: TOSHIBA R & D ORGANISATION (APRIL 1, 1989)



- Technology transfer by examples. Gathering expertise with own cases. Managers who have been successful in projects transfer the technology. Learn from mistakes made in US.
- Inputs from external information sources. Eg, Rensellaer University professor spent a week in Toshiba teaching/participating in seminars with ~40 young engineers and managers.
- Dave: Toshiba hasn't got anything to learn from the West other than not to repeat mistakes made there.
- Toshiba's external scanning is active and systematic

- 1000 new engineers recruited from top ranked educational institutions every year. Problems with supply because competition for recruits so intense. Now having to recruit from lower rank universities and colleges. Recruits get 3 months initial "socialisation" training followed by ~1 year more intensive technical education. After arrival at factory/lab, recruits are assigned to small teams. Here they undergo further OJT under the supervision of more experienced engineers.
- Failure treated harshly in R & D environment but individuals supported in group setting so as to avoid that situation arising.
- Technology transfer from R & D to plant takes place via people. R & D people spend time (1 - 2 years) in the plant **after** the new technology has proved to be viable.
- When questioned re: conformist approach in Japanese schools and the effect of this on employee creativity, Kuwahara sidestepped the issue.

Fig 4: SCIENTISTS & ENGINEERS (AUGUST 31, 1898)

UNIVERSITY & COLLEGE GRADUATE SCIENTISTS AND ENGINEERS	15,000	21% OF TOTAL EMPLOYEES
DOCTORATE DEGREE HOLDERS	500	
MASTERS DEGREE HOLDERS	4,700	

13% WORK IN CORPORATE LABS

11% WORK IN DEVELOPMENT LABS

76% WORK IN OPERATION DIVISIONS & OTHERS

INFORMATION GATHERED DURING VISIT TO TOSHIBA'S FUCHU PLANT

Interviews with:

- Mr. Toshiyuki Matsushita, Specialist, Engineering Automation Systems Development Group, Engineering Administration & Information Systems Department
- Mr. Tadao Ichilawa, Senior Manager, Engineering Administration and Information Systems Department
- Mr. Tsutomu Sakamoto, Manager, Microelectronics Technology Group, Engineering Administration and Information Systems Department
- Mr. Shuji Tatebe, Specialist, Software Engineering Development Group, Engineering Administration and Information Systems Department

Fig 5: OUTLINE OF TOSHIBA FUCHU WORKS

MAIN PRODUCTS

Information Processing and Control Systems Group
Super minicomputers & super engineering workstations (32 bit)
Next generation integrated control systems and process sensors
CIM and plant automation systems
Water purification and sewage treatment systems
Building & road facilities systems
Distribution & banking systems

Energy Systems Group
Monitoring & control systems for power plants
Control equipment for power plants
New energy and energy saving systems
Automated power supply & distributed systems
Protection equipment for electric power systems
Computer-aided business operation systems for electric power companies

Industrial Equipment Group
Transportation systems (Maglev)
Elevators/escalators
Mechatronics equipment etc

Printed Wiring Board & Module Division
Printed wiring boards
High density hybrid functional circuits

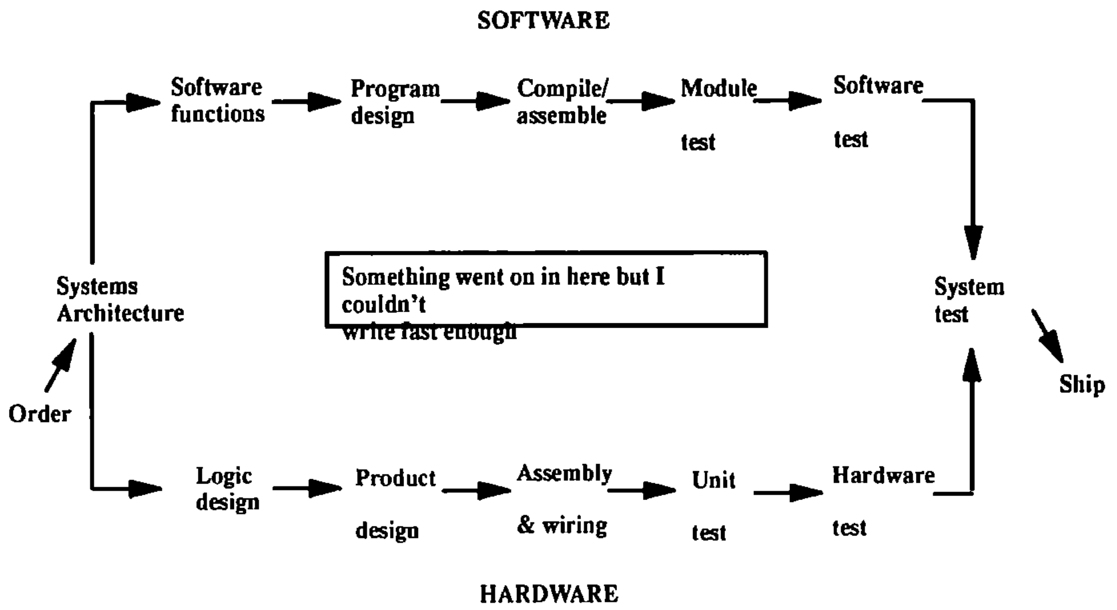
NUMBER OF EMPLOYEES
7,500 total, of which 4,200 are full-time Toshiba engineers
Of the 4,200, 20% develop software for midrange & process control computers, 15% develop microcomputer software, 20% are systems engineers (s/w & h/w) and 20% are hardware engineers. Remainder are in QA.

