DESIGN MODULARISATION: A SYSTEMS ENGINEERING BASED METHODOLOGY FOR ENHANCED PRODUCT REALISATION.

by

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CERTIFICATE OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this thesis, that the original work is my own except as specified in acknowledgements or in footnotes, and that neither the thesis nor the original work contained therein has been submitted to this or any other institution for a higher degree.

.... (Signed)

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ABSTRACT

The thesis concerns product design modularisation and its potential for meeting manufacturing and marketing needs. The premiss is that product manufacturing organisations have failed to take advantage of the full potential, taking a reactive approach to modularisation within their product architecture and subsequent manufacturing. The aims of the thesis are to develop a systems level framework for product and process integration, develop a structured methodology for design modularisation and finally, evaluate modularity through case analysis and software modelling.

Four case studies of manufacturers of complex products, taken from a range of industries are investigated and analysed. The case studies demonstrate the utility of a modular approach to product realisation and highlight an opportunity in guiding organisations into taking a more structured approach to modularisation.

To address this opportunity modularity is reviewed across a range of applications including the design of products, software, and manufacturing systems. Subsequent analysis presents the need for a total view of product realisation. A total view as embodied by systems thinking provides a framework, linking customer needs to new product delivery through a rationalised modular approach. Within this framework a methodology is developed for modular product realisation. The methodology combines a modular design process with best practice guidelines and self analyses and is implemented as a holonic product design workbook.

The evaluation of modularity and the workbook was carried out through company questionnaires, feedback, and modelling through the aid of systems engineering software tools, determining the appropriateness of the approach and examining aspects of workbook implementation within industry. The modelling evaluates modularity's impact upon product realisation and the product life cycle.

Conclusions show the importance of modularity and the framework of systems thinking in addressing broad industrial needs for dealing with customer requirements, new technology, complexity, and agile manufacture. Evidence shows the appropriateness and timeliness of the modular approach through examples of industrial demand and implementation. The methodology and workbook provide an accessible and customisable package, meeting needs for a structured implementation of modularity within industry. Further work is identified in investigating full industrial workbook implementation, continued methodology refinement, and investigation of the more analytical principles of modularity.

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ACRONYMS

AEM	Assemblability evaluation method	**IT**	Information technology
BIW	Body in white	**JIT**	Just in time
BUSM	British united shoe machinery	**JSF**	Joint strike fighter
CAD	Computer aided design	**LOM**	Level of modularity
CAE	Computer aided engineering	**MFD**	Modular function deployment
CAM	Computer aided manufacture	**MIM**	Module indication matrix
CE	Concurrent engineering	**MRP**	Material requirement planning
CIM	Computer integrated manufacture	**MWD**	Measurement while drilling
CM	Cellular manufacture	**NGP**	Natural gamma probe
CPLCP	Crosfields product life cycle process	**NVH**	Noise, vibration and harshness
DEP	Directional electronic probe	**PCD/G**	Pressure case directional / gamma
DFA/M	Design for assembly / manufacture	**PIP**	Product introduction process
DFMA	Design for manufacture and assembly	**PMTE**	Processes, methods, tools, environment
DGWD	Directional gamma while drilling	**PWD**	Pressure while drilling
DM	Design modularisation	**QE**	Quality engineering
EMT	Electromagnetic telemetry	**QFD**	Quality function deployment
FAST	Function analysis system technique	**SE**	Systems engineering
FMEA	Failure modes and effects analysis	**SME**	Small to medium enterprise
FPDS	Ford product development system	**SSDS**	Sperry-Sun drilling services
FPS	Ford production system	**STEP**	Standard for transfer and exchange of product model data
GT	Group technology		
HMS	Holonic manufacturing systems	**TPS**	Toyota production system
HOQ	House of quality	**TQM**	Total quality management
HPD	Holonic product design	**TRIZ**	Theory of inventive problem solving
IGES	Initial graphics exchange specification	**VA/E**	Value analysis / engineering

Chapter 1 Introduction

1

Objectives: This chapter provides:

- Background and domain of design modularisation
- Aims and objectives addressed by this thesis
- A guide to the research approach taken and the structuring of the thesis.

1.1 BACKGROUND

This thesis concerns design modularisation and its promotion of *design to manufacture* as a single process. It investigates the potential of modularisation in meeting manufacturing and marketing needs. The premiss is that product manufacturing organisations have failed to take full advantage of this potential, taking an ad hoc or localised approach to modularisation within their product architecture or the subsequent manufacturing through, for example, cellular manufacture.

The background to the thesis is the opportunity presented in guiding organisations into taking a more structured approach to modularisation. This opportunity is to be explored by taking a total view encompassing design modularisation within a systems level framework for product realisation. The total view then supporting the development of a design modularisation methodology for product and process integration. Linking customer needs to new product delivery and ultimately realising the potential of modularisation. Where modularity is the creation of discrete modules that are inherently different to common subassemblies, being self contained, having their own function and providing the ability to be combined and configured with other modules to form the product.

The total view promotes investigation of design modularisation within concurrent and systems engineering (Figure 1.1), where design modularisation is a systems (product and process) engineering based methodology applied to the life cycle development of complex products. Concurrent and systems engineering are reviewed as components of a total view. The hypothesis is that either approach taken in isolation is currently insufficient.

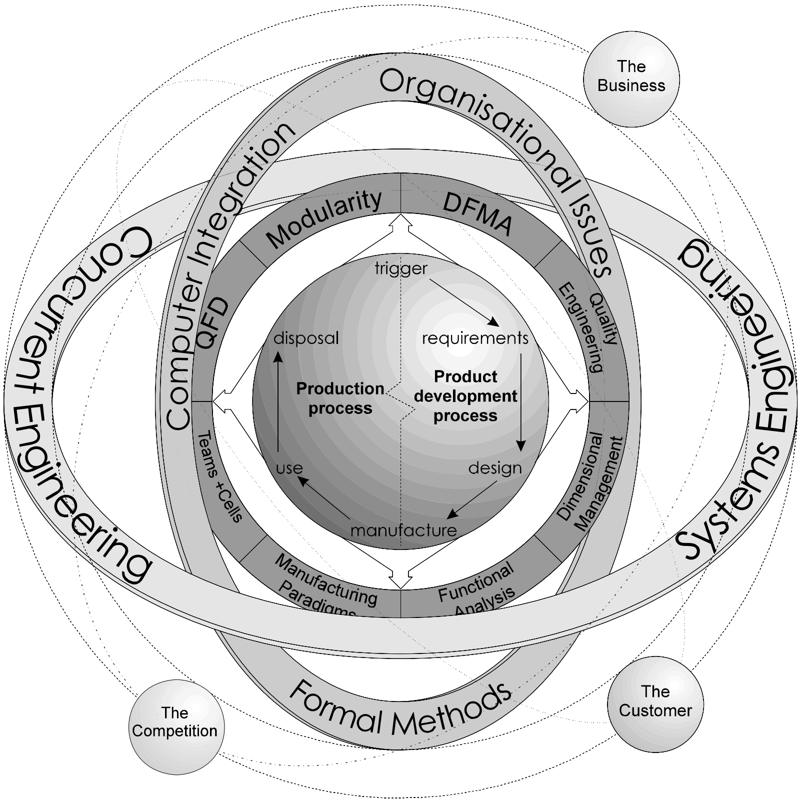

Figure 1.1. The Review Domain.

Concurrent engineering provides a broad range of tools and techniques, but provides a component centred approach, concerned with the division of labour and complexity (Prasad 1996). This approach has traditionally suffered from a lack of attention to the subsequent integration of the divisions. The resulting product is frequently sub-optimised as the product system is greater than just the sum of its component parts.

Alternatively, systems engineering takes a system level approach in which the integration of system elements is the key. Potential exists within systems engineering to subsume concurrent engineering (Leaney 1997), as presented in figure 1.2. However concurrent engineering has undergone many changes to reflect the need to take a total view. Systems engineering frequently misses the opportunity for the systems engineering of manufacture: thus transformation into the final aspect of the model is not yet complete.

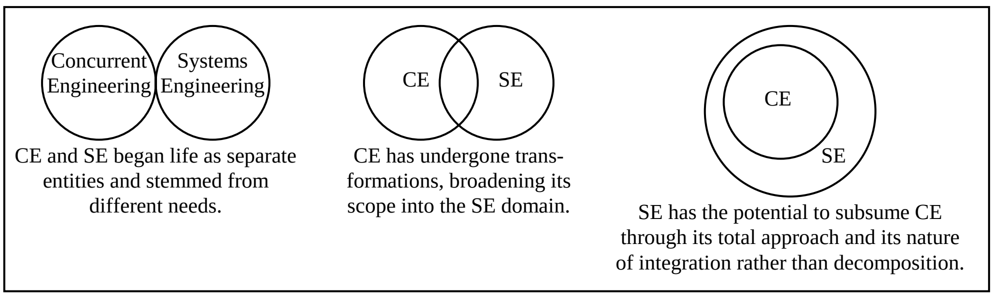

Figure 1.2. The Scope of Concurrent and Systems Engineering.

1.2 AIMS AND OBJECTIVES

The aims of this thesis are:

- **Framework:** Investigate the framework provided by systems engineering and its integration of manufacturing through the view of design to manufacture as a single process.
- **Methodology:** Develop design modularisation as a structured methodology for product development and the integration of design with manufacture.
- **Principles:** Investigate and demonstrate the underlying principles of design modularisation through case study analysis and the modelling of its characteristics and processes.

Specific objectives are:

Need: Investigate the need and application of design modularisation (DM).

- Identify opportunities for DM research.
- Develop industrial case studies across a range of company size and industry.
- Clarification and justification of the business drivers that modularity can address.
- Identification of general and specific needs for a modular approach.

Nature: Clarify the nature of design modularisation / modularity.

- Review the existing work on modularity and how modularity relates to the domain.
- Define the meaning of modularity.
- Determine the advantages and disadvantages of DM.
- Investigate the applicability of modularity.
- Analyse the manifestations of modularity such as enterprise holons and manufacturing cells.
- Highlight the need for a multi-functional approach to product realisation and the specific impact of DM on design, manufacture, marketing and the customer.

Framework: Investigate systems engineering (SE) as a framework for design modularisation.

- Review SE and investigate its neglect of manufacturing processes.
- Highlight the total view proposed by SE and its relation to DM.
- Develop a SE based framework for a DM methodology.
- Acknowledge the product and it's processes (including functional, development and manufacturing) as a system and the implications this has.

Methodology: Develop a methodology for design modularisation.

- Structure the amorphous area of modular design within a methodology for application.
- Consider its application to a range of companies and a range of products.
- Detail the methodology for DM addressing targeting, implementation, and maintenance.

Principles: Demonstrate and evaluate the methodology of design modularisation.

- Investigate the underlying principles of design modularisation that apply regardless of application format or circumstances.
- Determine processes and measurables that provide insight into the key elements of DM.
- Document and analyse case study experience.
- Solicit feedback from industry on the DM methodology.
- Model the influence of DM upon product realisation and highlight system links.

1.3 A GUIDE TO THE THESIS

Modularity is a field of study that is amorphous, being broad and ill defined, inherently complex and having strong ties to both industrial and academic arenas. The approach taken accommodates these facts through the determination and application of a structured and descriptive approach to the research (Whitney 1995). The approach consists of:

- A literature survey in order to clarify and determine a boundary to the domain. This process will also identify the links and provide orientation between DM, SE and the techniques and tools this subsumes.
- Case studies to provide primary evidence of the need for DM and the industrial concerns of a wide range of manufacturing companies. Case studies also provide the opportunity to influence an industrial process in line with the research.
- Questionnaires to determine the industrial view of modularity, reinforce the need for DM and how this need may be satisfied.
- The investigation of the links through SE and the implications of DM through a model.
- The implementation of a DM guide or process template.
- Determination of measureables for DM and how these may be used as an indicator for opportunity.
- Demonstration of DM and its evaluation against the measurables.

The thesis is structured to reflect the approach taken. Providing background through the literature, developing a need through consultation and work with industry, and analysing the opportunities DM presents in meeting this need. Developing a structured response to the need that reflects the broader issues of industry. Finally evaluating the opportunity and application of the process as demonstration of its efficacy.

Chapter 2 Review

2

Objectives: This chapter reviews the literature in the domain related to DM within product manufacturing industry. Specifically:

- Concurrent and systems engineering, that are examined for their encompassing view
- A broader look at the existing examples of modularity and module-related work.

2.1 CONCURRENT ENGINEERING

In 1986, the Institute for Defence Analysis (IDA) Report R-338 coined the term 'concurrent engineering' (CE) to better reflect the concept of parallel processes. CE thus became the successor to the previous simultaneous engineering which had been used in the American automobile industry. In fact, CE was not so much a successor to simultaneous engineering but rather a rechristening (Backhouse & Brookes 1996). The IDA report also provided a definition:

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

The essence of CE is the integration of the product and its associated process, the divergence from the traditional Western development practice of sequential engineering (CALS 1991). As the commencement of each distinct stage is not dependent upon full completion of the preceding stage, overlapping activities can take place, leading to concurrency in product development (Syan 1994). The paralleling of life cycle functions in conjunction with robust design, cost effectiveness, reduced lead time, and increased quality (Prasad 1996; Creese & Moore 1990) are all components of CE.

The quality of communication between disparate life cycle functions is extremely important to the effective use of CE. Communication and information sharing though is only one aspect of CE. Keys (1992) proposed three generic elements to CE: multi-functional teams, computer aided design and manufacture (CAD/CAM), and formal methods.

Dowlatshahi (1994) proposed five elements: information systems, CAD/CAM, life-cycle engineering, design for manufacture and assembly (DFMA), and organisational and cultural change. These can be modified to give a complete and balanced view that CE is composed of:

- Information Technology and specific instances of this such as computer aided design and manufacture (CAD/CAM).
- Formal methods (tools and techniques such as design for assembly (DFA)).
- Company organisational issues such as team-working and the extended enterprise.

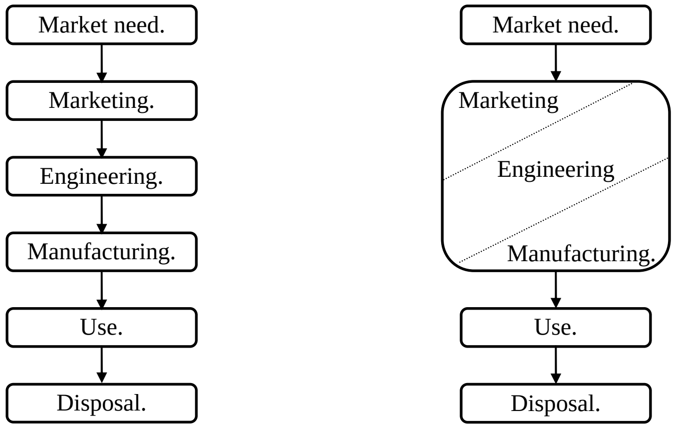

Figure 2.1. Sequential and Concurrent Product Life Cycles.

The application of information technology and specifically computerised tools is often seen as central to a company's implementation of CE (Backhouse & Brookes 1996). This aspect in particular has received considerable attention as the embodiment of CE both in industry and academia and has tended to be hi-jacked by those promoting salvation through CAD/CAE/CAM (Leaney 1995). In spite of this, it is important that equal consideration be given to all aspects of CE.

The information technology aspect of CE provides the ability to speed up and integrate development processes directly through computer based design, evaluation and manufacture tools, and indirectly through the use of electronic information storage, retrieval, exchange, and manipulation.

The formal method element of CE combines the processes for dealing with many particular aspects of a products development such as: the application of customer requirements, the consideration of ease of assembly, and the analysis of potential failures, with the framework provided by consideration of the whole life cycle from different view points.

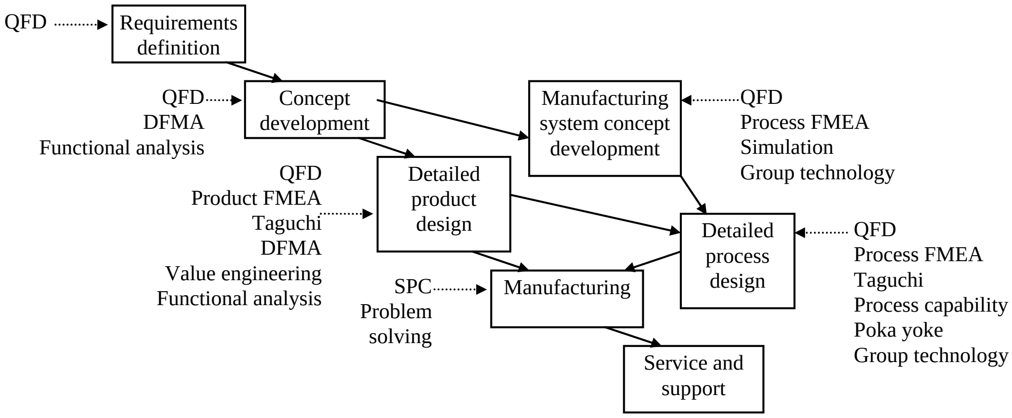

Figure 2.2. Formal Methods in the Product Life-Cycle.
(adapted from Brown, Hale and Parnaby 1989).

The final aspect to CE, that of organisational issues relates to the business and its processes. Paradigms such as the extended enterprise relate to the operation of the business, its departments, and its suppliers and are high level issues for business development. Implementations such as teams and cells relate to the processes of engineering and manufacture and are lower level issues for product development.

In summary, CE is an integrated approach to the product life cycle and is a strategic element in dealing with the pressures upon product development through the competitiveness of the business environment. CE provides a methodology for dealing with the dominant market trends of: reduced product life cycles, increased product diversity, variety, and complexity, and customers demanding products more closely targeted to their needs and wishes.

2.1.1 COMPUTER INTEGRATION

Computer integration is an essential aspect of CE that provides an enabling structure for the use of formal methods and a basis for organisational change. The key is the integration, from the standpoint of information flow and technology, of all the areas of the business concerned with the process of product introduction, starting from its initiation through its design and planning stages onto production, quality control and finally, sale (Warnecke 1993a).

Though there is no agreed definition of what constitutes a CIM environment the Computer and Automation Systems Association of the Society of Manufacturing Engineers define CIM as:

> the integration of the total manufacturing enterprise through the use of integrated systems and data communications coupled with new managerial philosophies that improve organisational and personnel efficiency.

A computer integrated system for CE is made up from a number of elements such as CAD, CAM, CAE and CAPP (Bedworth, Henderson & Wolfe 1991). Though these systems have received considerable development it is the integration of these individual systems with a central database that is the key to successful computer integration. Figure 2.3 shows the integration of these systems (Warschat & Wasserloos 1993). Such enterprise wide systems are also the focus of enterprise modelling, the use of computer tools for rapid business re-engineering and continuous improvement. The integrating nature of such systems is highly related to CIM providing powerful information management throughout the business (BAAN 1997).