CONTRIBUTION TO TOSHIBA GROUP SALES **15%**
- **PCB: 5%**
- **Information Processing: 30%**
- **Energy Systems: 25%**
- **Industrial Equipment: 40%**

GROWTH RATE: **(1976 - 1989) 10% p.a.**
(recently) 13% - 15% p.a.

- System Engineering Centre (SEC) is where most software and systems engineers work. Used to be called the Software Factory.
- STEP (Software Technology and Excellent Products) & TP (Total Productivity) movements have recently been combined into the FTP50 (Fuchu Total Productivity 50) movement in commemoration of the 50th anniversary of the Fuchu plant.

Fig 6: TOSHIBA FUCHU PLANT PRODUCT DEVELOPMENT CYCLE



- STEP (Software Technology and Excellent Products) & TP (Total Productivity) movements have recently been combined into the FTP50 (Fuchu Total Productivity 50) movement in commemoration of the 50th anniversary of the Fuchu plant.
- Network: 5 LANS; 400 MHz optical network; 3000 workstations, PCs and midrange PCs connected up.
- 3 levels of computers:
  - Mainframe: NEC
  - Midrange: Toshiba
  - PC (Engineering Workstations, laptop EWS, laptop PCs)
- Use Vmail (Toshiba), Email (not secure enough) and Imail (not directly connected to control system, no updating of databases, only people to people)
- Hardware design environment: 4 levels with each level networked in a distributed environment as shown in Fig 7 below. See also document entitled "Distributed CAD system through hardware design"

Fig 7: CGDP ARCHITECTURE

CORPORATE LEVEL: Mainframe, large/complex simulation e.g. ASIC, FEM for mechanical strutural analysis, document & product management, common database

DEPARTMENT LEVEL: Super-mini computer, engineering documents, ASIC simulation & network gateways

GROUP LEVEL: Midrange computer, ASIC, PCB, mechanical & logic design

PERSONAL LEVEL: IBM compatible PCs, J-3100 series laptops, AS-1000 Sparc laptops

- PCs and laptops used for logic and firmware design
- Organisation to support designers e.g. special department to support PCB design; layout designers support function designers; ASIC Centre supports function designers ("If you want to design a new ASIC first talk to the ASIC Centre")
- Timing analysis, thermal analysis
- 3/4 years ago, stopped prototyping and only did simulation, but at that time simulation cover was limited. Solution was to move to HDLs.
- They have had to develop their own tools. 60% of tools are in-house e.g. language description, behavioural simulation, synthesis, logic simulation. Rest are from commercial vendors.

SOFTWARE

- Software development environment is called New-SWB (New Software Workbench). See paper presented at 30th Anniversary IPSJ Conference, 1990. Develop software systems products for power generator control systems and hybrid systems (realtime, minicomputer, AI, CAD, information processing). Standard parts library for software; management of the design process; "nagashi-ka"
- Have a software production line; don't use formal methods for requirements specification, only design review; final goal is to fully automate this production line, but at the moment, it is only "assisted" by computers.
- Characteristics: Programming-in-the-large & programming-by-the-many
- Learning process: paper based, DDD (data of design defects) documents, gathered from designers, explains causes of defects, phenomena, countermeasures. Plan to automate this as part of F(uchu)-CIM-D(ocument).
- Have tools covering the whole lifecycle of software development.
- Software engineering tools make or buy? Decided to make their own and sell later.
- Carry personal workstations to customer sites.

HARDWARE

- Gate arrays: 30K - 50K gates; developed by logic synthesis; mounted front and back; SMT from 5 - 6 years ago; 8 layer multiwire boards
- 2 - 3 completely new designs per year
- Sparc-LT (compatible with Sun Sparc); 8 mb - 40mb main memory, 200 mb hard disk; shape/aesthetics determined very early; 2000 units/month; 4 workers per line; each step takes 10 minutes so total assembly time is 40 minutes; 30 minutes for test; barcodes for revision status and full traceability
- Concept to first delivery = 2 years but shortening the development lifecycle depends on the market requirement. Eg. if the market is asking for a smaller machine, shorter or longer development cycle depends on the status of the technology. But the pressure is always to shorten the cycle.
- Information feedback from shop floor to design done using a special QC sheet; also takes place during special QC meetings

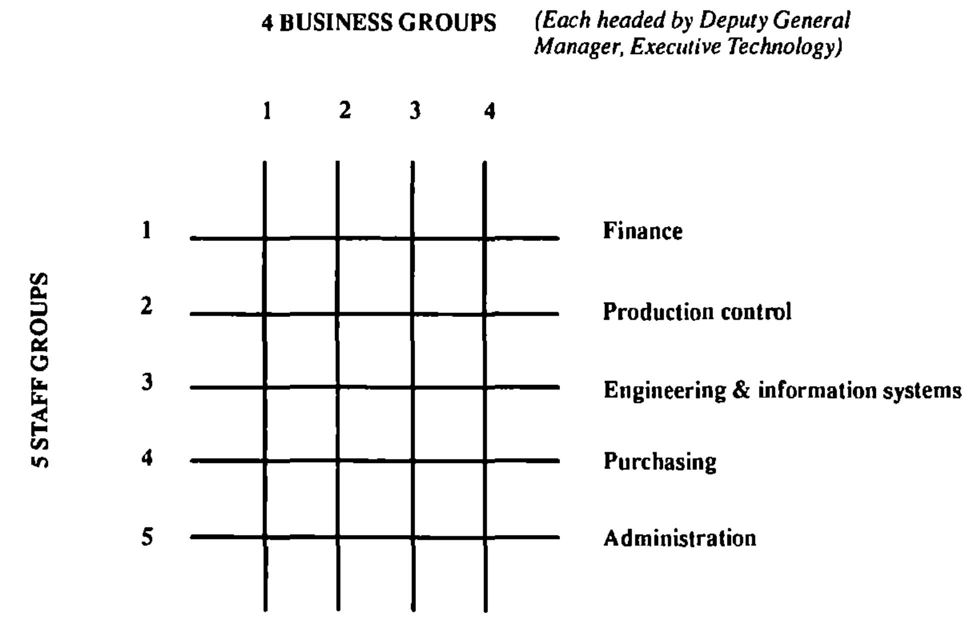
POWER GENERATION CONTROL SYSTEMS

- Factory is 230 metres long
- Nuclear power station control systems take 1.5 years from beginning to end, including 6 months integration test. Products are hand crafted; most use microprocessor technology; integration requires few engineers, but these must be "key" people; more effort up front
- Essentially use same software source code for each control system; different configurations but reused software

STRONG POINTS

- Good communication between various development stages
- Mechanical, functional, electronic & software engineers talk together from an early stage
- After first product is shipped, they have an early stage control where the number of products checked depends on the type of product

FIG 8: FUCHU WORKS MATRIX ORGANISATION



INFORMATION GATHERED DURING VISIT TO TOSHIBA'S OME PLANT

Interviews with:

- Mr. Ginzo Yamazaki, Senior Manager, Engineering Administration & Factory Information Systems Dept.
- Mr. Shinji Nishibe, Senior Manager, ASIC Engineering Dept.
- Mr. Kouji Yoshizaki, Senior Manager, Engineering Productivity Development Centre, Technical Planning & Coordination Division (Head Office)

Fig 9: OUTLINE OF TOSHIBA OME WORKS

MAIN PRODUCTS

Information Processing and Control Systems Group

Distributed Data Processing Computers
(e.g. TP90 which is like IBM AS400)
Minicomputers
LAN Equipment
Packet Switching Units
Data Conversion Units
Small Business Computers
Personal Computers
Word Processors (mostly Japanese WP)
Workstations
OCR equipment
Winchester Disk Drives
Other Computer Peripheral Devices

Software
Package Software: *Integrated software development support systems, accounts management systems, Total production & inventory management systems etc*
Distributing & Banking Systems: *Hotel management systems, Car dealer sales management systems, Mail order systems, Freight tracking systems etc*
Government Systems: *Expressway toll collection systems, Metropolitan expressway traffic control systems, Patent office paperless system etc*
Industrial Systems: *Automatic Warehouse control systems, Office automated building system, Engineering information management system, Worldwide information network system etc*

NUMBER OF EMPLOYEES

3,700 of which 1,400 are engineers, 700 are in manufacturing control, 400 are part time and the rest are contracted in from subsidiaries and from software engineering companies
OME factory has two subsidiaries: Toshiba Computer Engineering Corp. (300 engineers) and

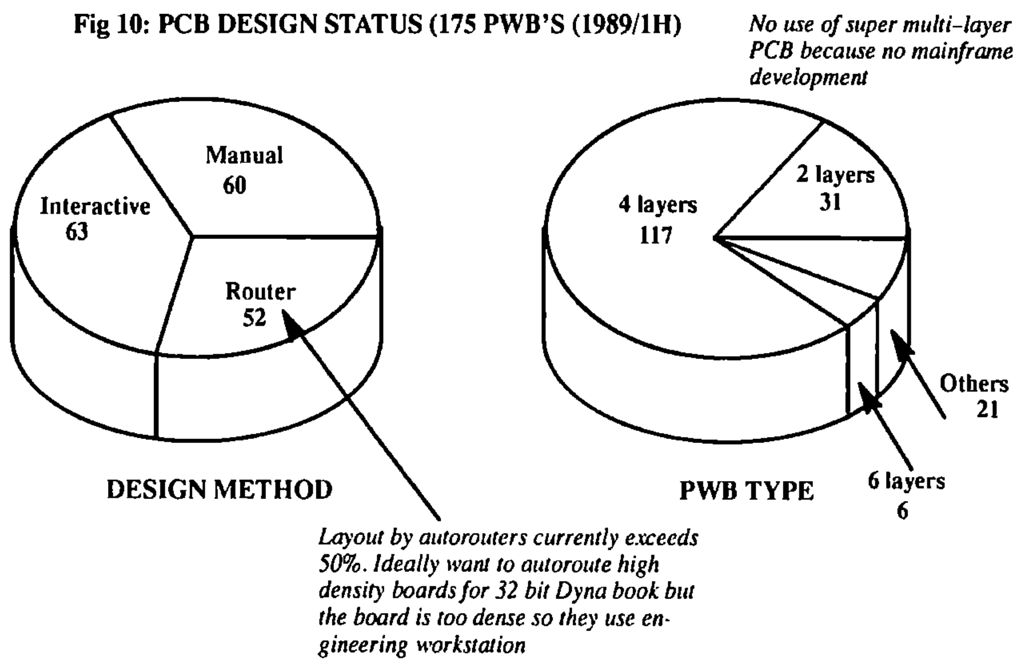
Toshiba Software Engineering Corp. (300 engineers) bringing total employees to ~ 4,300

- Distributed Processing Systems: V-Series, TP-series are both being used to establish CIM (Computer Integrated Management) in Ome works
- Toshiba has largest market share in Japanese wordprocessors

- Laptops use plasma displays (100 mb hard disk, higher speeds) and LCD
- Dyna book A4 size notebook computers. Largest has 1.6 mb main memory expandable up to 8 mb together with 386 processor. Problem is battery power -- only gives 2 hour usage. They are changing the batteries from NICAD to hydrogen NICAD which have 1.5 times the capacity of the normal batteries.
- **Mr. Nishibe, Senior Manager of ASIC Engineering Dept:** Involved in development of Ome work's design automation system. No plans to sell this outside Toshiba. TOP Designer (Toshiba Ome PCB Design Environment & Resources)

TOP DESIGNER

Fig 10: PCB DESIGN STATUS (175 PWB'S (1989/1H)



- They design 400 completely new boards every year.
- System CPU board for midrange computers can be autorouted. 12 layers, 2 CPUs. Continuing to improve autorouters.