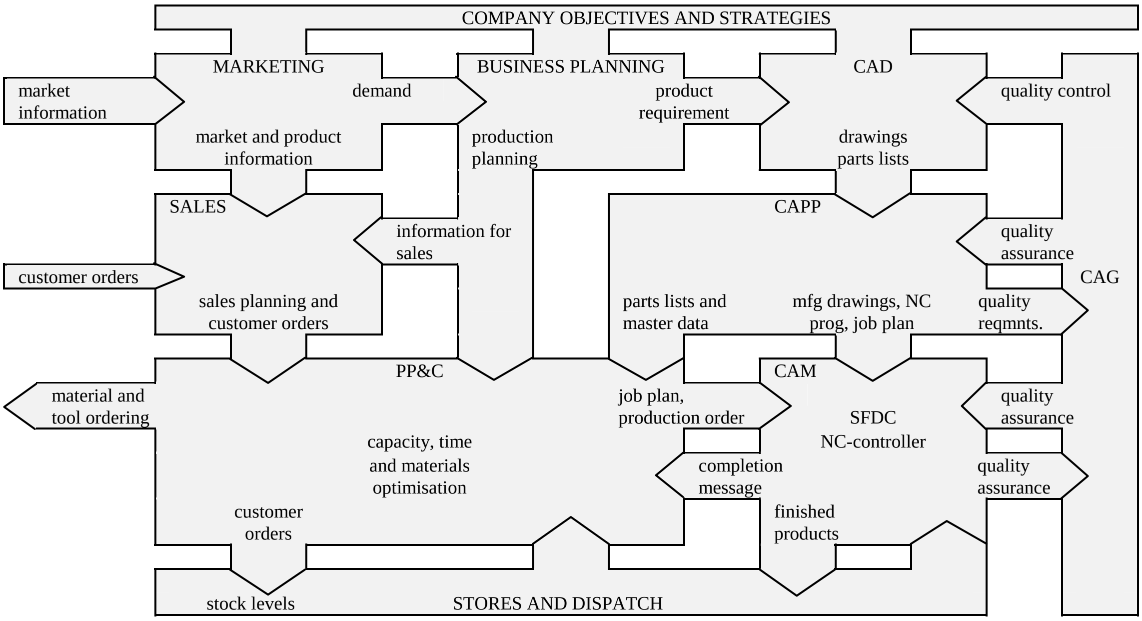

Figure 2.3. The Integration of CIM Components.

It is unfortunate then that the integration of these systems is the most difficult aspect to implement successfully. Greenhalgh (1991) presents three generic inhibitors to CIM:

- Hardware and software. The lack of integration and compatibility between systems such as CAD and CAM make tasks such as producing a process plan directly from CAD difficult.
- Database management. The use of distributed processing systems can create unique problems.
- Self learning, diagnosing and other expert system development. In CIM some decisions will have to be made by the system and this requires the development of expert systems.

Engel (1990) also highlights five faults of CIM systems: 1. overconfidence in the capability of computers; 2. overconfidence in optimisation theory; 3. major difficulties with forecasting; 4. today's CIM views factories too lightly; and 5. automation makes poor use of human talents.

These difficulties have arisen partly from the historical development of computer systems and can be attributed to disparate introduction and system incompatibility. Strategies to overcome these problems include the development of communication standards such as initial graphics exchange specification (IGES) and the standard for transfer and exchange of product model data (STEP). Modular systems that are designed from the outset to be compatible are also a possible solution. However much of the development is at random, aimed either at ill-defined long term goals or purely at solutions to specific short term problems (Wainwright, Tucker & Leonard 1994).

2.1.2 FORMAL METHODS

Formal methods are a broad group of tools and techniques applied to aspects of product realisation. The following sections address a number of formal methods covering design to manufacture and from encompassing frameworks such as QFD to specific tools such as FMEA.

2.1.2.1 Design for Manufacture and Assembly

It is widely accepted that 75-85% of the cost of a product is committed during the design and planning activities (Andreason, Kahler & Swift 1988; Nevins & Whitney 1989; Sheldon & Perks 1990; Prasad 1996). Therefore, consideration of manufacturing and assembly problems at the product design stage is the most cost effective way available for reducing costs and increasing productivity (Syan & Swift 1994).

Three well known design for assembly techniques are those of Boothroyd-Dewhurst, Lucas design for assembly (DFA), and Hitachi assemblability evaluation method (AEM), (Leaney 1996). These techniques are evaluative methods that analyse the cost of assembly of designs at an early stage in the design process, and use their own synthetic data to provide guidelines and metrics to improve the assemblability of the design (Leaney, Abdullah, Harris and Sleath 1993).

Design for manufacture analyses are used to aid in the detail design of parts for manufacture. DFM tools such as design for machining and design for sheet metalworking have been developed by the Boothroyd-Dewhurst partnership to address specific processes and the design of parts suited to those processes (Boothroyd, Dewhurst and Knight 1994).

Since the early implementations of DFMA tools, steps have been taken to provide a more integrated approach covering a greater portion of the product life cycle. Boothroyd-Dewhurst have developed a number of Windows based tools and Lucas DFA has recently been incorporated into an integrated suite called TeamSET (Tibbetts 1995).

The tools are specific implementations of a basic set of guidelines for DFMA which are aimed at raising the awareness of engineering to the importance of manufacture and assembly. The generic guidelines (Leaney & Wittenberg 1992) are presented below:

1. Aim for simplicity.
2. Standardise.
3. Rationalise product design through standardisation and modularity.
4. Use appropriate tolerances.
5. Choose materials to suit function and production process.
6. Minimise non-value-adding operations.
7. Design for process.
8. Adopt teamwork.

2.1.2.2 Quality Function Deployment

Quality function deployment (QFD) is a formal method to facilitate multi-functional planning and communication in a CE environment (Menon, O'Grady, Gu and Young 1994). QFD enables a development team to specify clearly the customer's wants and needs, and then to evaluate each proposed product or service capability systematically in terms of its impact on meeting those needs (Cohen 1995).

The QFD process involves mapping customer requirements onto specific design features and manufacturing processes through a series of matrices. QFD can be employed at two levels. To translate requirements of one functional group into the supporting requirements of a downstream functional group or as a comprehensive organisational mechanism for planning and control of new product development (Rosenthal & Tatikonda 1992). A localised application typically involves the first of these matrices (Figure 2.4). This matrix has the most general structure and is often called the house of quality (HOQ).

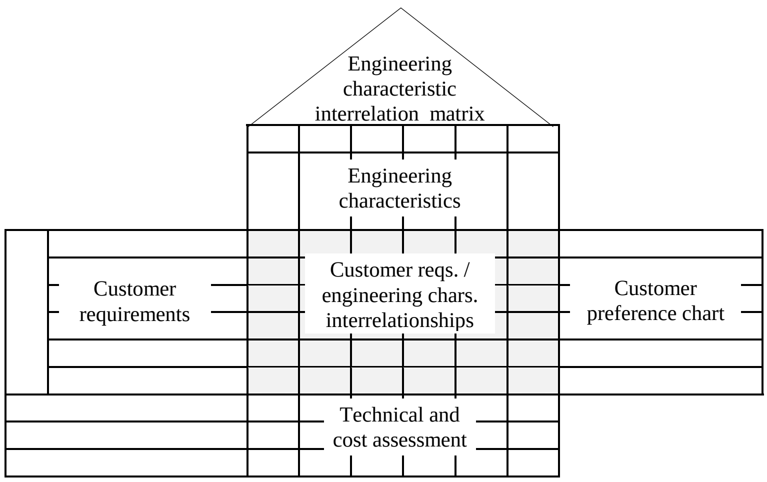

Figure 2.4. The House of Quality Matrix.

After the house of quality matrix a number of additional matrices may be used to deploy the customer requirements through to production planning. Cohen (1995) presents the Clausing 'four-phase model' (Figure 2.5), that mirrors the process of design and manufacture. Similar models exist for developing services, processes, and software. The ability of QFD to be deployed in this manner makes it unique among formal methods in its ability to span life cycle processes.

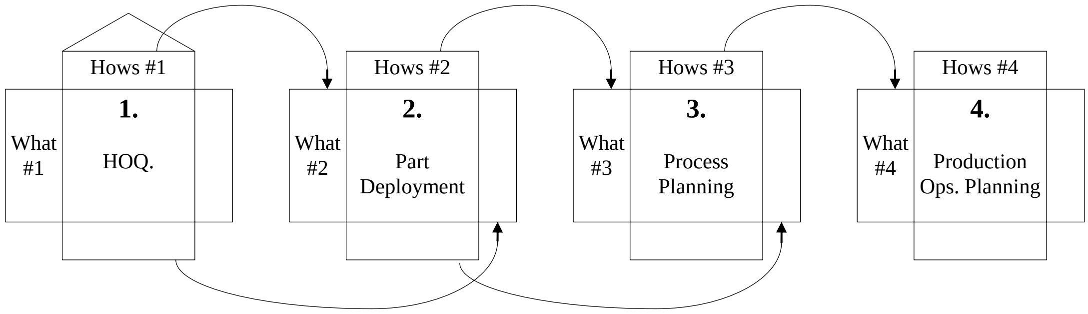

Figure 2.5. The Four Phase QFD Model.

Matrix	**What**	**How**
House of Quality	Voice of the Customer	Technical Performance Measures
Part Deployment	Technical Performance Measures	Piece-part Characteristics
Process Planning	Piece-part Characteristics	Process Parameters
Production Operations Planning	Process Parameters	Production Operations

QFD has seen successful use at the Ford Motor Company and Toyota (Hauser & Clausing 1988), General Motors (Schilke 1994), Boeing, Hughes, Digital Equipment, Hewlett-Packard, AT&T, and ITT (Menon, O'Grady, Gu and Young 1994), realising a number of issues:

- QFD increases customer satisfaction by mapping the voice of the customer directly onto the technical solutions of the product.
- QFD facilitates the forming of a multi-disciplinary team and maintains their focus on meeting customer requirements through every stage of development.
- QFD aids the prioritisation of development tasks in maximising benefit to the customer, resulting in an improved product and reduced product cost.
- QFD promotes good communication between all departments involved in the development process using a common customer-oriented language.
- QFD reduces the product development cycle time by aiding design changes, promoting a right-first-time approach, and supporting a CE environment.
- QFD relies upon team work and thus requires attention to communication and co-ordination.
- QFD has inadequate support tools, hindering negotiation of the wealth of information represented by a comprehensive QFD analysis, and preventing valuable links with existing computer systems such as CAD/CAM.
- Ford use a QFD stage 0 for pre-planning (prior to the HOQ) when the initial scope is broad.

2.1.2.3 Functional Analysis

Functional analysis or function analysis system technique (FAST) is a design method aimed at providing a complete view of a design at any stage of the development process in terms of functions and the interrelationships and dependencies of those functions.

It is therefore applicable to system, product or process design. Functional analysis provides a means of considering a problem at different levels of definition and focuses the process toward the essential functions of a solution, rather than the solution itself.

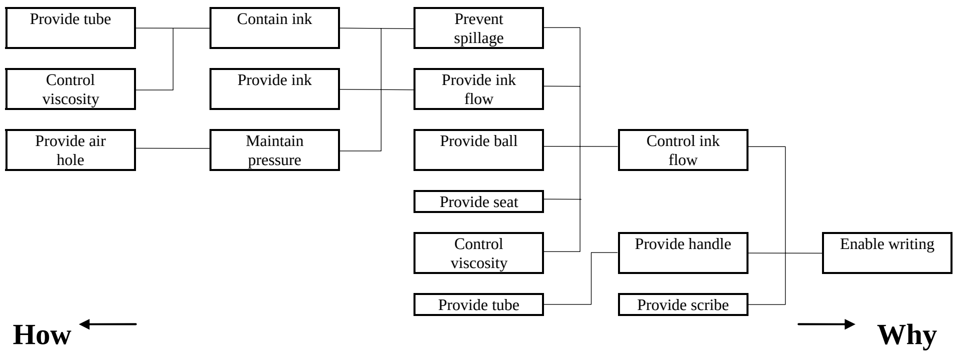

Figure 2.6. The FAST Diagram for a Ball-Point Pen (Fox 1993).

The process of functional analysis is based around the expression of functions for the design in terms of conversion of inputs and outputs, using a verb + noun definition. A FAST diagram is used to represent the functional relationships between all the functions of a system (Figure 2.6).

2.1.2.4 Value Engineering

Value engineering is a team based evaluative technique which assigns a value to a product, where a product may be anything from individual component parts to complete systems. Care must be taken with the understanding of value as it is heavily dependent on the circumstances in which it is measured (Fox 1993).

The process attempts to enhance the value of the product by increasing its functional capability, for the same or lower cost or conversely, reducing cost whilst maintaining the same functional capability. The goal is to eliminate unnecessary features and functions by optimising the value ratio. This value can be divided into two components: a use, or functional, value and an esteem value. The use value reflects how the product satisfies the user's needs, and the esteem value is a measure of the desirability of the product, a marketing and advertising concern. The two values are investigated analytically by a team of experts based on a preliminary design. (Cross 1989).

2.1.2.5 Failure Modes and Effects Analysis

Failure modes and effects analysis (FMEA) is a structured approach to the identification and evaluation through a risk priority number (rpn) of possible modes of failure in a system, product, or process. Failure is taken in its broadest sense, not as a catastrophic breakdown but as a consequence of not meeting a customer's requirements. The aim is to anticipate and design out all possible failures before they occur, removing the potential cost of these failures to manufacturing, in warranty claims, and in loss of customer satisfaction.

Part	Function	Potential failure mode	Potential effects of failure	Severity	Potential causes of failure	Occurrence	How will potential failure be detected?	Detection	rpn	Actions
tube	provide grip	hole gets blocked	vacuum on ink stops flow	7	debris ingress into hole	3	check clearance of hole	5	105	enlarge hole or remove cap
ink	provide writing medium	incorrect viscosity	high flow	4	too much solvent	2	QC on ink supply	4	32	introduce more rigid QC
ink	provide writing medium	incorrect viscosity	low flow	4	too little solvent	2	QC on ink supply	3	24	no action required
ball & seat	meter ink supply	incorrect fit	ball detached	8	total failure	2	inspection checks	3	32	
ball & seat	meter ink supply	incorrect fit	ball loose	6	blotchy writing	3	sampling checks	6	108	introduce in process checks
plug	close tube	wrong size	falls out	4	moulding process not in control	2	no current checks or tests	8	64	eliminate part or control process variation

Figure 2.7. Product Failure Mode and Effects Analysis Table (Fox 1993).

2.1.2.6 Quality Engineering

Dr. Genichi Taguchi is possibly the most well known advocate of quality engineering (QE), so much so that Taguchi methods are often synonymous with QE. According to Taguchi (Taguchi 1993) quality engineering pertains to the evaluation and improvement of the robustness of products, tolerance specifications, the design of engineering management processes, and the evaluation of the economic loss caused by the functional variation of products.

In this instance, robustness or a robust design is defined as (BS 7000 Part 10. 1995): Design of a product that is insensitive to variations in its manufacturing or use. Taguchi defines quality from the view that a lack of quality is the amount of functional variation of products plus all possible negative effects, such as environmental damages and operational costs. Taguchi evaluates quality through a quality loss function (Figure 2.8). The quality loss function is expressed as the square of the deviation of an objective characteristic from its target, assuming the target to be the desire to meet customer satisfaction, any deviation from that value will mean a level of reduced satisfaction for the customer. Furthermore the greater the deviation, the greater the dissatisfaction to the customer.

The concept also highlights that it is not acceptable to just keep the parameter within the set limits, but that it is necessary to keep as close as possible to the nominal or target value.

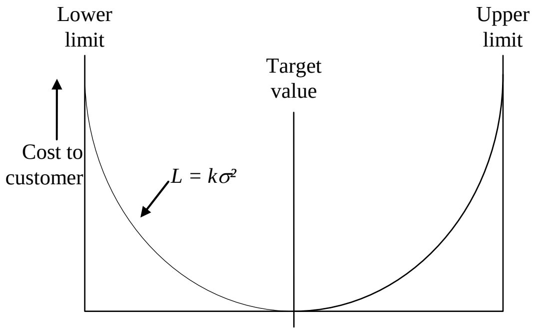

Figure 2.8. The Quality Loss Function.

2.1.2.7 Group Technology

Group technology (GT) was first defined in 1959 in the book: Scientific Principles of Group Technology. The English translation (Mitranov 1966) describes GT as:

> ..a method of manufacturing piece parts by classification of these parts into groups and subsequently applying to each group similar technological operations.

On the shop floor GT facilitates the grouping of machine tools and other facilities around components that have similar processing characteristics. These groups then simplify manufacturing planning, flow of work, minimise set up times and component lead times. Mitranov believed that this process could be used to obtain economies of scale even with small scale, batch or jobbing production.

The classification and coding of parts for GT is based on a number of possibilities including: design and manufacturing attributes or, frequently, a combination of both (McMahon & Browne 1993). Though GT is aimed toward the efficiency of manufacture, in design GT promotes standardisation, reduces design duplication, reduces the number of parts needing to be held in stock, part numbers and the associated documentation. GT also allows part data retrieval and reduces the development lead time.

However, GT was initially restricted to maintaining functional layout of machines whilst improving machine productivity. As GT has developed, a different term has been used to represent a broader interpretation that expands upon process based groups including the formation of groups around products and people (Alford 1994). This broader view is termed cellular manufacture though the distinction is not always clear. Burbidge (1994) suggests that these groups complete all the parts or assemblies they manufacture. The group machines are laid out together in a designated area and are manned by their own team of operators.

2.1.2.8 Theory of Inventive Problem Solving

The theory of inventive problem solving was developed by Genrich Altshuller from work that began in the 1940s. Altshuller conducted a study and cataloguing of patents looking for principles of innovation. The basic findings were that over 90% of the problems engineers faced had been solved somewhere before. From this, Altshuller developed an extensive, scientifically based problem solving method which incorporates numerous inventive principles and the laws of engineering system evolution (Barnard 1996). This method was entitled the theory of inventive problem solving, teoriya resheniya izobretalelskih zadach or TRIZ

It was recognised that the most elegant inventions were solutions where an engineering contradiction had been overcome with little or no compromise. To aid the engineer in addressing a contradiction 40 fundamental principles were entered into a matrix (Figure 2.9) of 39 engineering parameters that highlighted the principles that had been successfully utilised by previous inventors with the same contradiction.

Feature to improve. / Undesired result.		1	2	3	4
		weight of moving object	weight of non-moving object	length of moving object	length of non-moving object
8	volume of non-moving object		35, 10, 19, 14	19, 14	35, 8, 2, 14
9	speed	2, 28, 13, 38		13, 14, 8	
10	force	8, 1, 37, 18	18, 13, 1, 28	17, 19, 9, 36	28, 10
11	tension, pressure	10, 36, 37, 40	13, 29, 10, 18	35, 10, 36	35, 1, 14, 16

Figure 2.9. An Excerpt From the Table of Contradictions (Altshuller 1994).

TRIZ uses a scientific and systems approach to guide the designer or design team to possible novel solutions or alternative perspectives. It addresses not only the system at hand but all subsystems and supersystems and also their state with respect to past, present and future trends (Ideation / TRIZ 1997). In addition, it facilitates rapid development of new products by identifying existing similar solutions, and because it is not industry or application based a solution may be found from totally unrelated products or processes, giving a market advantage over competitors following traditional lines of thought.

TRIZ has been adopted and developed by Ideation who have further developed the technique and developed a number of software modules. Since 1993 Ideation / TRIZ has seen use in 3M, Motorola, Chrysler, Ford Motor co. General Motors, Johnson & Johnson, Rockwell International, Xerox and an ever increasing list of others (TRIZ / Ideation Methodology 1997).

2.1.2.9 British Standards

British and International ISO standards offer rules, guidelines, frameworks and generally embody a widely agreed basis of best practice. Two standards of particular interest are BS EN ISO 9000 (1994) quality systems (formerly BS 5750), a quality management system directly aimed to meeting customer requirements and BS 7000 (Part 2. 1997) design management systems series, a standard which provides direct guidance on the design of manufactured goods.