Fig 11: PCB DESIGN PROCESS

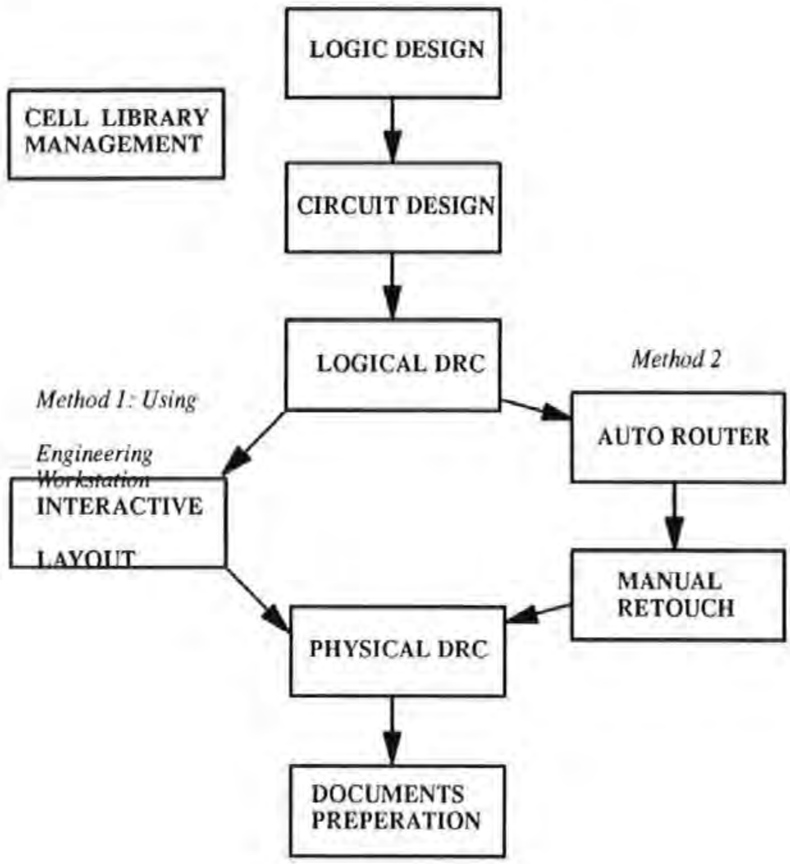
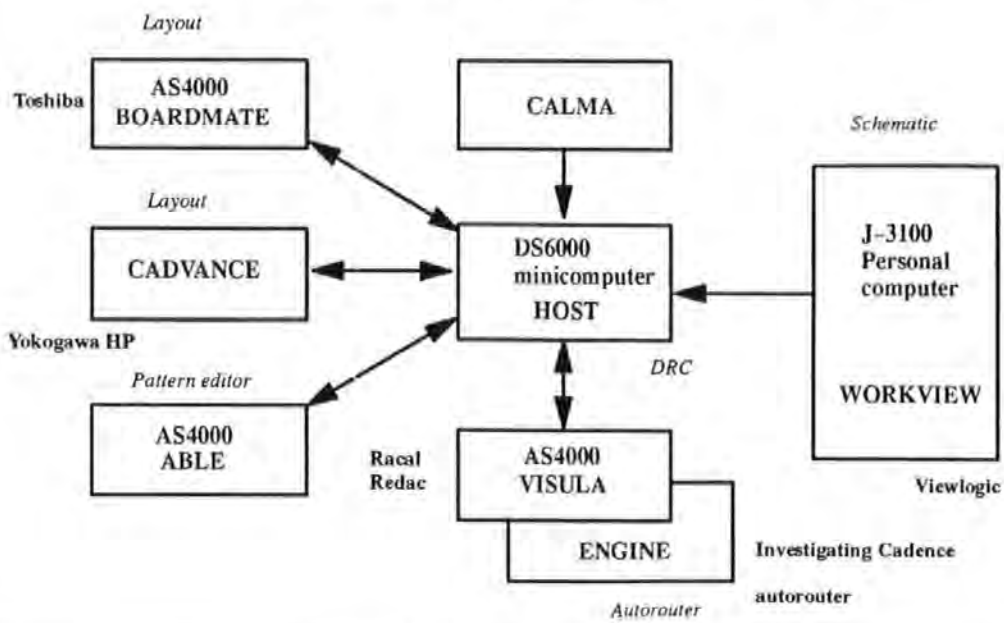
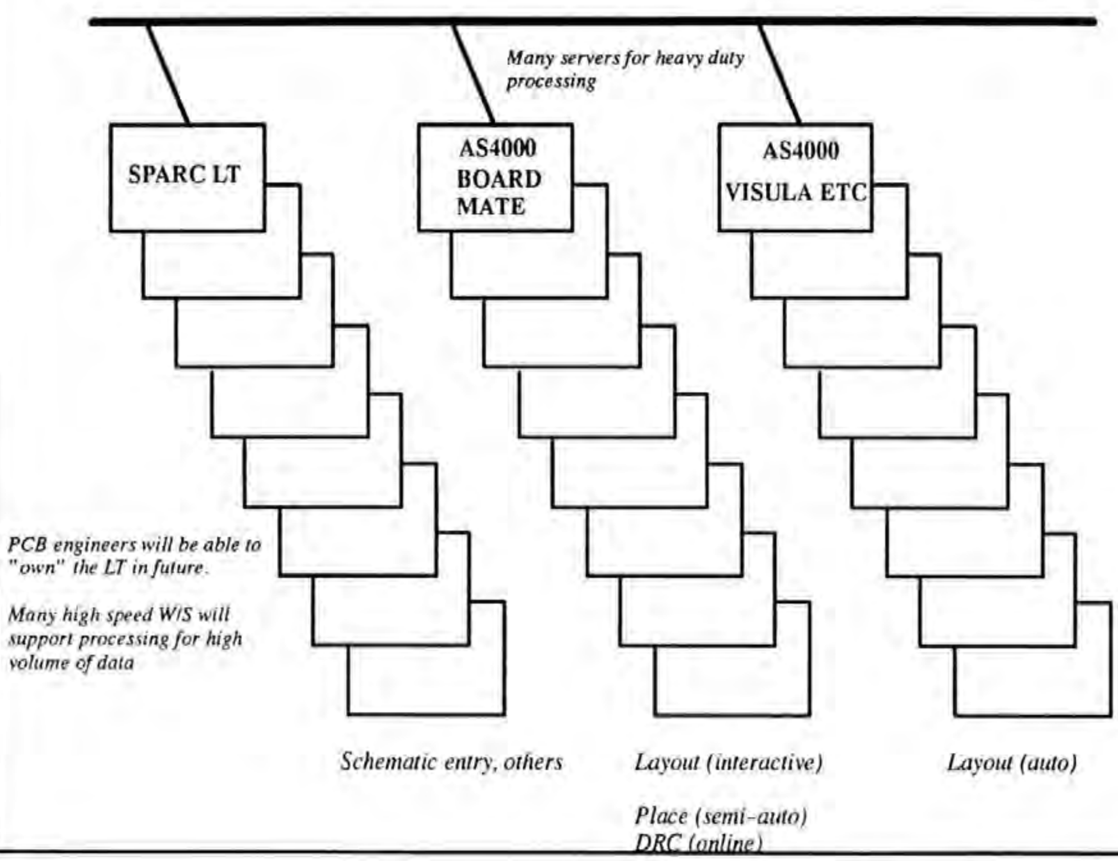