The BS EN ISO 9000 series provides a framework in which a company should plan the various stages of product development, identifying areas that affect quality and the procedures required to control these areas. In addition, the company should document this work and its commitment to quality so that it can identify its performance and use this information for quality improvement.

BS EN ISO 9001 guides the user to develop certain quality procedures and practices for the design, development, production, installation and service of products. The standard does not prescribe methods for quality design or production, instead it focuses on continuous improvement, meeting specifications and documenting the quality processes that occur.

BS 5750 AND BS EN ISO 9000 Quality Systems.	
Part number.	**Description.**
BS 5750 Part 4.	Guide to the use of BS EN ISO 9001, 9002, & 9003.
BS 5750 Part 8.	Guide to quality management and quality systems elements for services.
BS 5750 Part 13.	Guide to the application of BS 5750 Part 1. to the development supply and maintenance of software.
BS 5750 Part 14.	Guide to dependability programme management.
BS EN ISO 9000-1	Guidelines for selection and use. Replaces BS 5750 Part 0. 0.1
BS EN ISO 9001	Model for quality assurance in design, development, production, installation and service. Was BS 5750 Part 1.
BS EN ISO 9002	Model for quality assurance in production, installation and service. Replaces BS 5750 Part 2.
BS EN ISO 9003	Model for quality assurance in final inspection and test. Replaces BS 5750 Part 3.
BS EN ISO 9004-1	Guidelines. Replaces BS 5750 Part 0. 0.2

BS 7000 has a different approach to standards such as BS EN ISO 9000. BS 7000 is a guide and thus does not provide strict rules and requirements and does not allow accreditation. Instead it proposes good practice for the management of the design process. BS 7000 consists of 5 parts:

BS 7000 Design Management.	
Part numbers.	**Description.**
BS 7000 Part 1.	Guide to managing product design. Formerly BS 7000 (1989).
BS 7000 Part 2.	Guide to managing the design of manufactured products.
BS 7000 Part 3.	Guide to managing service design.
BS 7000 Part 4.	Guide to managing design in construction.
BS 7000 Part 10.	Glossary of terms used in design management.

The aim of BS 7000 is to try to raise awareness of the importance of good design management especially at a corporate level where such issues are not always paramount due to the near invisibility of design in business operations (Topalian 1997). It also aims to provide guidance on all aspects of design and clearly highlight the responsibilities of each design phase.

For our purposes BS 7000 Part 2 is the most relevant standard, dealing with the design of manufactured products. There are a number of important aspects to this guide, the first is the acceptance of design as an important element in the organisation. The standard highlights the responsibility of senior management to ensure successful design and that the company clearly focuses on the issue of design within its corporate objectives, strategy and identity. Other key elements for design at a corporate level include: positioning, visibility and integration of design, auditing of design management practices, and the environmental and legal dimensions of design.

BS 7000 Part 2 also highlights the holistic approach required for design. Product design is no longer seen as one element between marketing and manufacture but is instead a process that does not have discrete boundaries between disciplines and covers the whole product life cycle. The standard clearly defines the stages of a generic design process and draws attention to the need for careful consideration of each aspect of design. Not only does consideration have to be given to the detail of designing but also to the need to constantly consider customer requirements and awareness of who the customers are. Other aspects include product launch, the importance of software elements and the environmental pressures on recycling and product take-back.

2.1.3 ORGANISATIONAL ISSUES

2.1.3.1 Teamworking

The use of teams and teamworking is fundamental to CE. It is often seen as one of the simplest, and effective ways of improving the product development process. The need for a team approach is clear. The knowledge and expertise of a group is likely to exceed that of an individual, the thoroughness and creative ability of a team will in most cases exceed that of an individual, and a team will be inherently concurrent in its operation and ensure that information is communicated to all relevant personnel. Burns Morton (1948) defines teamwork as:

> the continuous condition of working together which make the most of circumstances, and persons, both individually and collectively, in the common interests of the group.

He also highlights eight factors, echoed by Tomkinson and Horne (1996), that influence the effectiveness of a team: its size, the character of the members, the outlook of the members, the length of time the group has been together, the degree of change in membership, the type of work, the manner of supervision, and the working conditions.

However teamwork can become an overhead, complicating the process, hindering communication and clouding decisions if not managed correctly. Smith and Reinertsen (1991) provide a number of criteria that are essential for efficient team function. The size of the team should ideally be limited to ten or fewer members. Members should serve willingly for the duration of the project, though this may only be true of a core team allowing the inclusion of specialists at the appropriate time. Key functions of at least marketing, engineering, and manufacturing should be represented and should be co-located. Belbin (1996) also identifies human behaviour types that can be identified through a simple questionnaire and used to improve the likelihood of team success.

Though there are only guidelines for team formation and success, it is a vital part of engineering development activity. Fortunately it is widely accepted as one of the key elements for integration of design and manufacture activities and subsequently the development of modular products.

2.1.3.2 Cellular Manufacture

Cellular manufacturing (CM) provides an organisational framework that allows a modular approach to system design and facilitates the introduction of programmes such as CIM, JIT, and TQM (Alford 1994). CM expands upon the theory of group technology, grouping products with the processes and personnel required to produce them. These groups form the basic cells from which the whole production process is structured. A cell may be defined by the processes that go into it, and the particular products that require those processes, or by a recognisable product encompassing some part of the production process. The distinction gives the cell its identity, where a process based cell can produce different products yet retain its identity. A product based cell would be linked to that particular product, modification to the processes would not effect the identity of the cell, yet removing the product would remove the cell.

Though the cellular manufacturing concept typically implies the co-location of products, processes and people in a group known as a real cell, a cell may exist where the group is not located in one physical location. Some of the resources may be shared with or assigned to other cells as requirements change, this is known as a virtual cell (Bedworth, Henderson and Wolfe 1991). The advantages and possible disadvantages of CM include:

- Simplified scheduling as cells can be scheduled as a single entity.
- Minimised materials handling as parts move only short distances within the cell.
- Material tracking and control is minimised.
- Tooling and gauging control is improved with reduced tooling inventory.
- Set up times are minimised, with an associated increase in throughput.
- Higher worker morale and motivation through teamwork and increased responsibility.

- Breakdowns become more disruptive.
- Cell operator training is more important.
- Unmanned cell costs can be high.
- Independent cells are difficult to create. Thus cells cannot be effectively isolated from other parts of the factory.

2.1.3.3 Flexible and Agile Manufacturing

Manufacturing flexibility is an essential part of addressing the market pressures for increased variety, reduced lead times and improved quality. Corrêa and Slack (1996) highlight the benefits of manufacturing flexibility particularly the change in competitive strategy from economies of scale to economies of scope. However care must be taken when dealing with manufacturing flexibility as the term has no agreed definition, in fact there are a number of flexibilities that are subsumed within the general concept. Possibly the best generic definition of flexibility is the ability to respond effectively to changing circumstances (Nilsson & Nordahl 1995), or the ability to cope with the uncertainty of change effectively and efficiently (Tincknell & Radcliffe 1996). Specific types of manufacturing flexibility include:

- Volume / mix flexibility - to accept a change in production volumes or a range of products.
- Product changeover flexibility - to changeover to the production of a new product.
- Operational flexibility - to absorb changes to the product during its working life.
- Routing flexibility - to manufacture or assemble along alternative routes.
- Machine flexibility - to perform various tasks on a variety of parts.
- Location flexibility - to move the production of a particular product to different factories.

Not only does the type of manufacturing flexibility have to be defined, but also the level of flexibility. Tincknell and Radcliffe (1996) propose that flexibility is the highest level, and that further down the scale the system becomes versatile and then capable. Versatility is the ability to change between known states, and capability is the underlying functions or envelope of operation.

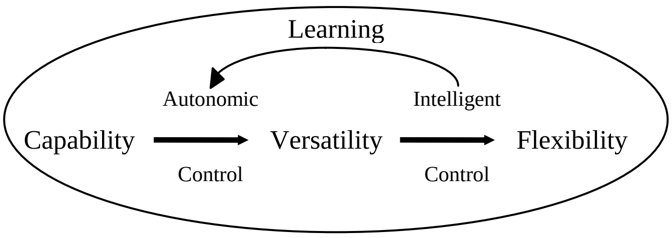

Figure 2.10. A Framework for Modelling Flexibility (Tincknell & Radcliffe 1996).

Manufacturing flexibility relies upon manufacturing strategy and the implementation of flexible facilities and working practice, but equally the responsibility of design and engineering functions to provide a product that is sympathetic to flexibility. This includes the consideration of DFMA, part commonisation, product modularity, and an up front loading of effort. Manufacturing flexibility is a collection of product and process design concepts, aimed at ensuring the competitive edge of a manufacturer (Barnett, Leaney and Matke 1995). Issues for flexibility are:

- Typically flexible systems will have greater short term cost, but will realise greater long term savings. However care must be taken as flexibility cannot be achieved indefinitely.
- Flexible systems will typically be more complex both in design and in operation.
- Flexible systems must be given time for adaptation, thus decreasing the time available for the actual operation for a given cycle time.
- Flexible systems can be developed to accept changes in capacity, but this will affect the size of the facilities and often require the inclusion of redundancy.

Agile manufacturing is a concept that has gained momentum in enabling rapid response to market needs. It aims to provide the flexibility of response with the efficiency of lean production, not only in the manufacturing environment but throughout the whole organisation. Gould (1997) defines the agile approach as: the ability of an enterprise to thrive in an environment of rapid and unpredictable change, and draws comparison between this goal and those of other initiatives such as mass customisation, the fractal factory, holonic manufacturing, and holonic enterprise.

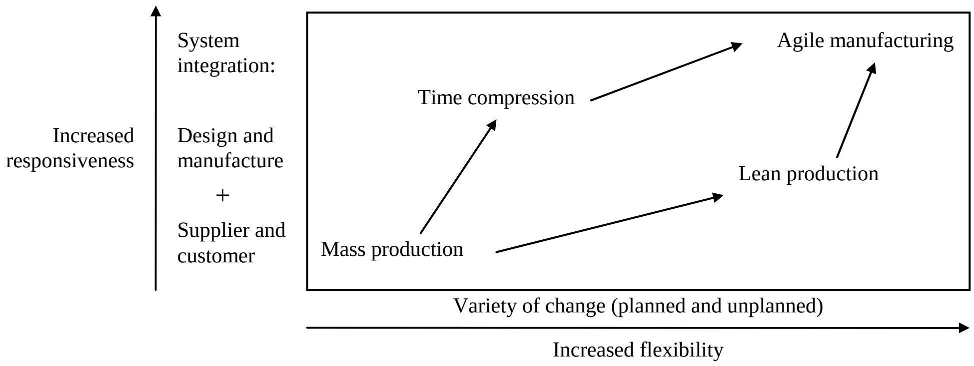

Figure 2.11. The Paths to Agile Manufacturing (Booth 1995).

Booth (1995) suggests that the path to agile manufacturing (Figure 2.11) is a combination of process integration to reduce lead time, and flexibility in minimising the costs of complexity associated with variety. He also proposes three aspects to the change to agile manufacture; the organisation, people's working methods, and information systems. Owen and Kruse (1997) group these into internal and external agility. Internal agility being the ability to respond rapidly to change by localised changes to the product or processes. External agility covers the organisational approach through the extended enterprise, companies focusing on their core competencies and forming strategic partnerships with suppliers to address change.

The final consideration is the product. As the product design is important in flexibility so it affects the concept of agile manufacturing. Appropriate consideration of design techniques and product architecture can facilitate agility by the provision of modular products, products that allow the introduction of variety late on in the manufacturing process and reusable design.

2.1.3.4 Mass Customisation

The term mass customisation was coined by Davis (1987) and was used to identify the process of providing customised products quickly and cost effectively. Custom products are typically the domain of the craft industry, expertly produced to exact customer requirements. Mass customisation offers the capability of providing these customer oriented products with timescales and costs normally associated to mass production techniques (Beaty 1996). Mass customisation aims to replace the economies of scale of mass production with economies of scope (Ross 1996). Thus mass customisation is a methodology that meets customers needs through variety and customised products, at a lower cost and reduced timescale through flexibility and responsiveness.

Magill (1996) introduces some generically applicable business drivers for mass customisation faced by the Special Products Division (SPD) of the bicycle manufacturer Raleigh Industries:

1. Saturation in increasingly competitive markets and the emergence of cheaper foreign imports had forced a downwards trend in pricing.
2. Market turbulence, through rapid fragmentation and shrinking segments combined with shorter product life-cycles, making product definition difficult for that elusive ‘average’ customer.
3. Customers were more knowledgeable and demanding about the goods on offer and it was becoming harder to differentiate the brand or products.
4. Customers demanded quick delivery and with heavy reliance on forecasting there were high stock and inventory costs, with product obsolescence being an additional expensive risk.

Mass customisation is possible with a range of philosophies that are classified by the nature and degree of variety offered to the customer. The lowest degree of customisation, and therefore the easiest is the provision of variety in cosmetic details such as colour, surface finish or material. The intermediate level of customisation is the ability to offer the customer a variety of functional options. The greatest degree of customisation is provided by those companies who can offer variety in the core elements of their product. Regardless of level there are three framework elements that must be addressed in order to move toward a process for mass customisation: customer focus, information technology, and business process focus (Ross 1996)

Customer focus requires an understanding of who the customers are and what they want. Through the capturing of requirements up front, customer needs will be used to shape the development of business processes into meeting these needs, in addition to making the processes quicker, cheaper and more consistent. Products and processes must be flexible enough to efficiently deal with the ensuing variety. They must also be modular, so that customer needs can be met by selecting individual pieces of each product and process module as required (Ross 1996; Magill 1996).

Information technology provides an integrating framework. The development of an integrated organisation is the key to the support of mass customisation; the speedy and efficient management of data, whatever it's form, from requirements through scheduling and order tracking, to EPoS (Electronic Point of Sale) data. In addition the product development and manufacturing strategy must be tuned to the goals of mass customisation. Again there are three possibilities (Ross 1996):

- Combinatorial assembly involves assembling combinations of components, sub assemblies or modules to provide variety and meet specific customer requirements.
- In-house processing involves the use of manufacturing processes such as CNC machine tools and requirements databases to provide the customer with a variety of form and function.
- Information content customisation is suggested by Ross (1996) as the ideal approach to mass customisation. It involves the customisation of products through software.

Though mass customisation is a serious challenge, it offers considerable benefits to both business and customer and a number of companies have put a mass customisation approach into operation including: Motorola, National Bicycle Industrial Company (Panasonic), Charles Letts & Co Ltd. (Ellis 1996), Raleigh Industries SPD (Magill 1996), and IBM (Beaty 1996).

2.1.3.5 Holonic Manufacturing

Central to the concept of holonic manufacturing is the holon. This term is derived from two observations by Koestler (1967). The first is from Simon (1962 & 1990) and is based on the parable of the two watchmakers (Appendix 5). The parable tells of the fortunes of two Swiss watchmakers, Bios and Mekhos. The conclusions drawn highlight the fragility of Mekhos' sequential assembly process to disturbance, and the greater robustness, ease of maintenance and repair of Bios' product, assembled through the hierarchical steps of subassemblies.

The second observation by Koestler is the relativity of hierarchies (Appendix 5). Intermediary structures such as subassemblies have characteristics associated with 'parts' and also with 'wholes' depending on the way in which they are viewed. Koestler uses the Roman god Janus to illustrate the concept. Like Janus each element has two faces looking in opposite directions: the face turned toward the subordinate levels is that of a self contained whole; the face turned upward toward the apex, that of a dependent part. The conclusion is that this Janus effect is a fundamental characteristic of all such structures in all types of hierarchies.

To represent these Janus-faced entities Koestler proposed the term 'holon'. Holons are autonomous self reliant units, which have a degree of independence and handle contingencies without asking higher authorities for instructions; simultaneously holons are subject to occasional control from higher authorities. Whatever the nature of a hierarchic organisation, its constituent holons are defined by fixed rules and flexible strategies, allowing it to act independently but also allowing decisions to be made. Thus a holon is simultaneously a whole or part of a whole.

Holonic manufacturing systems (HMS) are part of the Intelligent Manufacturing Systems (IMS) programme that addresses the so called 'fragility' of today's manufacturing systems (Valckenaers & Van Brussel 1994). The findings of an initial test case identify that the manufacturing industry of the future will have to be organised differently and will have to be more flexible in responding to the customer needs. Manufacturing systems will be highly decentralised and built from a modular mix of standardised, autonomous, co-operative and intelligent elements (Figure 2.12).

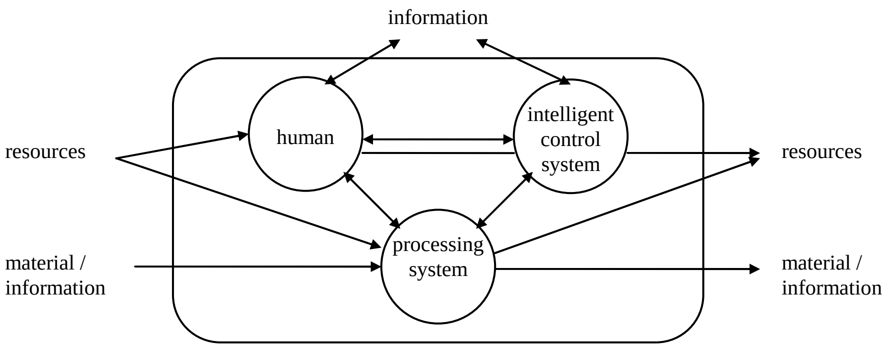

Figure 2.12. Generic Activity Model of a Holon (Leeuwen & Norrie 1997).

HMSs are composed of holons consisting of an information processing part and often a physical processing part. They are organised as a holarchy, which defines the basic rules for co-operation of the holons and thereby limits their autonomy. HMSs are, however, not organised in a fixed way, but can organise themselves dynamically to meet their goals, or adapt to changes in the environment. The proposed implications and benefits of holonic manufacturing systems are:

- The ability for rapid self-reconfiguration in response to uncertainty.
- The ability to form virtual companies within and across enterprise boundaries.
- The flexible reaction of the production system to requirements.
- Synergy through the co-operation of holons to achieve their full capability.
- Modularity, to allow interaction between a range of holons and allow easy upgrade of holons.

A further manifestation of the holon is in the form of the holonic enterprise. This builds on the nature of business process re-engineering, by defining a holonic network as a group of businesses that, co-operate in an integrated and organic manner, forming a system able to configure itself to manage each business opportunity that a customer presents (McHugh, Merli and Wheeler 1995). The development of concepts such as the holon will aid in the conveyance of designs throughout manufacturing and the business enterprise, by providing an increased awareness of manufacturing concerns, and a means of implementing new product development in a manner that utilises the core competencies of businesses, rapidly, and with considerably less disturbance.

2.1.3.6 The Bionic Factory

A CAM-I Japanese Interest group, also known as the Japan Advanced Technology Planning Committee an affiliate of Computer Aided Manufacturing International (CAM-I) has been set up to investigate the biological parallels to manufacturing organisations, though the concept of bionic manufacturing systems (Engel 1990).

Biological organisms provide three basic characteristics that bionic manufacturing systems aim to emulate, namely: spontaneity, versatility, and harmony. Biological organisms are autonomous units that communicate with their environment. Every organism obtains information from its environment which it can used to regulate an activity (spontaneity). Each organism can perform tasks in response to the information (versatility), yet all share a natural ecology (harmony).