Fig 12: TOP DESIGNER SYSTEM ARCHITECTURE



- Turnaround time for current TOP Designer is too long because operator has to transfer data from one computer to another. Hence they want to realise the following distributed and integrated system:

Fig 13: TOP DESIGNER II



LOGIC DESIGN SYSTEM: (See Toshiba document "Logic Design System (Tools)")

- **Interface languages:** Toshiba has specific interface language. Don't use EDIF, international standards. Commercial tool products very expensive.
- **ASIC Design Flow:** Engineers design midrange computers like to use functional design method e.g. functional description language, functional schematic entry
- **Network:** ASIC designers prepare spec, do logic entry, function entry, test data entry on their LT workstations. Everything is done on their computers.
- Simulation accelerator is attached to VAX9000
- Zycad for logic simulation
- All engineers can access VAX9000 & Semiconductor Group host computer

- **PCVIEW System:** Many engineers in personal computer engineering don't like to use functional design method because PC logic circuits are almost the same in all kinds of computers so schematic entry is important.
- All computer engineers use LT workstations.
- **JCAD (1988 - 1991):** Toshiba is developing its own new CAD environment. Scheduled for completion in March 1992.
- Logic synthesis: 100K gate logic in a few hours. Design compiled using Synopsis software is unable to generate large volumes of logic at high speed
- Functional simulation accelerator: JFAL Accelerator. They want to develop small size (1 board) functional simulator for JFAL
- System Simulator: Use Zycad evaluator as simulation engine. 1.5 million gates therefore can simulate multiprocessor system of next computer at logic level
- JSET (Functional Schematic Entry System): Uses functional block symbols to input data
- FALCON (Logic Synthesis): Generates logic from FSET and JSET. Performance = 4 hours for 100K gates (AS4260C)
- JSIM (Multi-chip Simulation Architecture)

Fig 14: EXAMPLE OF DESIGN FLOW IN REAL LSI DESIGN WORKS

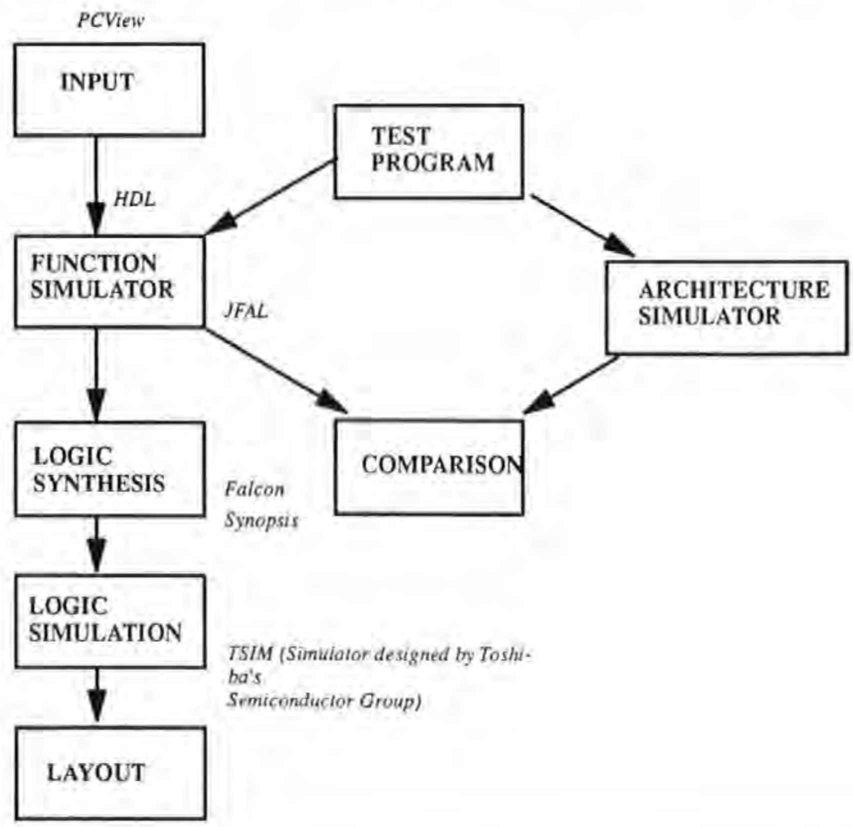


Fig 15: NEXT GENERATION CAD SYSTEM (SUPER-JCAD)

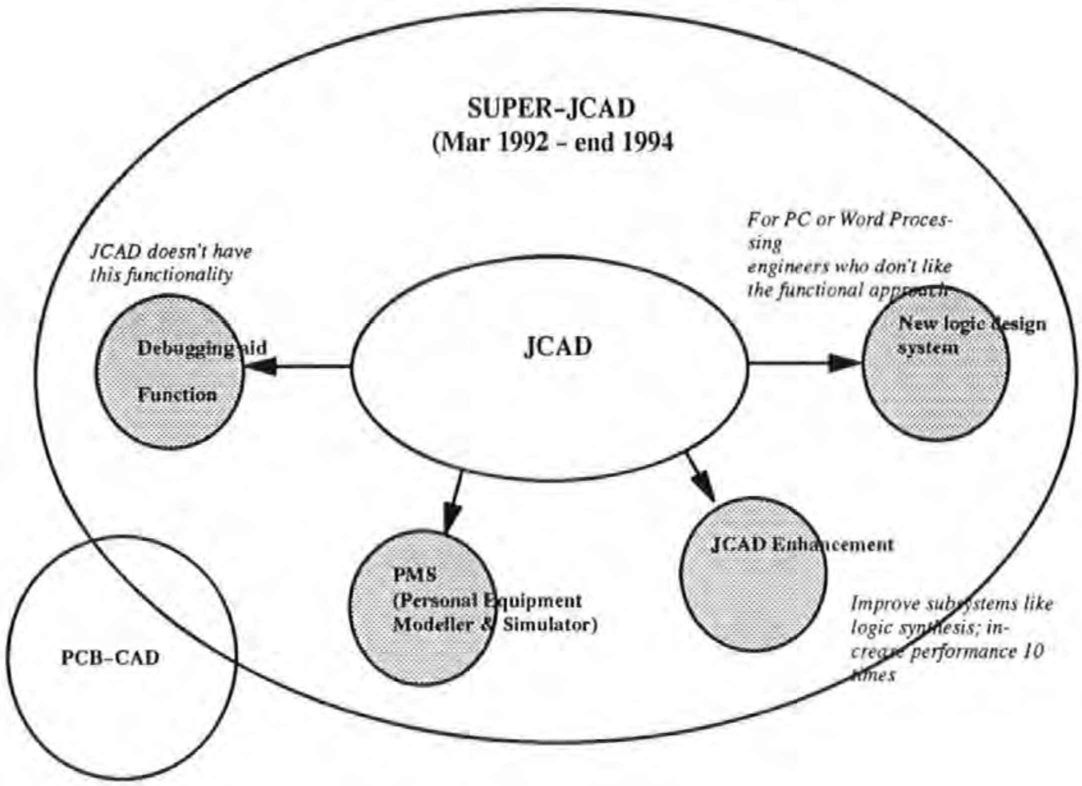
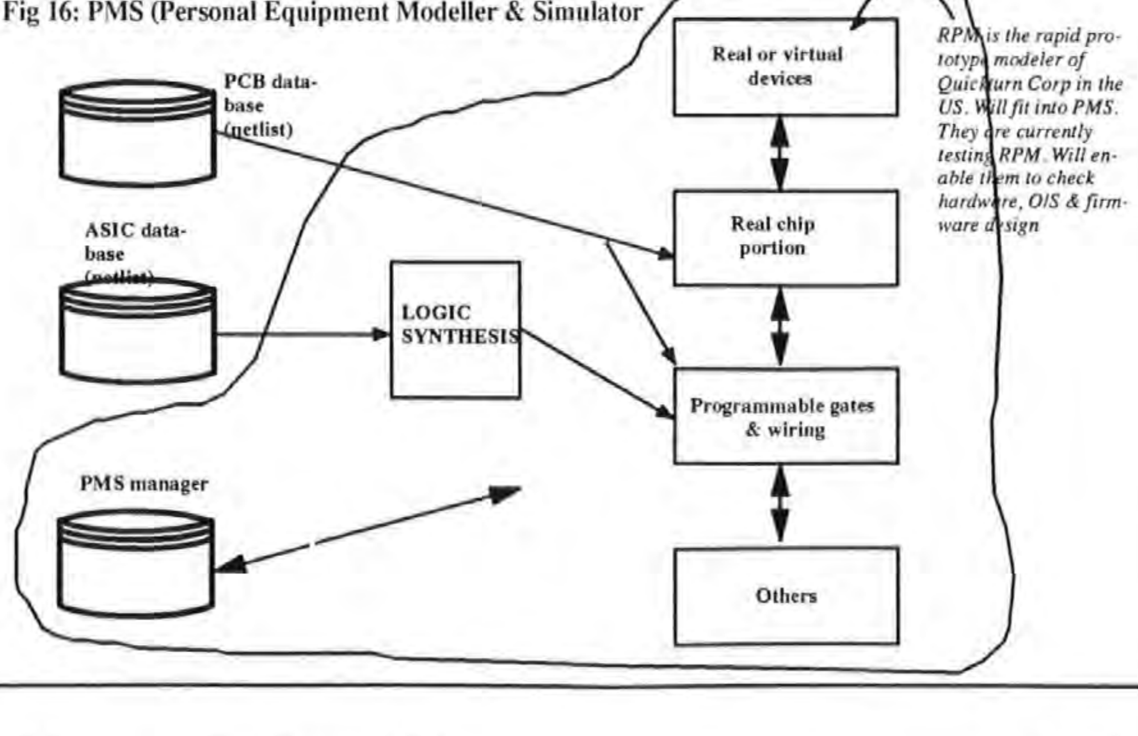


Fig 16: PMS (Personal Equipment Modeller & Simulator



- In current JCAD project, they have realised system simulation for midrange computers but can't simulate for personal equipment, e.g. floppy disk controller, hard disk controller, because it is difficult to simulate so many LSI functions
- **Requirements specification:** No software support. Discussion among team members. Checked after development.