In bionic manufacturing each system consists of autonomous elements that can be whole factories, individual offices or machines. Each system is linked by an information network with which all elements can exchange requests and responses simultaneously. Such a system concept places emphasis on flexibility, of physical machines and of computing models. A particular model being investigated for bionic manufacturing systems is that of modelons. Modelons are intelligence elements based upon Koestler’s holons, in that they are autonomous, and part of a larger modelon. Modelons consist of working space containing the objects to be processed and knowledge of the operations required for processing. Each object and operation is itself a modelon.

The information available throughout the hierarchy is based upon deoxyribonucleic acid (DNA) ensuring that all the knowledge of the system is carried or shared by all autonomous elements in the overall system. Other information can only derive from intuitive intelligence i.e. from the brains of operators in the manufacturing context. (Deasley 1994).

For the future the CAM-I Japan Interest Group have defined three areas of modelon research: a bionic design room involving the conversion of CAD and CAE tools into modelon format, a bionic manufacturing plant that will utilise moveable work units exhibiting the modelon properties of autonomy, spontaneity, flexibility, and communications, and bionic CIM.

2.1.3.7 The Fractal Factory

The fractal factory is a term coined by Hans-Jurgen Warnecke, the head of the Fraunhofer Institute for Manufacturing Engineering and Automation in Stuttgart, Germany. His proposal is that the increasing complexity observed within the management, control and operation of manufacturing has lead to the need for an alternative view of how the factory of the future may be organised. The use of CIM is one approach, but is found lacking in dealing with the numerous elements bearing multiple, often non-linear relationships with one another within the manufacturing system. Other new approaches such as complexity reduction, concentration on core areas, GT and cells, lean and agile manufacturing are highlighted. Warnecke thus introduces the term fractal factory to establish a common denominator to represent the complex behaviour of modern systems and to determine the commonality of the numerous approaches so that they may be integrated into a holistic approach. Above all, the term is used to stimulate awareness (Warnecke 1993b).

The term fractal was coined to represent organisms and structures in nature. Living organisms show the characteristics of extremely complex, interlinked, and ordered structures which cannot be defined by a static snapshot. Living organisms show the ability to constantly adapt to new conditions, new events and situations, by modifying their structures to address these needs. They are self-organising, self optimising and dynamic.

Fractal mathematics is a way of measuring these highly complex natural structures of dynamic change and self organisation. Such structures are the subject of the theory of fractal geometry devised by Benoit B. Mandelbrot (b. 1925) which has opened up the possibility for the mathematical treatment of these forms whose coarseness and structure basically remain the same when resolution is increased.

It is possible to discern two prime characteristics of fractal objects: Self-organisation where fractals within a factory have the freedom to use the methods appropriate to the particular task, with different fractals free to use different methods. Self-similarity where the structure (fractal factory) is made up from many similar smaller structures (mini fractal factories). Thus their properties reflect the structure of holonic and bionic manufacturing systems.

Taking the properties of fractal geometry and applying them to manufacturing technology a definition of a fractal is that of an independently acting entity whose goals and performance can be precisely described, and exhibit the same characteristics of self-similarity and self-organisation. Thus the fractal factory is an attempt to provide a model for corporate re-engineering that can provide a deterministic modelling of the complex global markets and corporate structures of today's industry, based upon a reflection of nature and the theories of chaos research.

2.2 SYSTEMS

In 1967 Jenkins highlighted that a piecemeal approach to system development was no longer acceptable in the light of increasing complexity, and increasingly harsh consequences of poor decision making (Jenkins & Youle 1971). What was required was a disciplined holistic approach to the development of systems, which can be defined as:

> An organised and interrelated set of components that fulfil a purpose.

Other definitions include those by Blanchard and Fabrycky (1990), Singh (1996) and Reilly (1993) and though definitions differ, they are mainly on the grounds of perspective. There is generally a greater consensus on the properties exhibited by a system (Blanchard & Fabrycky 1990; Pahl & Beitz 1996):

- A system has an overall objective or function. This function must be explicitly defined and understood in order that system elements provide the desired output for a given set of inputs.
- A system is a hierarchy of interdependent elements that perform together as a functional unit, these elements are referred to a sub-systems.
- A system is defined by its limits or boundary. Everything outside the boundary is considered to be the environment. A system will interact with its environment through inputs and outputs.
- Systems are composed of: components - operating parts of the system consisting of input, process, output; attributes - the properties or discernible manifestations of the components of a system; and relationships - the links between components and attributes.
- The properties and behaviour of each component of the system has an effect on the properties and behaviour of the system as a whole, and is influenced by at least one other component in the set. Thus any one component cannot be designed in isolation from the overall system.
- A system is more than the sum of its components as the set of components comprising the system always exhibits some characteristic that cannot be exhibited by any of its subsets.

2.2.1 SYSTEMS THINKING AND SYSTEMS ENGINEERING

Systems thinking stemmed from the finding that in order to understand complex biological phenomena the traditional reductionism of natural science was not the best approach. What was proposed was a systems approach that was systemic, or concerned with the whole (Checkland 1981; 1983). The systems approach in engineering often does not reflect this view and leads to systems engineering which is based on reductionism rather than systemic thinking (Kidd 1994).

Checkland (1981) introduces the terms 'hard' and 'soft' systems where a hard systems method is one that is designed to achieve given objectives. Hard systems have needs that can be clearly defined, and that the engineering challenge is to design and select the best among possible alternative systems. Soft systems methods are applied to situations where objectives cannot be taken as given (King 1988; Wilson 1990). The distinction is highlighted by Parnaby (1981), where the manufacturing system is seen in terms of 'hard'ware, processes, controls, inputs and outputs, etc., and where the 'soft' social processes such as human interaction are outside the system.

The IEEE-Std 1220-1994 (1995) provides the definition that systems engineering (SE) is an interdisciplinary approach to derive, evolve, and verify a life cycle balanced system solution that satisfies customer expectations and meets public acceptability. SE involves the application of efforts to (Blanchard & Fabrycky 1990):

1. Transform an operational need into a description of system performance parameters and a preferred system configuration through the use of an iterative process of functional analysis, synthesis, optimisation, definition, design, test and evaluation.
2. Incorporate related technical parameters and assure compatibility of all physical, functional, and program interfaces in a manner that optimises the total system definition and design.
3. Integrate performance, producability, reliability, maintainability, manability, supportability, and other specialities into the overall engineering effort.

Early processes for SE consisted of four major stages (Jenkins & Youle 1971; Yourdon & Constantine 1979):

1. Systems analysis. Includes formulation of the project, definitions and objectives for the system, and information and data collection.
2. Systems design or synthesis. Includes forecasting of the system environment, modelling and simulation, optimisation, and selection.
3. Systems implementation. Involves approval of the systems concept, construction and checking.
4. Systems operation. Includes use, appraisal and improved operation of the system.

This approach has been adopted by computer system and software engineers who have utilised this systems process as a structured and requirements driven approach to development. The appealing aspect of this approach is the ability to take an inherently ambiguous and complex set of requirements and apply a structured process to achieve an efficient solution. This process is also repeatable, independent from any one particular programmer, allowed implementations to be traced to customer requirements, and also considered the implications beyond implementation.

The increasing complexity of physical and human activity systems in general has seen the application of SE outside of the computer systems arena. SE can be applied equally well to products especially when they are complex enough that conventional development techniques are insufficient for the project's intricacies and uncertainties (Martin 1997).

The IEEE document a SE process (Figure 2.13) that illustrates the flow of requirements upon the system and how these are used to define the functions and finally the physical arrangement of the system. Though the most widely accepted representation of the SE process is the SE 'V' (Figure 2.14). The SE V represents a typical SE process where requirements are taken and functionally decomposed into modules (the downstroke of the V), then the system modules are synthesised into the completed system (the upstroke of the V).

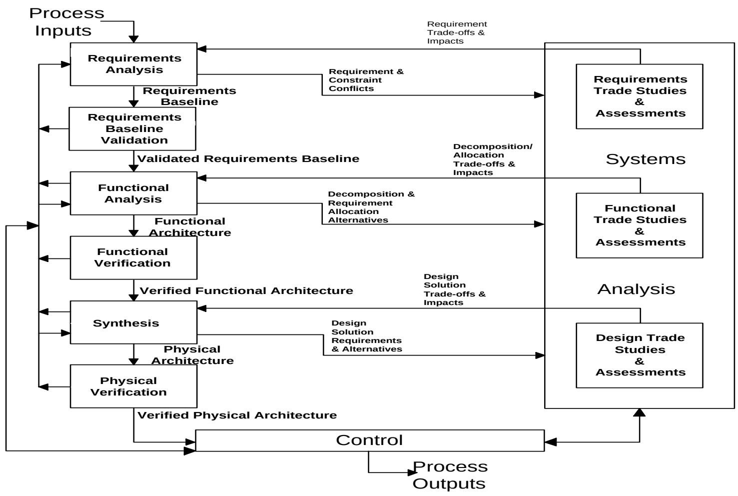

Figure 2.13. The Systems Engineering Process (IEEE-Std 1220-1994, 1995).

The functional decomposition process begins with requirements management. This typically consists of identification and capturing of all source documentation and media from which the requirements are captured and categorised and a systems analysis is performed. The system analysis consists of identification of the environment in which the system will have to perform, the tasks it will have to be capable of and the functional decomposition of the system.

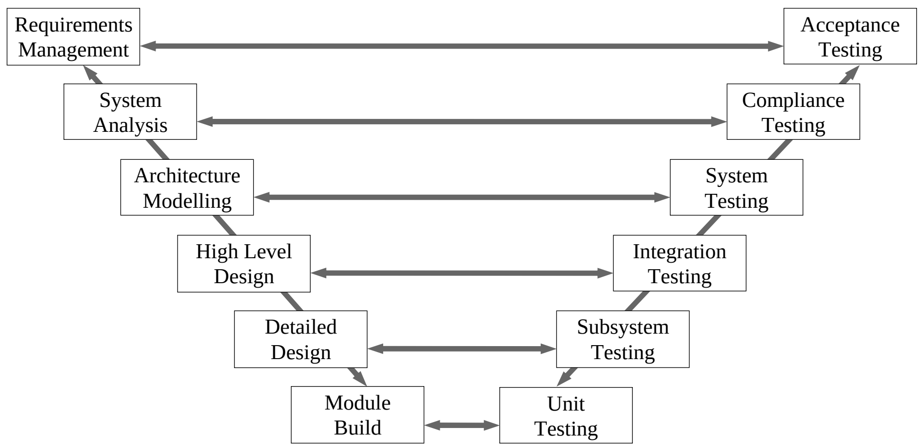

Figure 2.14. The Systems Engineering V (Walker 1997).

After the analysis the system architecture is modelled. This includes the identification of system elements and the system topology. The elements defined are then linked to requirements and are given performance constraints and budgets. High level design takes the architecture determined in the modelling of the system architecture and relates system elements to physical equipment.

High level design is followed by detail design where physical system equipment is broken down into its constituent components and interfaces. Functions are allocated to hard and software and requirements are further linked to system elements. Simulation is performed to verify the system. The final stage is that of module build. Software code is generated, hardware schematics are created and all mechanical and electronic components are designed. Engineering analyses are performed, a bill of materials is completed and pre-production samples are produced.

The rest of the process concerns validation (to ensure that the correct requirements are being addressed) and verification (that the requirements are being met in the correct way) of the system elements and their function in isolation and as a system. However, this typical SE process only provides a cursory consideration of manufacturing. The development of SE for complex computer systems and software has largely excluded the need for manufacturing. Thus SE, though considering the whole system and its design and maintenance only considers manufacture as the natural consequence of design.

Independent of the process followed Martin (1997) presents the relationship between processes, methods, tools, and environment (PMTE - Figure 2.15) and highlights the need for a balance when performing SE tasks. He also identifies seven key elements that will be present in a successful SE effort including a management plan (SEMP), a master schedule (SEMS), a detailed schedule (SEDS), a work breakdown structure (WBS), requirements, technical performance measurement (TPM), and technical reviews and audits.

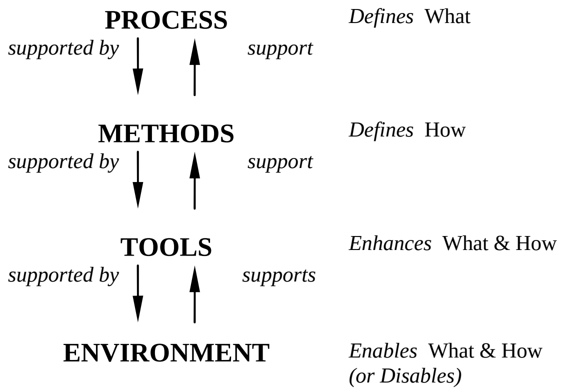

Figure 2.15. The PMTE Paradigm.

As an example the Toyota production system (TPS) typifies the best features of a structured systems approach. (Parnaby 1995) Combining hard and soft systems methods the TPS is not solely concerned with the technology of making automobiles but also with the role of people, the organising processes and the relationships and interactions (Whitney 1992a).

2.2.2 REQUIREMENTS

SE is a requirements driven process. Requirements are expressed as input criteria for design and are a collection of customer wants and needs, internal wants or needs, legislation, and any other characteristic or feature that is needed or wanted from the system. SE requirements are defined as statements that identify a capability, physical characteristic, or quality factor that bounds a product or process need for which a solution will be pursued (IEEE-Std 1220-1994, 1995). Seven groups of requirements can be identified (Blanchard & Fabrycky 1990):

1. Mission definition - the identification of the prime operating mission of the system, what the system is to accomplish, and how the system is to accomplish its objectives.
2. Performance and physical parameters - the operating characteristics or functions of the system such as size, weight, speed, accuracy, and capacity. Critical parameters should be highlighted.
3. Use requirements - the anticipated level of use of the system such as hours of operation, on-off sequences, and how it is to be used.
4. Operational deployment or distribution - the expected quantity of equipment, facilities, and personnel, and the expected location for transportation and mobility requirements.
5. Operational life cycle -the anticipated time that the system will be in use, the total inventory profile throughout the system life cycle, who will operate the system and for how long.
6. Effectiveness factors - operational availability, dependability, logistic support effectiveness, failure rate, maintenance requirements, and personnel efficiency.
7. Environment - a definition of the environment in which the system will operate including, temperature, humidity, terrain type, transportation requirements and handling.

Requirements and their management are fundamental to SE. Requirements must be collected or captured and analysed up front in the process. These will then form the basis of the system's success and after transformation into system parameters, will define the measurables of the system. There are a number of attributes relating to the development of a set of system requirements. Ideally a set of system requirements should be correct, unambiguous, complete, verifiable, consistent, traceable, and concise (Davis 1993).

2.2.3 MECHATRONICS

A recent enthusiasm for the development of mechatronics, the fusion of mechanical, electronic, and software elements, highlights one example of a practical application that requires a systems approach. Mechatronics is defined as:

> the synergistic combination of precision mechanical engineering, electronic control and systems thinking in the design of products and manufacturing processes (Tomkinson & Horne 1996)

Thus mechatronics requires the synergistic use of systems thinking. This is summarised by the definition that mechatronics is not a subject, science or technology per se, it is instead to be regarded as a philosophy, a fundamental way of looking at and doing things, and by its very nature requires a unified approach to its delivery (Millbank 1993). Mechatronics provides a practical example of the difficulties faced by the engineering of complex multidisciplinary systems. The combination of just three disciplines imposes problems due to (Buur 1989):

- The substance of design problems is different for all three fields.
- There is no common language between engineers.
- There is no cross-functional support either in education, or more specifically in tools and systems.

2.2.4 SYSTEMS ENGINEERING TOOLS

Systems engineering tools are organised into three broad categories: requirements management workbenches, system modelling environments, and SE environments (Loureiro 1996).

2.2.4.1 Requirements Management Workbenches

Requirement management workbenches address requirements management throughout the system lifecycle, including structuring customer requirements into system requirements and allowing requirements to be interlinked, traced, documented and viewed from a variety of perspectives (Williams & Allan 1995). Examples of requirements management workbenches include:

- RTM - Requirements Traceability and Management.
- DOORS - Dynamic Object Oriented Requirements System.
- SLATE - System Level Automation Tool for Engineers.
- CORE - cost-effective system engineering, analysis, and specification.

2.2.4.2 System Modelling Environments

System modelling environments provide the ability to study the feasibility of system design and to highlight design errors. Building upon the specified requirements in the requirements database, functions are defined and assigned to system components using representations such as $IDEF_0$, function block diagrams, state-transition diagrams etc. Allocation of system resources can also be carried out by the execution of the model. A dynamic model can be produced on the basis of the static model of a system or created directly by using general purpose system thinking packages such as Stella or Ithink (simple modelling building blocks based on flows, containers and links) (Williams & Allan 1995). System models can then be used for many operations including process modelling, product planning and development, and simulation. Examples of system modelling environments include:

- RDD-100 - Requirements Drive Development.
- JSD - Jackson System Development.
- SA-RT - Yourdon Structured Analysis Real-Time.
- HPM - Hatley-Pirbhai Methodology and TeamWork.
- STATEMATE.
- Booch & OMT - Unified method for object oriented development.

2.2.4.3 Systems Engineering Environments

Though requirements management workbenches and system modelling environments provide numerous tools they tend to be dedicated to specific phases of SE and lack the integration throughout the SE lifecycle. Cradle, developed by Structured Software Systems Ltd (3SL), is a SE environment that provides a fully integrated multi-user, multi-project tool through a number of modules (3SL 1996 - Figure 2.16). Though Cradle may not be as highly developed in any one SE aspect as other tools it is its integrating nature throughout the SE lifecycle, and to other tools, that provides the benefit within an SE environment.

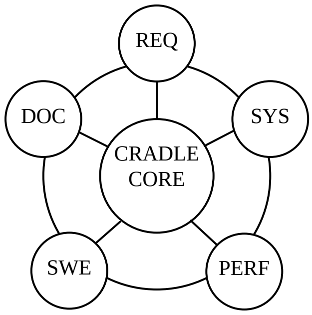

Figure 2.16. The Cradle Modules.

- CRADLE/REQ - Requirements management tool, able to deal with customer or internally generated source documents in a wide range of formats. It automatically identifies differences between versions of a source document and produces an impact analysis report.
- CRADLE/SYS - Systems modelling tool, with a method independent database. Cradle provides a number of integrated modelling notations to suit the user including: Data Flow and State Transition Diagrams, Function Block Diagrams, Behaviour Diagrams, Entity Relationship Diagrams, Structure Diagrams and Object Oriented support.
- CRADLE/SWE - Software engineering tool, supports code generation and reverse engineering. Languages supported C, C++, Ada and Pascal.
- CRADLE/DOC - Document management tool, containing numerous preconfigured report formats and a templating tool to replicate any company standard documents.
- CRADLE/PERF - Performance modelling tool, verifies the validity and integrity of a system early in the project lifecycle and provides graphical impact analysis.
- CRADLE/CORE - The key element of Cradle, including: configuration management, text and graphics reporters, workflow, project control and third party integration facilities. CORE has the ability to act as a framework for programme information. Allowing externally generated information such as CAD drawings, spreadsheets and DTP files to be configuration managed in one place, linking all programme information tightly together.

2.3 MODULARITY

The concept of a module is one used widely and often regarded as important to the development of competitive products. However the terminology of modules and subassemblies are often considered interchangeable and thus are mistakenly applied in a broad range of cases (Whitney 1992b). Modules have a number of characteristics discussed later that provide fundamental differences between them and convenient groups of components in a subassembly.

Modularity is typically utilised for its ability to rationalise variety through the partitioning of product functions (Pahl & Beitz 1996; Rampersad 1994; Smith & Reinertsen 1991; Shirley 1992; Parnaby 1995) and allow for flexibility of application (Erixon & Östgren 1993). This advantage has been applied widely throughout the electronics industry for computer manufacture (Haynie 1997). Within the automotive industry on the Max spider (Weernink 1989), the Renault Modus (Smith 1995) and within Visteon the new automotive supplier (Elvidge 1998). Also within the aerospace industry on the Joint Strike Fighter: a highly common modular range of aircraft for airforce, marine, and navy use (JSF 1997).

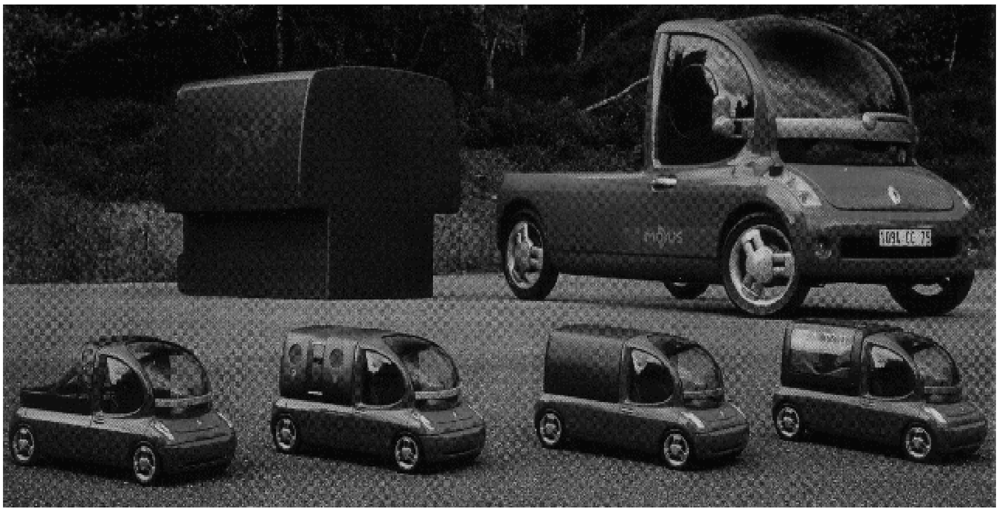

Figure 2.17. The Renault Modus.

However variety is only one aspect of product modularity. One of the key elements of modularity is its requirements for a system level view and the opportunity it provides for the engineering of both product and process in unison. Some of the following techniques highlight the benefit to both design and manufacture of a modular approach and the necessity of a true SE framework.

2.3.1 MODULAR PRODUCT DESIGN TECHNIQUES

2.3.1.1 Fractal Product Design

Earlier in the chapter we introduced the concept of the fractal factory from the Fraunhofer Institute in Stuttgart. The principles of the fractal factory can also be applied to the design process in terms of design fractals which co-exist, self-organise and self-optimise to achieve a common goal, that of customer satisfaction. They may be further applied to the product structure. Fractal product design is based on a product structure composed of product fractals. Product fractals are independent modules with a precisely defined functionality. Product fractals are also self-similar in terms of having standard mechanical and information interfaces. Thus product fractals may have dissimilar components and structures, but will maintain the same inputs and outputs (Warnecke, Schneider, and Kahmeyer 1994).

The IPA has developed a five step approach to fractal product design and is currently being implemented into a number of industrial projects.

1. Product analysis: Analysis of product range, product structure and functional structure.
2. Conceptual design of alternative product fractals: Development of alternative fractal product structures and morphological documentation of alternatives.
3. Conceptual design of fractal interfaces: Development of alternative standardised interfaces for product fractals.
4. Fractal assessment and validation: Quantified assessment of the developed product structures with respect to: function, quality, manufacturing, assembly, disassembly and recycling.
5. Fractal redesign and optimisation: Redesign and optimisation of the developed product fractals based upon classical redesign tools including: DFA, DFM, FMEA, QFD.

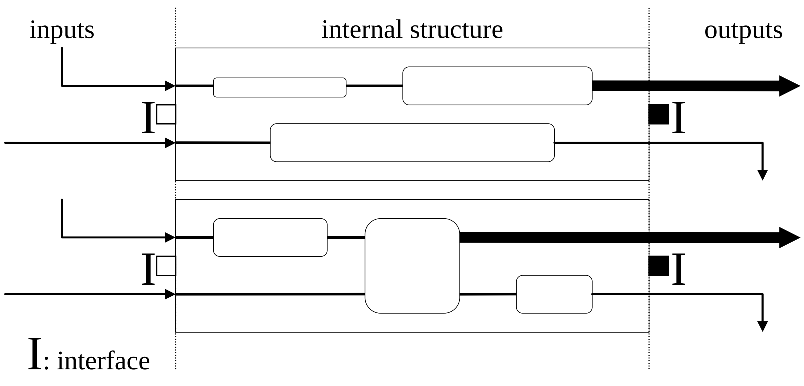

Figure 2.18. Self Similar Product Fractals with Standard Interfaces.

2.3.1.2 Modular Function Deployment

Development of product modules has been carried out by a Swedish partnership of the Department of Manufacturing Systems at the Royal Institute of Technology, and the Institute of Production Engineering Research, in Stockholm. The results from a study of seven companies who had changed from an integrated product to a product divided into modules proved to be encouraging enough to develop a method for identification of modules (Erlandsson, Erixon and Östgren 1992). The study concluded that there were six reasons for modularising a product:

1. Development. Parallel design of modules, simplified planning, use of carry overs.
2. Manufacture. Common modules, rationalised material handling, reduced rework.
3. Product variants. Variant modules allow adaptation of products for customer requirements.
4. Purchasing. Ability to buy in complete modules, reduced logistics costs.
5. Exchangeability. Upgrade, maintenance and rebuild all simplified.
6. Miscellaneous. Possibility for simpler recycling, and parallel manufacture.

The method consisted of seven stages and was carried out by a team who developed two QFD matrices and a Pugh (1990) concept selection matrix (Figure 2.19 -Erixon & Östgren 1993). Having identified modules, interfaces were identified and the most suitable modular groupings were selected and modules and interfaces analysed using DFA. A later development was used to synchronise the planning of product introduction with manufacturing system changes. This enabled a long term strategic product assortment to be defined (Erlandsson & von Yxkull 1993).

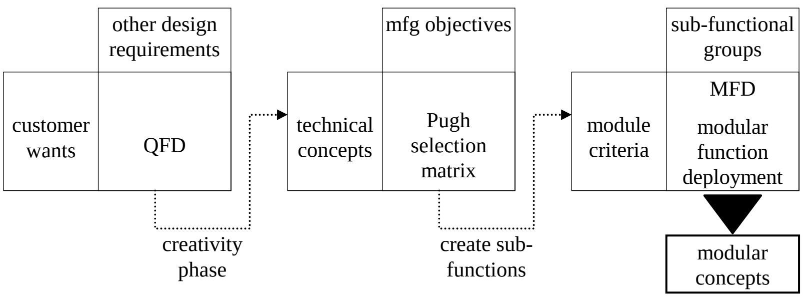

Figure 2.19. The Method for Developing Modular Concepts.

Further development includes a change of matrix name from MFD to modular indication matrix (MIM) with MFD used for the process as a whole (Erixon, Erlandsson, von Yxkull, and Östgren 1994). Matrix application has been overhauled using module drivers such as carry-over, styling, and upgrade, derived from direct questioning of users as oppose to module criteria, more guidance to the user and a greater consideration of interfaces (Erixon 1996). The MFD process now consists of five steps (Figure 2.20).

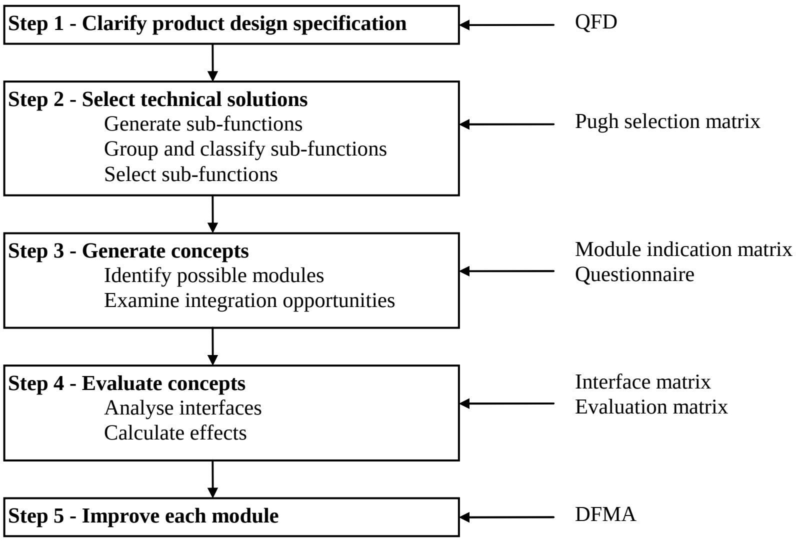

Figure 2.20. Design for Modularity - MFD Flowchart.

After completion of stage 3 and the MIM, modular concepts are evaluated against the so-called universal virtues - cost, time, quality, efficiency, flexibility, risk and environment (Olesen 1992). The evaluation occurs using the modularity evaluation chart (MEC) (Appendix 6). including lead times in development and assembly, development, system and product cost, quality, development capacity, variant flexibility, service, and recyclability. The metrics are used as a benchmark for a good modular design and centre around the number of parts N_p , modules N_m., average part assembly time T_{norm} , and interface time T_{int} in the new product. For a new product objectives are:

$$N_P = 0.7 * Old\ N_p \qquad\qquad N_M = \sqrt{N_P}$$

Lead time in assembly is provided by the following equation:

$$L = (N_p T_{norm}) / N_m + (N_m - 1)T_{int} \qquad\qquad Objective = 20 \sqrt{N_p} - 10$$

The MEC also provides nine rules of thumb (below) to support the search for the best modular concept. Stage 5 completes the process by application of DFMA evaluations to each module.

- Ensure that every new variant of a module can be used in several product variants.
- Minimise the value: [N_m * total modules for all product variants (N_{mtot}) * $\sum T_{int}$].
- Refine interfaces to minimise final assembly time, aiming for 10 seconds per interface.
- Maximise the share of separately tested modules.
- Maximise the share of carry-over modules and purchased modules.
- Limit the number of different materials in a module (material purity).
- Do not divide a function in two or more modules (functional purity).

2.3.1.3 Ulrich and Eppinger's Modular Product Design

According to Ulrich and Eppinger (1995), determination of product architecture is a system level design decision. Product architecture classifies the major groupings of physical elements as chunks. A products architecture is then identified as a scheme by which the functional elements of the product are arranged into physical chunks and by which chunks interact. The most important characteristic of a product architecture is its modularity. A modular architecture has chunks that implement one or a few functional elements in their entirety, and interactions between chunks are well defined and are generally fundamental to the primary functions of the product. The implications of product architecture are:

- Product change. Modular products allow changes to be made to isolated elements to accommodate upgrade, wear, or reuse etc., without affecting the design of other chunks.
- Product variety. Modular products allow a greater degree of variety through the use of a reduced set of standardised chunks.
- Component standardisation. Standard modules can be used that implement a few widely used functional elements. Standardisation simplifies design and increases manufacturing volumes.
- Product performance. To the extent that a performance characteristic depends on the size, shape, or mass of a product, it can generally be enhanced through an integral architecture.
- Manufacturability. One aspect of DFMA is the integration of components, a modular architecture inhibits the integration across chunks but still allows chunks to be treated as separate products for manufacturing and assembly purposes.
- Product development management. Teams can be assigned to individual chunks. Chunks are more easily taken up by suppliers. A greater up front effort simplifies downstream processes.

In order to establish the product architecture Ulrich and Eppinger (1995) propose a multi-disciplinary approach to a four step process:

1. Create a schematic of the product. Constituent elements may be physical, critical components, or functional. A recommended maximum number of elements is 30.
2. Cluster elements of the schematic. Involves assigning elements to chunks through consideration of geometric integration and precision, capability of suppliers, etc.
3. Create a rough geometric layout. A geometric layout in two or three dimensions aids the team to visualise if the proposed chunks will integrate physically.
4. Identify the fundamental and incidental interactions. Fundamental interactions are represented by chunk connecting lines on the schematic. Incidental interactions arise because of the physical implementation of functional elements and are not represented on the schematic.

Pimmler and Eppinger (1994) highlight the importance of interactions in the light of complex product decomposition and modular products. Interactions are extremely important in these cases as complex products have many possible decompositions, and that combining the separate sub systems into an overall solution can be difficult.

The area of interest is an additional stage where interactions are identified prior to determining the architecture, and how its information is used in later stages of the process. Interactions are then classified into four types of generic interaction: spatial -identifying the need for adjacency, energy - for energy transfer, information - for information or signal exchange, and material - for material exchange. Not only are the interaction types defined but also their importance and whether they are beneficial or detrimental. For example, spatial interactions would have the following:

Required	(+2)	Physical adjacency is necessary for functionality.
Desired	(+1)	Physical adjacency is beneficial, but not absolutely necessary for functionality.
Indifferent	(0)	Physical adjacency does not affect functionality.
Undesired	(-1)	Physical adjacency causes negative effects but does not prevent functionality.
Detrimental	(-2)	Physical adjacency must be prevented to achieve functionality.

Once this information has been determined it can then be used in the next step, clustering of elements into chunks. Figure 2.21 shows an interaction matrix and how it may be used to cluster elements. It bears many similarities to Burbidge's production flow analysis (PFA) that groups parts for group technology purposes (Burbidge 1975).

	A	B	C	D	E	F	G	H	I	J	K
Radiator A		2 0 0 2	2 -2 0 2								
Engine fan B	2 0 0 2		2 0 0 2								
Condenser C	2 -2 0 2	2 0 0 2		2 0 0 2		-2 2 0 2					
Compressor D			2 0 0 2		1 0 0 2	0 2 0 2					
Accumulator E				1 0 0 2		1 0 0 2					
Evaporator F			-2 2 0 2	0 2 0 2	1 0 0 2		-1 0 0 0	0 0 0 2		2 0 0 0	
Heater core G						-1 0 0 0		0 0 0 2		2 0 0 0	
Blower motor H						0 0 0 2	0 0 0 2		2 0 0 2	2 0 0 2	
Blower control I								2 0 0 2		2 0 0 0	
Evaporator case J						2 0 0 0	2 0 0 0	2 0 0 2	2 0 0 0		2 0 0 0
Actuators K										2 0 0 0	

Front end air chunk

Refrigerant chunk

Interior air chunk

legend: S E / I M — S = Spatial, E = Energy, I = Information, M = Material

Figure 2.21. Clustered Interaction Matrix for a Climate Control System.

2.3.1.4 Further Sources

A number of other techniques relating to the development and analysis of product modules exist and are grouped together here. These particular techniques are generally less well developed or accessible than those already covered such as Smith and Reinertsen (1991) who address modularity but do not provide a process, merely consideration of various factors such as assigning functions, redundancy, interfaces, and technical risk.

Pahl and Beitz (1996) present a modular product development process related to their planning and design process. Specific considerations include:

- During the initial project planning, additional attention should be paid to product functions and the variants of the overall function, and the market expectations for variants.
- During concept design, function structure should be determined such that overall function can be achieved by essential functions and additional task specific possible functions.
- Solution principles are then found for implementing the functions. Functions are combined in a single implementation if advantageous.
- Implementations are then evaluated with the help of technical and economic criteria.
- Once a concept is selected the individual modules are designed in accordance with their functions and the production requirements.

Suh (1990) suggests that good designs meet two design axioms. The independence axiom says that design solutions for functional requirements should be kept independent. The information axiom says that the information content of a design should be minimised. The interpretation is that there should be a mapping of single design parameters to single functional requirements and that the design should be kept simple in all respects. These axioms relate to modularity as modules that can be seen as virtually independent, avoid interaction complexity, allow parallelism, and simplify information processing requirements in a design project (Shirley 1992).

Kohlhase and Birkhofer (1995) present a computer aided process for modular system development based upon a software package designed to allow modular structures to be developed, examined, and evaluated. The aim of the program is to develop structures for modular systems that will replace existing product ranges. The structures are developed before individual modules to address the issues that arise due to module interactions. The package represents modular structures through the use of polyhierarchical graphs (Figure 2.22). Where nodes represent modules and links represent interactions. Link numbers refer to the number of modules required to construct more complex modules or modular products.

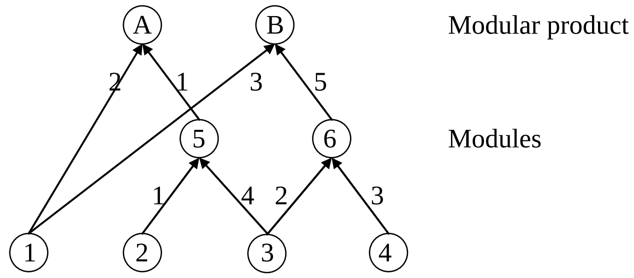

Figure 2.22. A Graph Representation of a Modular Structure.

Once described the modular system is examined to identify the trade off between the reduction of administration, distribution and product costs, and the realisation of customer requirements. The program allows different modular structures to be examined with respect to their cost to optimise this trade off and identify the appropriate structures to meet the overall criteria. The program finally allows modular systems to be evaluated to determine an overall rating and the flexibility. The variants of a modular system are rated against technical and economic criteria in the form of a target product; the product that is demanded by the customer. Overall rating is plotted against flexibility and those modular systems exhibiting the highest levels of both properties are chosen.

Svendsen and Hansen (1993) present a procedure for the decomposition of mechanical systems and their specifications. The process is directly relevant to the identification of modules within a product architecture. Their basis is a functional decomposition of the system in order to ensure that subsystems still fulfil the overall functions of the composite mechanical system.

The formal approach to the synthesis of mechanical systems is provided by the law of Hubka (1967). The law says that there exist causal relations between functions and means of a mechanical system. These relationships can be expressed by the function / means tree (Figure 2.23). The function / means tree expresses the system in a hierarchy of function and means levels linked by causal relations. Functions are expressed as verb + noun combinations and are met by means at a lower level, which in turn, require a number of subordinate functions in order to operate. Functions can be work (above a means) or additional (below a means), additional functions being further sub divided into: control /regulate, auxiliary, driving and connect / support functions. There are also three types of means: organism, organ, and functional surface parts.

To develop the function / means tree the system needs are transformed into one or more purpose functions. These means represent the alternative mechanical systems that can realise the same function. After several means are identified an optimum means and configuration is chosen as the solution concept. This means will require a number of functions to be fulfilled. The procedure is then repeated for each subsequent function until all the means are of the type functional surface. These functional surfaces are then integrated into components for the system.

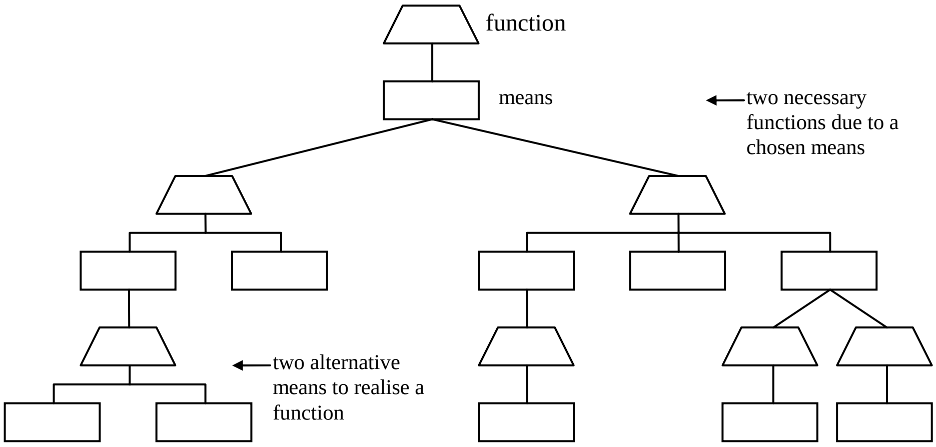

Figure 2.23. A Function / Means Tree.