OME TOSHIBA CIM (OT-CIM)

- Two factories selected, OME and Yokosuka. Ome CIM complete in 1991.
- Why CIM? Market getting more competitive, faster technological innovation etc
- 4 types of CIM:
  - **Indent Systems:** Parts & products, order-based production e.g. heavy apparatus
  - **CIM for product orders based on market perspective (OME):**
  - **CIM for off-the-shelf products:** e.g. WP, LT
  - **CIM for standard components:** e.g. cathode ray tubes, semiconductor devices
- OME system is used where purchase order received from the customer triggers system development.
- For laptops, minimum lot size is 20 units so the production line is suitable for those volumes. They can make all models of laptop on the same production line.
- When conceptualising about the CIM system they would implement, they chose to model existing vs proposed systems using Japanese "manga" cartoon-style drawings (see enclosed example). See OT-CIM document for details. **Get Emiko to translate this.**
- PCB assembly takes 1 week. System assembly takes 1 week. Before they established the CIM system, they had no quotation or reservation system, but now a salesman can do this. This year is the last year of the OT-CIM project
- **Development of information systems towards the 21st century:** Distributed processing systems (1982 - 1984), Combined FA, OA, EA (1985 - 1987), Combined the above with HQ marketing, management etc (1988 - 1990).
- Toshiba has CDGP (Corporate, Department, Group, Personal) computer-usage philosophy which means they use computers which are suitable for their particular requirements. No single engineering database. Several engineering databases e.g. documentation.
- **OT-CIM main purpose:** Halving total production lead time, halving inventory
- **Production quantity:** Trebled 1985 - 1990
- **Employee numbers:** Hardly any increase in same period
- **Total production lead time:**

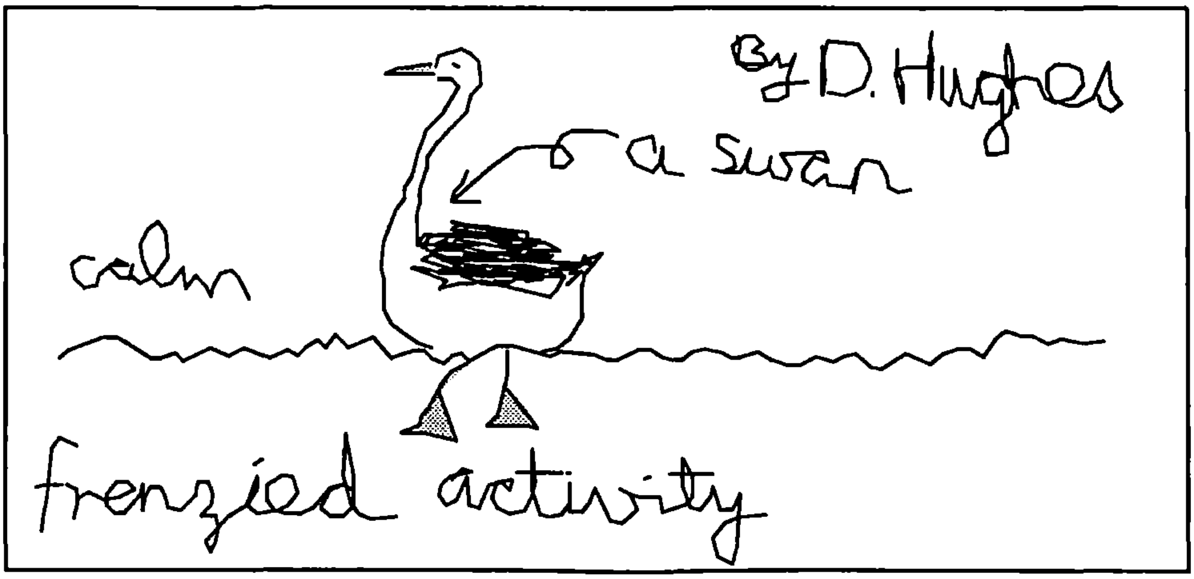
'87	'90
100 *(70% sales, 30% production)*	50

- **OT-CIM keypoints:**
    - Information "Glasnost" through such features as booking system, sales information etc
    - Market orientation
    - Distributed processing on CDGP lines
    - Online/realtime
    - Globalisation (will begin transferring OT-CIM to other Toshiba factories)