Dowlatshahi (1992) presents a process of optimising product design in a CE environment. The process consists of a five stage algorithm based on a modular architecture:

1. Decompose the system. A modular product design is utilised to increase efficiency and practicality. Modules need to be cohesive, bounded, or be self contained. The process must be hierarchical in nature allowing further break down of individual modules. Modules are initially based on the natural seperability or modularity of a product (Neville 1989) where there are a greater number of interactions within modules than between.
2. Establish feasible parts space. The end result of the innovative descriptive design process is the optimal design alternative. For large complex products the optimal design alternative consists of several modules for which all individual parts should be specified. All of the parts specified will have a number of part options or variations.
3. Reduce the number of part options. Part options are reduced by excluding all inflexible, impractical, or undesirable part options by a screening process based upon criteria such as friction level, lining strength, fade recovery etc.
4. Calculate attribute-based utility values. This stage incorporates CE design attributes into the objective function of the optimisation model in stage 5. This is accomplished by comparing and evaluating all paired combinations of module/part options until the utility values of all part options belonging to each module have been calculated.
5. Model and optimise the product design. At this stage the objective function and constraints are formulated from the utility values. A group technology scheme for part options selected in the product design is employed using the objective function that optimises the utility values between two part options.

The results of this process are a number of optimised design attributes for the part in question. In conclusion the technique provides an analytical process for optimisation of design attributes leading to the identification of product configurations.

2.3.3 SOFTWARE DESIGN

Software engineering is a structured application of scientific principles to the orderly transformation of a problem into a working software solution and its subsequent maintenance (Davis 1993). The actual software engineering process mirrors the design process for mechanical products starting with the analysis of requirements, through design, coding (analogous to manufacture), testing, and operations or use. The process also has to address many of the same problems faced by mechanical product design. Software engineers have long recognised the requirement for simplifying, structuring, and validating / verifying programming code. The demands for increased software functionality, performance, and a reliance on software to provide product variety have placed great importance on the implementation of these requirements.

One of the key issues of software engineering is modularity (Bell, Morrey and Pugh 1992). Modularity refers to the architectural structure of the software in the same way as mechanical product modularity refers to the architectural structure of the mechanical product. It has been stated that modularity is the single attribute of software that allows a program to be intellectually manageable (Pressman 1992). The definition of a software module is that of a fairly independent piece of code that typically has a name, a number of instructions and some data of its own. A module is invoked, or called from other modules, and similarly uses other modules.

The architectural structure of the software is the end product of the design method. Though there is no agreed standard design approach, four individual techniques can be identified:

- Functional decomposition - the functional breakdown of the overall program function.
- Data flow design - a mapping of the constituent elements with their interrelationships.
- Object-oriented design - the mirroring of real world entities by programming objects.
- Ad hoc methods.

Due to the lack of a unified approach a number of guidelines for software module development have been identified. The first aim is to develop modules that are self contained, and have as few references as possible to other modules. A software architecture should exhibit the minimum of interaction between modules i.e. low coupling, and conversely, a high degree of interaction within modules i.e. high cohesion. Low coupling is achieved by passing the minimum of parameters between modules and avoiding transfer of control. High cohesion is achieved developing modules that have strong and well defined functions. Yourdon (1979) summarises this by saying that highly interrelated parts of the problem should be in the same piece of the system.

Module size should be monitored carefully. The module size is an important issue as it will effect a number of aspects of the programs development (Figure 2.24). Many small modules increases interconnections and reduces the efficiency of the program but makes comprehending the function of each module easier. A few large modules reduces the interconnections but increases the complexity of each module.

Global data is data that can be widely used throughout a piece of software and widely accessible to system modules. If modules are to be developed efficiently global data should be minimised or removed completely. The reasoning for this is that modification to an individual module may well affect global data, in turn affecting other modules.

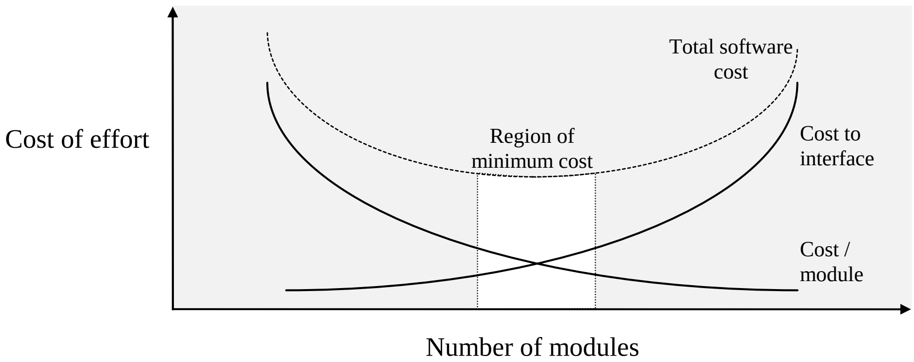

Figure 2.24. Modularity and Software Cost (Pressman 1992).

The use of information hiding or encapsulation also aids the development of a modular program architecture. For each data structure, the structure itself, the statements that access it, and the statements that modify it should all be part of a single module. This isolates design changes to a minimum of modules, reduces the complexity of module interfaces, and improves the comprehensibility of the design and so makes design, testing and maintenance much simpler.

The final guide is to develop common or shared modules that are independent of the program in which they function. Such modules allow reuse of code and thus reduce development times and are known elements in terms of reliability and function.

2.3.3 ELECTRONIC CONTROL

Electronic machine control problems mirror those of more mechanical based products. The development of complex and highly dedicated systems to meet customer requirements has resulted in manufacturer specific and closed systems. Such systems provide compatibility problems between systems and thus hinder flexibility to the user and the development and application of advanced factory automation (Harrison 1991).

Work such as that done on computer numerical controllers in developing a generic platform, upon which hardware and software modules can be selected and configured (Toh & Newman 1995), provides a valuable insight into dealing with complex systems and a high degree of customer demand for variation.

Computerised control involves a large amount of custom design work aimed at accomplishing specific control tasks. This custom work results in a closed system with the disadvantages that controller function enlargements, and transition between different manufacturer controllers, and even controllers from the same family are difficult.

It has been suggested that in this field it is important to a develop modular approach to control systems in terms of a family of control modules which can be configured to provide the desired functionality (Weston, Harrison and Moore 1989). Open systems are the result of these requirements. The main goals of an open system being: interoperability, portability, scaleability, and interchangeability. Interoperability will only be guaranteed by using standardised data semantics and behavioural models, communication and interacting mechanisms. Portability allows the system components to operate on different platforms. Scaleability is a feature which enables the customer to increase or decrease the functionality of a system by upgrading or downgrading specific components. Interchangeability allows the interchanging of one component with another due to its capabilities, reliability or performance.

The realisation of open control systems is the facilitation of advanced machine automation, modular manufacturing systems and a general increase in efficiency (Tsukune, *et al*. 1993). Modular production systems take the modularity of control a step further by utilising standardised production modules to allow rapid configuration for production introduction and change. Modular production systems also promote JIT, low WIP, high machine utilisation, and reuse of production hardware (Rogers 1995). In addition to direct production benefits the overall manufacturing aspect of product realisation is facilitated through the linking of product functions, features and modules to manufacturing modules.

Having comprehensively reviewed the domain of the research the thesis continues in chapter 3 where four industrial case studies are presented. Conclusions drawn provide a basis for subsequent research activity.

Chapter 3
The Case for Modularity

3

Objectives: The introduction presented the premiss that product manufacturing organisations have failed to take full advantage of design modularisation, taking an unstructured and localised approach to its application. This chapter investigates aspects of that premiss and develops the case that a fresh approach to product realisation is required by manufacturing based companies striving to meet current and future market trends. The chapter provides:

- Modularity case studies as a baseline for review of industrial needs
- The response to those needs
- A basis for a way forward in determining the need for a fresh approach.

3.1 MODULARITY CASE STUDIES

In mid-to-late 1994 a number of companies were contacted regarding the broad concept of modularity and how this may relate to a range of industrial scenarios. The companies were identified through existing links and specific examples selected on the criteria of interest, applicability and range. Over the following two and a half years the company relations developed into close working relationships. Through observation, conversation, structured interviews and active participation this case study material is presented. The four company case studies are:

Companies	Products
Sperry-Sun Drilling Services, Cheltenham	Sensory Equipment
Crosfield Electronics, Peterborough	Digital scanners
Ford Motor Company, World-wide	Motor vehicles
British United Shoe Machinery, Leicester	Shoe manufacturing equipment

The relationships with each company were understandably different. In the case of Sperry-Sun Drilling Services and Crosfield Electronics, a considerable amount of time was spent in Cheltenham and Peterborough involved with the respective development processes. This included discussions and interviews with engineers and support staff from all departments. Joint work was carried out on a number of product aspects and particularly the process of development with respect to modules. The case studies summarise the extent of this work (further specific details may be found in Appendices 1 and 2.), the issues faced by the companies, the processes employed, the results observed and suggestions for a way forward.

The relationship with Ford Motor Co. also involved a close working relationship on the topic of flexibility. Working visits were made to locations in the UK, Germany, Belgium, Netherlands, Portugal, and the USA. Again, a considerable amount of time was spent with engineers from all departments and also included interviews with many of Ford's suppliers who deliver the flexible concepts. The relationship regarding the body electronics was limited to interviews and correspondence with the engineers. The case study represents a summary of the considerable efforts into flexibility and their particular angle on modularity. Body electronics are also presented as an example of successful modularity application and the inspiration and guidance of a SE approach.

The relationship with British United Shoe Machinery involved interviews and discussions with engineers from design and manufacturing functions and observation of their working practices and products. The case study summarises the review of their current situation, their interest and appreciation of modularity, and identifies possibilities for future opportunity.

Other companies such as British Aerospace (aircraft), Willet Systems (coding and labelling equipment), and PIOS Ag (computers), were also consulted and discussions held. These are not included directly as case studies but they are referenced where appropriate throughout the thesis.

3.1.1 COMPANY INTRODUCTIONS

3.1.1.1 Sperry-Sun Drilling Services, Cheltenham

Sperry-Sun Drilling Services (SSDS), Cheltenham are a small company of around 70 employees, and are the UK arm of a much larger corporation (2500 employees) based in Houston, USA. SSDS design, manufacture, test, service and support a number of products that are used in an ever diversifying market, under increasingly harsh environmental conditions. The products consist of electronic sensors and instrumentation for civil engineering and oil industry applications (Figure 3.1). The applications are primarily in the form of measurement whilst drilling (MWD) operations and the products are designed to allow these measurements to be taken in order to determine a range of information such as direction of drilling and the formation being drilled through. The products are operated by the company as a service to the customer. Over time the customer needs have grown as new applications have been envisaged and the requirements on performance have been increased.

In order to meet the needs of the customer the company has developed a range of products. These products exhibit a number of characteristics (Marshall 1997a):

- They have been developed in response to specific customer needs
- They have evolved to incorporate improved and / or new technologies
- They can be used in combination to provide a variety of service
- They are backwardly compatible with existing products already in service.

The development of this product range directly met customer needs but led to a situation that posed a number of difficulties to both SSDS and for the operators of their products. The constraint of backward compatibility, has over time, presented a problem with the number of interfaces required to ensure compatibility between products of differing ages. This was not a problem when the number of product options was low, but with the increase in possible combinations and a likely continued increase in the future, the situation became prohibitive to both business and operator needs. Coupled with this was an unstructured and somewhat ad-hoc design of products. Presenting problems with; part standardisation, increased stock holding, product re-engineering, poor time management, and continued 'fire-fighting'.

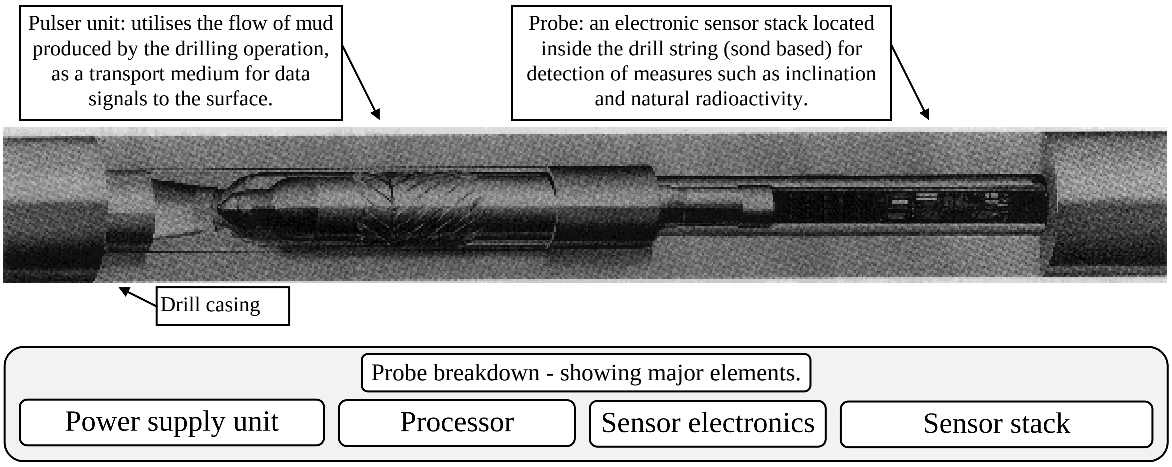

Figure 3.1. A MWD Pulser and Probe.

The solution to this, and a number of specific technical needs was the development and implementation of a new product development strategy that mapped out the needs of both the business and customer, and provided a framework for dealing with a number of issues including customer requirements, increasing product and process complexity, and the introduction of new technology. The product development strategy was to be based on a modular product philosophy, and be linked with business objectives and a strong quality management process.

The framework for a successful product development strategy was put in place during 1995 by the definition of Cheltenham's business objectives and corporate mission statement (Appendix 1). The focus was understanding and exceeding the customer's expectations and providing benefit to the business as a whole in a continuous improvement culture.

3.1.1.2 Crosfield Electronics

Crosfield Electronics is a medium sized company of around 1800 employees based in Peterborough. Crosfields are currently a subsidiary of Fuji (previously Dupont & Fuji) and design and manufacture colour, electronic imaging scanners for the pre-press printing industry in a very competitive and currently expanding market. These devices take film footage or stills and digitise the information to allow image manipulation from a computer based software package prior to magazine or newspaper printing. A new family of products also allow hard copy to be produced.

When the case study was initiated Crosfields produced a range of products that varied mainly in their capability for size of photographic material used. These products exhibit a number of characteristics (Marshall 1997b):

- They are evolutionary resulting in a large part count and high complexity
- They require a large assembly area and skilled assembly personnel
- They take 3 days with a skilled engineer per machine to test
- They are becoming increasingly difficult to update.

Though still meeting customer needs this range of products was nearing the end of its useful life and the possibilities for future evolutions were constrained due to the complexity and already heavily modified product architecture. Crosfields also suffered from a traditional over-the-wall development philosophy where manufacturing input was introduced only when the components had to be ordered. Time slippages in the order of months were also common. The market at the time showed little competition and so such practices were still successful.

However, the then parent company Dupont realised that this situation could not last and made efforts to improve the development process. Encouraged by this, Crosfields proposed a number of changes to both process and product towards the end of 1993 / beginning of ’94:

- Introduction of the Crosfield product life cycle process (CPLCP) (Figure 3.2) from Dupont
- A greater and earlier input by the manufacturing designers within a CE environment
- Development of a new product to meet customer need yet simplify design and manufacture.

Using the new development process (CPLCP) for the first time Crosfields began development of their new product the Phoenix in Feb. ‘94. The Phoenix had a number of specific aims such as a greatly reduced part count and variety, a simplified assembly process, reduced complexity, smaller physical size, simplified test requirements, and a greater reliability and reduced cost.

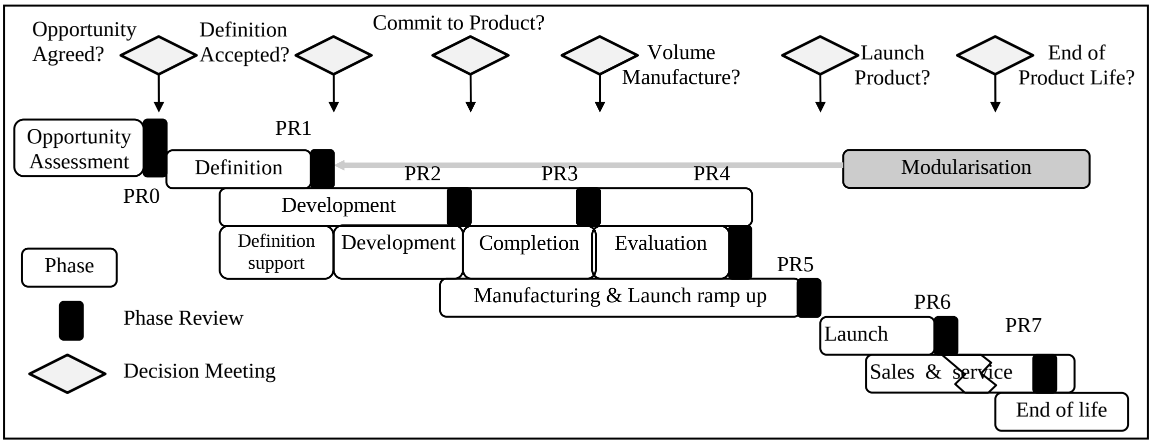

Figure 3.2. Crosfields CPLCP and Modularity Timing.

During the formation of product teams the issue of work partitioning proved to be the initiation of the concept for a modular product architecture. Teams could be assigned to modules with the appropriate expertise for the technology on which they would work. This then developed into the concept for a technique to aid in the process of module definition and identification of the interactions that occur between modules. The result was a modular product development process that formed part of the first engineering activity of the CPLCP, the definition phase. This provides the necessary mind-set of the team toward a modular product and integrates modularity issues early-on.

3.1.1.3 Ford Motor Company

Ford Motor Company are a world wide company of around 300,000 employees, of which 80,000 are based in Europe. The company is one of the so-called 'big three' automotive companies. The past few years has seen Ford re-engineer their business processes (Hammer & Champy 1993) on a global scale under the banner of Ford 2000. Ford 2000 is based around 5 core processes one of which is the Ford product development system (FPDS), an integrated corporate PD system that includes initiatives such as the establishment of a dimensional control culture (Leaney 1995). Ford wished to rationalise product development on a world wide scale. Processes that were different in the United States from those of Europe would now be the same. This aim had many potential advantages allowing process changes to be easily disseminated but also facilitating the production of global cars. Such a vehicle would be identical wherever it was produced allowing plants to be cloned rather than developed separately, allowing production to be manipulated flexibly to meet local demands without the expense of providing extra capacity. The global car would also have major impact upon the accompanying administration, supplier involvement and many other knock on effects.

Ford were also interested in meeting the needs of a customer that was straying away from accepted norms, becoming more discerning in its choice of product. Ford classified this need with the development of niche products (Barnett, Leaney and Matke 1996). One of the major problems with niche products is the considerable difference in perspective from their familiar and comfortable mass production processes. Production lines are typically designed to produce one vehicle variant, changes in design require different manufacturing lines for production. On a mass production scale (e.g. 200,000 p.a.) this is an economic process, for the relatively small volumes of niche products (50,000 total) the approach is prohibitively inflexible and expensive. Thus investigation into flexibility is being carried out to meet these niche product's needs.

3.1.1.4 British United Shoe Machinery

British United Shoe Machinery (BUSM) are a medium sized company of around 1000 employees based in Leicester. BUSM are a subsidiary of the USM Texon group, a manufacturer of high performance machines and materials for the world's footwear manufacturing industry. The BUSM product range consists of machines designed for every stage of the shoe making process, totalling about 80 products and variants. Recent gradual recovery of the European market coupled with stable US and Far East markets has improved the prospects for BUSMs business. However there is a noticeable change in the demand, moving away from complex (typically > 15000 components), highly functional machines to simpler and cheaper products requiring less skilled operators. The BUSM products exhibit characteristics that affect their response to this trend:

- The products have evolved into highly complex and costly systems
- The machines provide computer control and have a high degree of automation
- The production volumes are relatively low and lead times are high
- There is a potential for considerable commonality between products.

3.1.2 APPROACHES TAKEN TO MODULARITY

3.1.2.1 SSDS Cheltenham's Product Development Strategy

The strategy developed builds upon the modular nature of the product range where the products are developed as modules with a limited number of specific functions that can be combined by the operator to provide a variety of services to the customer. The modularity is taken to a lower level where subassemblies within the products become modules. This then allows standardisation across the product range, reduced product development times, improved manufacturing efficiency, and an ability to upgrade old products still in service with minimal disruption to the customer.

The strategy comprises the following steps during development of a modular product. The steps are based upon the concept of a generic modular product development process that was the initiation of the process developed by the author, presented in chapter 5.

- Identify Project team and specialist skills likely to be required
- Capture requirements including key elements from existing and possible future products
- Loosely define a level of modularity to guide module development
- Document product technical specification in a clear, concise and traceable manner
- Utilise parallel development of modules by assigning module teams
- Develop rough layout / schematic of proposed product based on specification
- Determine possible modules and interface concepts
- Create a rough geometric layout to ensure fit and compatibility
- Test modules against specification
- Detail design.

Note: The consideration of manufacturing and assembly issues is not presented as a single point to avoid the view that it is performed at a specific sequential stage. Such issues should be considered throughout the whole process to ensure the integration of design and manufacture.

The case study now follows the implementation of the strategy to two core products in need of replacement. The 150º C (operating temperature capability) *directional gamma whilst drilling* (D(G)WD) system, or specifically the *pressure case directional* (PCD) and *pressure case gamma* (PCG) probes.

The process truly began with the inclusion of the modularity goal as part of the corporate objectives. This step ensured that there was a company-wide 'buy-in' of the concept and that it provided a universal platform for the integration of disciplines and the utilisation of resource in achieving business goals in an effective and efficient manner. A CE environment was facilitated through a total quality management (TQM) philosophy and the use of multi-disciplinary teams, the co-location of employees in related functions, and the encouragement of co-operation and communication between all departments.

The detailed implementation of a modular strategy was initiated with the analysis of the existing products and the documentation of key elements within them. This analysis aimed to ensure backward compatibility with existing products to maintain high customer confidence and identify possibilities for standardisation and rationalisation. The analysis identified a number of elements that required consideration.

1. A high degree of functional, but low physical, commonality between the two products.
2. A distinct common / dedicated split of functional areas.
3. No real justification for the low physical commonality.
4. Possibilities for novel design changes to improve performance and ease of manufacture.
5. A possibility to introduce a new standard communication interface to the product range whilst still maintaining backward compatibility.
6. A starting point for a new company product platform and philosophy. There was an opportunity to provide a generic platform for future products. This coupled with the business changes and focus, presented itself as a new company philosophy for understanding and exceeding customer requirements.

In addition to the identification of key elements, a level of modularity was determined to include a generic platform element and to develop modules at a mechanical and electronic package level. Thus electronics packages could be developed within constraints by separate teams, in parallel to the mechanical design based around the same constraints. This provided a benchmark for product development, and allowed parallel development of the associated modules.

The culmination of this concept development phase was the generation of a technical specification document (Sep.‘95). This document was refined to meet the needs of the new product development process. The new specifications showed a SE influence by providing an up-front record of requirements on the new products, and traceability to who generated those requirements.

Once the requirements were signed off in the technical specification the requirements were used to develop a rough layout of the product. The layout provided information on key features, constraints and provided sufficient detail for the team to determine possibilities for modularity. Possibilities related to existing and future product requirements to ensure compatibility and extended life. The criteria used for module identification were primarily those presented below:

1. *Standardisation* was used to provide a generic product element that covered the common functional areas. This generic element could then be used as a platform for future products.
2. *Manufacture* was addressed through the commonality elements, complementing the common areas of functionality with common areas of mechanical and electronic design.
3. *Localisation of change* was considered important in allowing existing products to be upgraded through the retro-fit of new modules.
4. *Supplier capability* allowed modules to be sourced completely from one supplier increasing economies of scale, reducing overheads, and providing a better relationship with the suppliers.

In addition to module identification, interfaces were also identified and analysed. This was especially important between the generic platform module and the dedicated variant elements. The capability for a new interface standard was also included to enhance the flexibility of the design, improve ease of operator use, and reduce complexity and stockholding.

Once module concepts were agreed, a rough geometric layout was conducted to ensure module fit, and compatibility with the existing equipment and products. Finally the proposed modules were checked against the technical specification to ensure that the requirements were being met at an early stage when changes were relatively straight forward and economic. Once signed-off the product went onto detail design.

In addition to the specific modular features of the strategy there were a number of complementary initiatives to improve the development process. Component standardisation was employed wherever possible to ease manufacture and assembly, reduce stock holding and part inventories, and provide greater economies of scale. Total procurement was employed such that modules were sourced complete from individual suppliers. This was accompanied by a rationalisation of the supplier base and a shifting of responsibility of component quality from SSDS to the suppliers.

Manufacturing input is now much earlier in the development process including the manufacture of prototype products, as opposed to engineering, so that production problems can be identified early.

3.1.2.2 Crosfield's Modularisation Phase

The modularisation phase was added to the CPLCP in order to define modules from which to form the product. Criteria are features and functions that are deemed essential by the team. For the Phoenix, the module teams established an extensive list of criteria including items such as: can be tested, is replaceable in the field, self contained etc. The phase consists of the following steps and is initiated with the definition of module criteria.

- Define Module Criteria
- Establish a Preliminary Module List
- Test Modules Against Definition Criteria
- Develop Module Interaction Chart
- Establish Final Module List
- Document Interface and Test Specifications

Following the definition of module criteria a preliminary module list is created. Here the strategy requires that all components within a product must belong to a module. This must be carefully considered to ensure that conflicts do not occur at a later stage. The use of teamwork and good communication enhances the possibility that module definition is performed at an optimum. Modules are established according to groupings of function and also like disciplines such as electronics and optics. It was discovered that the product could be decomposed quite readily and provided possible modules that could be investigated for buying in complete from a supplier.

Having defined the modules they are then tested individually against the earlier defined criteria. This allows modules to be examined in greater detail to establish the degree to which the criteria are met. For example, some parts are critical to access whereas others require little or no access at all. The final function of this stage assesses each criterion against each module to determine a pass or a fail. Modules exhibiting an unacceptable number of fails can be re-defined and then looped back to be checked against the criteria.

Once the modules satisfy the criteria to a level agreed by the team, module interactions are addressed. Interactions are analysed using a simple matrix known as the Phoenix module interaction chart (Figure 3.3). This key procedure consists of putting modules along the axes of the matrix, and in the intersections, stating the nature of the interface to four degrees: Optical, Electrical, Mechanical and critical as shown below.

Modules		**1**	**2**	**3**	**4**	**5**	**6**
Top skin	**1**		M	M	M	-	-
Bottom skin	**2**			ME	-	(M)	M
System board	**3**	O = Optical Interaction			-	-	-
Power supply unit	**4**	E = Electrical Interaction				-	-
Lens	**5**	M = Mechanical Interaction					O
Mag. drive & platform	**6**	(?) = Critical Interface					

Figure 3.3. The Phoenix Module Interaction Chart.

This process allows the module teams to determine the type of interaction between modules and which teams will have to closely interact in development. It also allows critical interactions to be targeted. If any modules prove to have intractable interaction problems then modules can be re-defined and the interfaces analysed.

The culmination of the interaction analysis is the final module list and the teams to which the modules should be assigned. From the list, cost targets can be established and individual specifications drawn up for interfaces and test requirements.

3.1.2.3 Ford's Flexibility Research

A co-operative project between Ford and the department of Manufacturing Engineering, Loughborough University, was initiated during 1994 to address one particular aspect of flexibility. One of the key inhibitors to manufacturing flexibility lies with body construction, where the sheet metal shell or body in white (BIW) is assembled. This phase of automotive manufacture contains a high degree of capital equipment outlay on tooling and facilities that traditionally are dedicated to the product for which they are intended. This dedication is where the possibility of flexibility is severely limited and it is this area that most flexibility work is targeted to allow flexible assembly of numerous vehicle platforms.

Though targeted directly at flexible assembly solutions, the breadth of the topic allowed the research to address influencing factors such as product design. Thus in order to satisfactorily meet the needs for manufacturing flexibility, equal consideration had to be given to product flexibility and, particularly, modularity. The topic of flexibility for body construction is extremely complex and the list below represents a sample of the issues determined that influence flexibility (Marshall 1997c):

- The cost of flexibility is usually 30% greater than for a non-flexible equivalent.
- Flexibility investment must be for a limited time period due to the redundancy of equipment.
- Cycle time has a great impact upon flexibility. The potential for flexibility will be lower and the cost greater as the cycle time decreases due to reduced time for facilities to configure themselves to the variety.
- A flexible solution will generally require a greater quantity of floor space.
- Flexibility will increase the complexity of systems and thus the required skill base of operatives and maintenance engineers.
- As complexity increases so does the likelihood of breakdowns.
- There are two main types of flexibility: for model change, and for variants.
- The desired flexibility must be chosen early on in the design of the system.
- Capacity flexibility is difficult to achieve as lines are designed to a production volume. Redundancy must be incorporated to provide flexibility.
- As flexibility increases the requirement for skilled operatives and maintenance engineers can become an issue in counties where these skills will be in short supply.
- Part commonisation should be routinely performed. The Japanese have proved successful in this area; a process the Europeans find difficult.
- Communication is absolutely essential between Engineering, Manufacturing, Stamping and Suppliers. Mazda are a good example of this discipline.

- The first few design steps are crucial. Typically little time is devoted to these steps within Europe. Japan places emphasis on these steps and realises fewer problems downstream.
- In Europe a supplier gets an order 11 months prior to job. 1. In the USA this time is 36 months.
- Engineering do not have sufficient grasp of simple manufacturing issues that would be simple to implement early on but very difficult downstream.

3.1.2.4 BUSM's Approach

The complexity and manufacturing issues are visible to BUSM and considerable effort has been targeted at investigating possibilities for DFA, QFD, and modularity. These are in addition to manufacturing implementations of material requirement planning (MRP) systems and a form of cellular manufacture. It is well understood that a rationalisation of products is required and a suitable test project has been identified on which to begin the initiatives.

3.1.3 THE OUTCOME

3.1.3.1 Sperry-Sun Drilling Services, Cheltenham

The benefits gained from the implementation of the new modular strategy have been widespread. New product development is much simplified and responsive. The re-use of modules reduces the engineering effort required to realise a new product and ensures that the customers needs are met quickly. Design changes and upgrades have also benefited in the same way through forward compatibility and the ability to upgrade selective modules, addressing customer requirements pre-emptively and allowing existing products to be upgraded with greater efficiency.

Complexity has been addressed through decomposition into modules, partitioning of dedicated and common areas and a reduction in interfaces and provision of generic modules. This has improved management, design, manufacture, service and use of the product.

Modules have simplified and allowed more efficient manufacturing and assembly tasks. This has been achieved through the early involvement of manufacturing but also a reduction in part numbers and part variety, thus reducing stock holding, parts inventory, lead times (from 12-20 weeks to 6-8) and increases the economies of scale and quality (2.5% rejects to 1.2%) for part orders. Assembly sequences are generic across the majority of products and variety can be introduced late on in the assembly process providing a flexibility to the build plan. Testing is simplified as modules can be tested separately and also by the supplier ($190,000 saving). There are also less varieties of products to test and a reduced requirement for test tooling and facilities.

The implementation of the process has also seen some general benefits including administration and documentation overheads reduced, a closer knit and more motivated development operation with engineers more appreciative of functions outside their own and an emphasis on finding and addressing problems early on.

3.1.3.2 Crosfield Electronics

The impact of the changes made and the implementation of modularity upon both the development process at Crosfields and the Phoenix has been considerable. The development process has benefited by becoming structured, concurrent, and through the introduction of formal review stages that require a product to pass the requirements in order to proceed. The process has also been facilitated through the modular product architecture. Modules allow teams to be formed around modules and these teams to work in parallel. The definition process ensures that attention is given to the interfaces between modules and thus collaboration between teams.

The opportunity seized through the approach to development of design and manufacturing as an integrated whole has also benefited both process and product. Design for assembly is becoming a part of design philosophy extending its usefulness beyond the Phoenix project and ensuring that manufacturing issues will be considered during design as a natural part of the process.

The Phoenix has realised many advantages through this new approach. The product has a greatly reduced part count (6000 to 1500) and part variety (2500 to 350) even though redundancy was required to standardise on interfaces and to facilitate modules. The product is less complex and uses self locating parts and top down assembly. These attributes and the ability to assemble modules in any order has simplified and speeded the assembly process (5 days as oppose to 2 weeks). Testing has been reduced (3 days to 4-6 hours) and facilitated through in-built module diagnostics. Testing is also more efficient through modules being testable off line at module workstations before final assembly.

The improvements in efficiency and the production of the Phoenix has also seen a greatly improved reliability in use. Mean time before failure has exceeded all expectations showing an increase from 500 to 8000 hours. Failures are also easier to address when they have occurred through simplified disassembly and the ability to rapidly swap modules.

3.1.3.3 Ford Motor Company

The research has resulted in a number of approaches to the facilitation of flexibility for car body construction. The underpinning of the approach is a series of guidelines aimed at increasing the awareness of manufacturing and design engineers alike to the issues of flexibility and their impact on the ease of assembly and the economics of manufacture of niche products. From these guidelines development is continuing into a methodology and framework for flexibility to aid engineers at key times in the product life cycle to positively influence the flexibility of the product and the process. A software tool to aid in flexible tooling production is also being developed.

An important finding of the research is that many of the barriers or constraints to flexibility within body construction is the isolated manufacturing view. Flexibility is seen to be a manufacturing problem yet a compromise of flexible manufacturing technology and processes and a flexible yet standardised product design provides the most effective and efficient way forward. The approach with most promise is that of a modular architecture, be it a modular configuring tool, designed to accept different parts for assembly, or a modular vehicle design that can accept anything from different powertrain (suspension, engine, transmission) to different front end module for mid life update or ‘facelift’.

The implementation of modules to the product design poses a particular challenge. Product design is a complex task that must focus on delivering the best technical and aesthetic package to the customer. Modularity has the potential to facilitate this delivery but the product engineering process has a historical legacy and a resistance to engineering changes that constrain any exterior style aspects of the vehicle. However the possibilities for modularity are manifold and Ford have invested in a project that will utilise a number of exterior modules. The project is known as the BW-153 a small (smaller than Fiesta size) car that will have a number of variants for niche markets, and significantly will feature a front and rear end module consisting of panels, lights, wiring and other trim components.

On areas hidden from the immediate attention of the customer modules have already been accepted, especially within the trim stage, powertrain, and electronic body systems. The trim stage is where all the accessories are fitted to the painted BIW. Modules include a completed dash with wiring, steering, stereo etc. built up off line. Powertrain can offer a modular selection of variants through engine options though this is marred by different engines requiring different mounting points, or a sub mounting between the engine and the BIW.

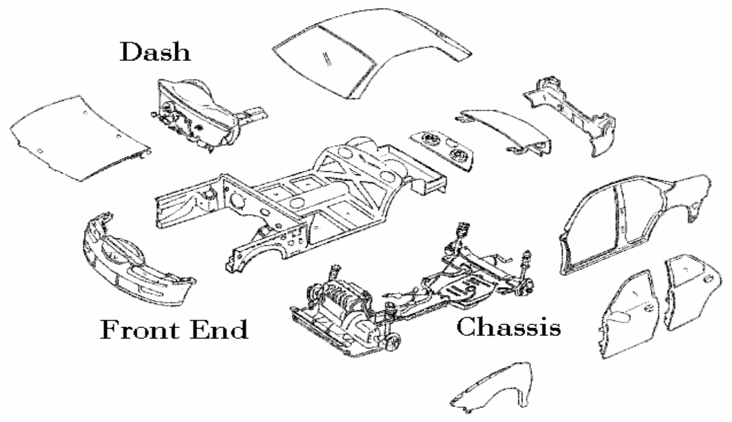

Figure 3.4. A Modular Automobile Structure.

Electronic body systems utilise a modular approach through multiplexing based upon a SE framework to their vehicle electronics. One of the main issues is the need to address customer requirements and the complexity this introduces to the systems. Features such as security, window control, locking, seat movement, cruise control, engine management, ABS, traction and adaptive damping present difficulties with the interactions of these features, fault finding and the physical complexity of the wiring. Modularity in the form of multiplexed electronic modules allows a reduction the complexity of a single integrated product by partitioning of the functions. This improves quality and reliability, allows easier testing of system functionality, reduces weight and ultimately reduces cost. The use of a generic protocol allows standard communications between modules and minimal interconnections. These improvements then simplify assembly and any subsequent service or maintenance to the systems (Elvidge 1996).

3.1.4 FUTURE OPPORTUNITIES

3.1.4.1 Sperry-Sun Drilling Services, Cheltenham

Though the move to a structured approach to modularity has improved many aspects of the development process within SSDS Cheltenham there are a number of areas that are to be addressed in a process of continuous improvement.

1. The development and documentation of a formal development process and strategy. This process would detail the stages of the whole product life cycle. Deliverables for each stage would be clearly identified and consist of a number of formal reviews, that must be passed in order to move on. The process would be familiar to all employees and would aid in managing the time, quality, and cost of product development. The strategy aspect would be objectives for future product development, and include the plans for proliferation of the platform modules developed. These ensure that development is at least partially pro-active rather than reactive.

2. It may be useful to set a life span for products to compromise on the backward compatibility versus upgrade, trade-off.
3. Some work should be done into structuring and improving the capturing of requirements. It is difficult to provide products that are meeting customer needs when it is not known what the customer really wants. Questionnaires, interviews, group meetings, and operational experience will have to be combined in order to build up clear and applicable requirements lists.
4. The proliferation of standardisation practice to individual components. The development of a preferred components list is one proposal to deal with this in a convenient form. Standardising on components throughout the product range would further increase the benefits seen for the standardisation between the PCD and PCG.
5. Increased and earlier involvement of suppliers in the development process.
6. Improved documentation management. If design processes, formal reviews, product strategies, and preferred components lists are to be successful there must be some way to efficiently manage the documentation. The documentation has to be maintained and reviewed itself periodically, it has to be disseminated to ensure all employees are familiar with their role and the overall picture, and it has to be conveniently accessible otherwise it will be all too easily ignored. The use of the companies own intranet provides a possible suitable medium, but could potentially do with someone who's sole responsibility is this function.
7. Further investigation into the possibilities for modularity within products. A number of existing standardised elements could possibly be developed into modules. They could then be used generically across a wider range of existing and future products.