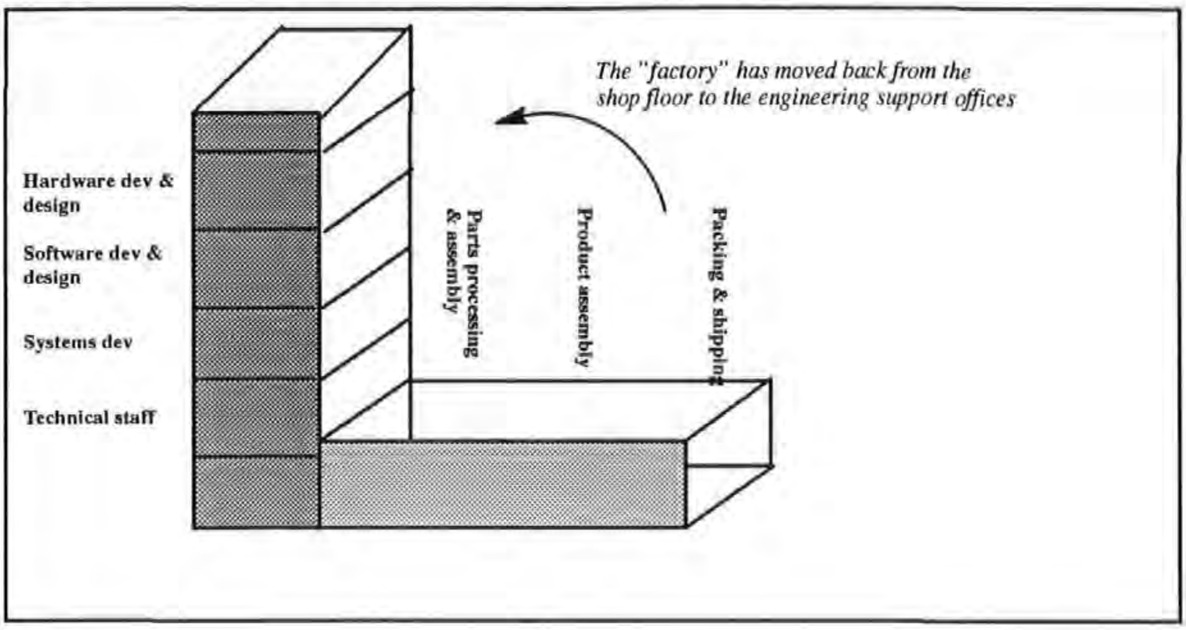
INFORMATION GATHERED DURING OME FACTORY TOUR

- LCD active matrix colour screens on latest LT products. Biggest problem is yield. One bad bit means you have to throw away the entire screen.
- Announcing a new laptop model every year. Advanced technology included as much as possible for competitive reasons.
- In Four Design Path Model, Toshiba has the same design path for low and high risk products, but the approval process is much stricter for high risk ones. They qualify new machines into 4 ranks: A, B, C, D. If a product is ranked as "A", it requires strict checking and must have general manager approval before it can go to mass production. A "B" ranked product would require senior management level (e.g. Mr. Yamazaki) approval
- Started using SMT 6 years ago. TAB technology has been adapted for use in memory cards
- Any design errors which crop up in production are recorded manually and sent to the design engineers for action.
- On the shop floor, 1 iteration to correct a problem is acceptable. > 1 iteration is not acceptable.
- Electronic kanban
- Smaller distributed processing machine takes 1 day to assemble. Larger DPS machine takes 2 days.
- Flexible workforce
- Laptop development cycle = 1 year; 6 months for Japanese word processor; 2 years for upper range DPS machines.
- **Laptop assembly:** Laptops located on rack above each assembly station. They monitor the work offering guidance where required. Product taking an active role in its own creation. See Business Tokyo March 1991 article "Power in your pocket". Minimum lot size = 20 units.
- **Soldering:** Flow & reflow
- Each production line is requested to reduce lead time and space. If they reduce space, the line is allowed to make whatever use of the freed up space they like. In one case, the space has been used as a meeting area for small group activities.

- Small groups have around 10 people in them. Groups of 3 or 4 considered too small. See interview with Takemura shacho.
- Qualification process includes shock testing, stress testing etc. If product not qualified, it is not shipped.
- The OME plant has a clean room for production of 3.5" hard disks. They produce 30,000 per month. They have just started production of 2.5", 40mb hard disks.
- Power supplies. Automated mounting ratio = 74%.
- Awards for small group activities, e.g. good suggestion. Group gets a chance to make a presentation of their activities to senior management.
- Suggestions are ranked on a scale of 1 – 7. Up to rank 6, unit manager can decide what to do. Suggestions ranked 7 have to go to a senior management committee for approval.
- **Engineering Change Control:** Manual ECC system. A few change orders for each new product, but more for the larger DPS products. No change orders for ASICS. Only changes to the database! (Oh yeah??)
- Toshiba has been trying to source components from overseas but many vendors can't meet the company's requirements in terms of specification and quality.
- **Engineering Data Centre:** Data for all products. Factory wide information accessible to all engineers using their laptops. e.g. patent information, design rules, purchasing specification document, electronic & mechanical drawings
- ODICS -- 1 workstation in each department which allows engineers to look at engineering drawings. Special elongated screen.
- **PCB CAD:** DS6000 series machines. NC data is "walknet" using floppy disk. No direct links to shop floor yet for PCB autoinsertion.
- Engineers not trained to use CAD/CAE systems at university. Toshiba train after recruitment.



- Manufacturing is under control because engineering is so good.



- Mechanical designs are output to drawings and sent to subcontractor moulding companies. Enclosure is prototyped in wood (not polystyrene). Industrial design/aesthetics for functionality & features.
- All electronic designs (PCB, ASIC etc) are sent automatically to semiconductor fab or PCB production areas. NO drawings.
- **Production control office:** People everywhere. Open plan office "divided" into PCB Dept, DPS Dept, PC Dept, Japanese WP Dept etc. All engineers using LT terminals/computers. Ordering, checking materials, simulating whether the OME factory can produce a particular product. All orders from HQ only via Email system.
- Product development management by review steps
- **Keypoints:**
  - Market-oriented design. Two markets — product market, component market
  - Need new technology to compete with IBM, Compaq etc. Recognise that there are high risks are involved in such a policy but "we have to do this." Trade off between risks and benefits decided by top management
  - **Communication is key!**
  - To be competitive they must reduce their costs by 20% per year