3.1.4.2 Crosfield Electronics

Since the release of the Phoenix (Aug. '95) Crosfields have suffered a number of setbacks. The Phoenix's success was marred by a marketing error resulting in a design with a reduced demand from that predicted. Crosfields have also had to release (Jan. '96) three new products (Mercury, Gemini, and Apollo) simultaneously to replace their core products in order to survive. The new products had to be developed extremely rapidly (<12 months) and under great pressure. This has seen a return to some of the more unstructured development processes and an ad hoc application of the CPLCP purely to push the products through to market.

One specific comment made was that the CPLCP review points were ignored, "The process was telling us that we weren't ready, and we aren't." resulting in manufacturing difficulties and design changes even as the first products were being manufactured.

In retrospect Crosfields are not happy at having to deliberately ignore many of the lessons learned with the Phoenix. The new products do not meet the standards that the Phoenix set but the integration of some of the concepts and philosophy has shown results even in this unstructured environment. The products are not modular but do have common features, are easier to assemble, and take advantage of the workstation assembly process and the testing procedures involved.

Crosfields have effectively but not efficiently bought themselves time. It is this time that can be used to ensure that all future products follow the Phoenix lead and take advantage of the valuable lessons learned. Crosfields have a corporate mission to become world class in manufacturing. A number of areas must be addressed in order to achieve this and other opportunities:

1. All products will now be developed using the CPLCP and formal use of the reviews. Modularity will also be employed and other techniques that proved useful such as DFA. This aim also has senior management backing, with the managing director stating that products will never again be developed in the way the Mercury and its brothers were.
2. A product strategy is required that maps out all existing and potential future products. Module commonality and capability could then be determined in advance. Planning of this nature also alleviates a degree of the pressure encountered when it was realised that core products were not competitive. A lot of attention has been given to managing around products, attention has now to be focused on the detail of products.
3. Customer requirements capture and analysis needs to be addressed. The problems with the Phoenix highlight the importance of ensuring that this stage of development is done as effectively as the downstream processes.
4. Further development of the modularity definition phase. Some of the operations are left to team initiative and present an opportunity for a more structured approach. The analysis and development of interfaces present distinct possibilities in this regard.

3.1.4.3 Ford Motor Company

Ford presents an interesting case. The sheer physical size of the company allows situations where successful and efficient development on body electronics can be done in a SE framework with an appreciation of product modules, whilst body engineering can still be relatively unaware of either approach. Ford are addressing these issues with recent (i.e. 1997) initiatives for company wide education for employees on SE, and the application of modules is becoming increasingly widespread. For an application on such a scale there are always a number of opportunities:

1. The application of modules to the BIW and a more efficient implementation in powertrain. A modular vehicle can facilitate flexibility goals but also offer greater advantages through a more customisable and readily updated design, and the ability to offer variety without many of the associated costs (economies of scale vis-à-vis economies of scope).
2. The implementation of a form of modular development process. Integrated into the existing Ford product development system (FPDS) a modular definition process could focus engineering towards the possibilities for a modular architecture rather then the restricted view of their traditional development approach.
3. A strict approach to the following of SE across all areas. Special attention to be paid to relating all decisions and later changes to customer requirements.
4. A greater appreciation and of manufacturing issues within body engineering and flexibility to accommodate them. The momentum of dimensional management within the organisation presents an opportunity to ensure that design and manufacture are taken as a single process. The potential lies with the co-ordinating role of the dimensional control function that is neither part of engineering or manufacturing but has goals and a language (quality) common to both.

3.1.4.4 British United Shoe Machinery

The product range produced by BUSM provides great potential for enhancement with respect to complexity, manufacture and assemblability, and commonality. The evolutionary nature of the product's development has resulted in a requirement for a step change rather than a continued gradual refinement. A number of opportunities are present to ensure future success:

1. Small DFA projects have shown potential improvements of approximately 25% even for small subassemblies (Boon *et al.* 1997). There is definite potential for a rigorous application of DFA principles throughout the entire product range.
2. A strategy for modularity to structure activities in the development of product modules and the plan for common modules across the range. The framework associated with such a strategy would also integrate the initiatives on DFA and other techniques of potential such as QFD.
3. The development of an initial modular product, leading to the development of a range of modular products. A series of generic modules common to a range of products will have considerable impact upon complexity, manufacture, new product development, service and ultimately the customer.
4. A formal process of identifying and structuring customer requirements. The development of a SE process allowing customer requirements to be linked to design and manufacturing decisions.

3.2 CASE REVIEW

This section is based upon analysis of the case studies and presents a summary of the main trends and issues faced by the case companies as a cross section of manufacturing industry, much of which is backed by the literature. The case study issues and concerns can be categorised into four broad industrial issues or needs:

1. Efficient deployment of customer requirements
2. A rationalised introduction of new technology
3. A structured approach to dealing with complexity
4. Flexible or agile manufacturing

These issues are generically applicable to today's manufacturing companies and the case study work has shown them to be directly addressed through design modularisation. The issues' numbered attributes relate to the previous list where the initial number is the strongest association. The issues identified include:

• Change in customer attitude from passivity to activity	**1**, 3
• Demands for increased product variety	**1**, 3, 4, 2
• Increased product requirements	**1**, 3, 2
• Development of ad-hoc and specially built products in order to be responsive	**1**, 4
• Unstructured product reengineering	**1**, 2, 3
• Insufficient attention to the early stages of development	**1**, 4
• Requirements for reduced lead times	**1**, 4, 3, 2
• Increased competition	**1**, 4
• Global markets with localised requirements	**1**, 4
• Increased legislation	**1**, 3
• Responsibility for whole product life cycle	**1**, 2, 3, 4
• Lack of a total view	**1**, 2, 3, 4
• Lack of manufacturing involvement within design	**1**, 4
• Inefficient product upgrade	**2**, 1, 3
• Rapid technology advance	**2**, 1, 3,
• Increasing product complexity	**3**, 1, 2
• Increasing design and manufacturing process complexity	**3**, 4, 1, 2
• Evolutionary product designs	**3**, 1, 2
• Lack of commonality and standardisation	**3**, 4, 3
• Increasingly demanding and complex test procedures	**3**, 1
• Lack of integration between processes	**3**, 1
• Poor product reliability	**3**, 1
• Increased pressure upon manufacturing for flexibility and speed of response	**4**, 1, 3
• Manufacturing legacy of processes and facilities inefficient in today's markets	**4**, 1, 3
• Reduced batch sizes	**4**, 1
• Responsibility increasingly forced downstream to suppliers	**4**, 3, 1

3.2.1 THE MODULARITY RESPONSE

The case studies have shown a common response to the broad range of issues presented. Though each case has utilised modules it has been for a different aspect of the advantage that is available. Modularity confers a range of process and product based enhancements that together form a package for meeting current and future requirements and pressures.

- Manufacturing industry faces a number of challenges from the customer. It has been shown that the main issues are how to meet increasingly specific customer demands without the added burdens this can place upon development and production costs, time and quality.
- Modularity within a SE context has been proposed as a strategic approach.
- Modularity provides product variety to the customer. However the variety can be offered efficiently through a limited number of modules and the use of common modules. Variety can also be introduced without unnecessary reengineering, in reduced timescales and at lower cost.
- Modularity allows customers to have control of the variety offered through module configurability, providing flexibility in operation but also in support through improved serviceability and upgrade.
- Modularity presents an opportunity to manage process complexity and combine teams with the modules for which they are responsible. Requirements for modules to integrate together then encourages integration across teams and presents a greater system for efficient and effective product development.
- Modularity addresses product complexity through decomposition of systems, partitioning of functions, analysis of interactions and modular assembly. The resulting effect is greater product reliability, service, and product upgrade.
- Modularity allows more efficient and effective manufacture and assembly. Part standardisation addresses quality, economies of scale and improved supplier relations. Processes can be structured around the product, modules assembled in parallel, testing can be done on individual modules, variety introduced late and thus orders rapidly fulfilled.
- Modularity also provides structure to the application of other related processes such as DFA, value engineering and group technology.

The case studies and their use of modularity has shown that modularity offers an advantage to a range of product manufacturing companies. However, the case studies have also shown that there is a definite need for a structured approach to modularity in a form sympathetic to industry needs. In order to meet this need the requirements for a fresh approach are investigated in chapter 4 and developed in chapter 5 into a structured modular development process.

Chapter 4
Modular Design: a Fresh Approach to Product Realisation

4

Objectives: Regarding the literature review and the case study material, there are a number of issues or requirements that must be addressed through the development of a fresh approach. This chapter addresses these concerns by clarifying the area of DM and laying the foundation for a DM process through:

- A definition of modularity
- An analysis of modularity in relation to the framework and methodology
- The requirements for a fresh approach to design through modular products.

4.1 DEFINITION OF MODULARITY

So far modules and modularity have been used as purely generic terms, and have been open to interpretation. This chapter begins by providing a definition of modularity to which development of the methodology and the specific instance of a modular design process can be related. The standard English language definition (Oxford English Dictionary 1984) provides:

> **module** *n.* **1.** a unit or standard used in measuring. **2.** a standardised part or an independent unit in furniture or buildings or a spacecraft etc.

However, a structured analysis requires a much more specific definition if the essence of modularity and its inherent benefits are to be accepted. The aim is to provide a definition that relates to system modules. Thus encompassing the main focus of product modules but also manufacturing and business entities that exhibit module-like properties. John Young (1994) of the Ford Motor Co. provides a definition in line with these needs, however it does not capture all the desired elements. For this work the following definition will be used for a module:

> A (sub)system that comprises a group of individual elements that form an independent, co-operative, self contained unit with one or more testable composite functions.

Such a definition exhibits the following properties:

- Modules are co-operative subsystems that form a product, manufacturing system, business etc.
- Modules have their main functional interactions within rather than between modules.
- Modules have one or more well defined functions that can be tested in isolation from the system and are a composite of the components that form the module.
- Modules are independent and self contained and may be combined and configured with similar units to achieve a different overall outcome.

Following this definition modularity is defined as:

> **modularity** *n.* **1.** being modular **2.** the theory of module creation. - **modularisation** *n.* the specific process of creating modules.

4.2 ANALYSIS OF MODULARITY

The case study material and literature review have provided some clear requirements for a fresh approach through modularity. This section analyses these requirements with respect to the framework and methodology for DM.

4.2.1 THE NEED FOR MODULARITY

One of the common aspects of the businesses studied in chapter 3, is the change in customer attitude from passivity to activity. In the markets in which these companies operate, political and economic factors have resulted in a combination of increased affluence of the individual and a human vanity that has developed a lack of tolerance to mass produced ‘generic’ products and stimulated a demand for customised products (Wright & Bourne 1988). The implications are widespread including product variety, product and process complexity, and the manufacturing response. Markets have also become global, presenting new opportunities and new competition. The global automotive industry has seen Western manufacturers under increasing pressure from Eastern industry (Clark, Fujimoto and Chew 1987; Fujimoto 1989; Altshuler, *et al.* 1984).

For much of manufacturing industry this trend is unfamiliar, and often the existing business, product, and manufacturing systems cannot deal efficiently with a demand they were not designed for. The legacy of heavy automation and mass production has hampered the response of many companies above the small craft industry to these growing stimuli. A review of the history of manufacturing has highlighted the trends that have been followed and the situation where the legacy from manufacturing solutions that were suited to the concerns of the time but no longer meet the concerns of today have to be constantly redressed (Figure 4.1). Previously the demand for these products has been met by adaptation of existing products, rapid and unstructured re-engineering, ad-hoc solutions, and specially built products (Shirley & Eastman 1990).

Roobeek and Abbing (1988), and Rogers (1990) have identified a number of limiting factors such as increasing product complexity, poor integration and support of computer systems and tools that have constrained the manufacturing response. Drucker (1990) provides an analogy between today's manufacturing factories and a cumbersome battleship navigating in adverse conditions. Whereas a post modern factory would be a flotilla of smaller vessels or modules which serve to compliment each other whilst moving in the same direction. Such an organisation would not only be more flexible but allow rapid design changes in response to demand.

In a more structured attempt to meet customer requirements companies are looking at the flexibility within product and process to manage variety (Andreasen & Ahm 1988). Potential lies within combinations of philosophies from custom manufacture to mass production through mass customisation. Moving from economies of scale to possibilities within economies of scope (Roobeek & Abbing 1988). Section 2.1.3.4 shows modularity to be a key aspect of a mass customisation approach.

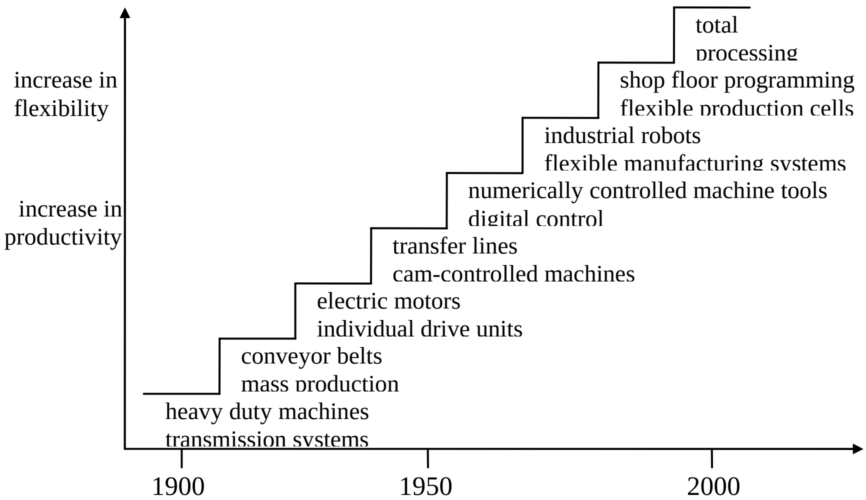

Figure 4.1. Development Stages in Manufacturing Technology (Warnecke 1993b).

The case study material has provided a snap-shot of these concerns (below). These four broad issues to which modularity has been proposed as an efficient approach are now considered in turn.

1. Efficient deployment of customer requirements
2. A rationalised introduction of new technology
3. A structured approach to dealing with complexity
4. Flexible or agile manufacturing

4.2.1.1 Customer Requirements

The case studies have shown particular responses to customer requirements. Two issues become apparent. The first is the process of managing the requirements, distilling the information from the customer into a product specification. The second is the realisation of these requirements into a completed product or a variety of products. These can be further broken down into:

- The identification and selection of the customers who are to be served
- The identification and selection of their requirements
- The interpretation, deployment and use of requirements in a product development process
- Increasing product variety without unnecessary variety of components, designs, and processes
- Managing the complexity of products and the accommodation of new technologies
- Maintaining a low product cost, by keeping design, production, service and disposal costs low.
- Minimising the time of development for new products and delivery time for ordered products.

The requirements management issue was an aspect that all of the SME case companies need a more structured approach to, and one that Ford was beginning to appreciate fully. SE provides a fresh perspective, focusing development activity on meeting customer needs. SE also provides a framework for tools such as modularity and other formal methods. SE then provides the linking mechanism, facilitated through IT and CIM, to allow requirements to be identified, documented, analysed and distributed throughout the development process into the physical and functional implementation of the product.

The Kano model (Figure 4.2.) presents a model for customer requirements and how they change with expectations and time. Basic requirements are necessary to achieve a basis for customer satisfaction, performance related requirements bear a direct relationship to customer satisfaction and any exciting requirements always add to customer satisfaction (Fox 1993).

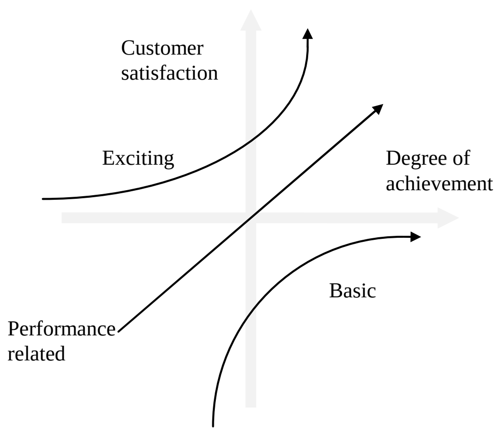

Figure 4.2. The Kano Model.

4.2.1.2 New Technology

Meeting customer requirements increasingly requires a constant upgrade through the integration of new technology. New technology meets customer requirements and must be managed within the variety of products. This is especially true for electronic systems employed by all of the case studies, and in the electronics industry as a whole, where technology life is often very short (Bray 1994; Haynie 1997). To the customer this means that improved performance from upgraded technology and new technology is more easily available and affordable. However technology advances rapidly render technology obsolete. Companies must consider the implications for backward compatability and the constraints this will place upon development.

Upgrade and new technology integration also present time scale concerns. Product development for an upgrade requires considerable resource and timescales can often be greater than the time for another generation of new technology to be developed. Upgrade can also command development costs and effort equivalent to new product introduction.

4.2.1.3 Complexity

The natural consequence of meeting customer requirements and maintaining a level of technology raises yet another issue, that of complexity (Syan 1994). Modern product systems typically incorporate a greater number of features, include inherently more complex technologies, and combine a greater number of technologies in a single system than ever before. Products are typically combinations of technologies, and are structured from components to the completed product (Figure 4.3). Hence it becomes increasingly true that market success depends on the ability of the manufacturer to integrate all such technologies (Tomkinson & Horne 1996).

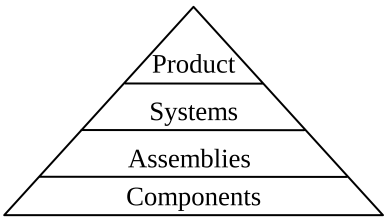

Figure 4.3. The Product Hierarchy.

Management of complexity involves not only product complexity but also development and manufacturing process complexity. The co-ordination across departments, suppliers and with customers requires considerable planning and control especially when combined with modern industrial pressures for reduced costs and lead times (Groover 1987), an issue directly addressed by product and process integration through the total view of SE.

4.2.1.4 Flexibility

The traditional response of industry to the issues of variety and complexity is typically that of flexible manufacturing solutions to what are seen as manufacturing problems. Manufacturing flexibility in this context refers to flexible facilities and tooling, and if taken in isolation only addresses the problem in the short term with associated high monetary and complexity costs. Alternatively SE presents a total view. The application of flexibility to the product and process will facilitate manufacturing flexibility, and the use of flexible systems will then aid the overall design to manufacture process (Marshall & Leaney 1995a). Agile manufacturing embodies the application of flexibility and process integration, lead time reduction, and more enterprise-wide philosophy of concurrent and SE. On analysis it offers similar goals as mass customisation, holonic manufacturing and the fractal factory (Gould 1997).

4.2.2 REVIEW ANALYSIS

SE is a comprehensive approach to the life cycle development of complex products and/or processes. Though the application of modularity primarily concerns the early phases of development, it has implications for the whole of the product life cycle. From an analysis of SE and modularity it is proposed that both address the complexity of product and process from the inclusion of new technology and the strive to meet customer requirements. Thus a SE framework provides the ideal carrier for modular product development and its wide ranging impact on all aspects of the business and the customer.

Upon examination the SE process relates strongly to a broad process for module development: accumulation of requirements, identification of the product's functions and possible combinations of products, identification of product elements for module definition, detail module design and production.. A modular development process will also require consideration of the operation of individual modules and also their operation as a whole product.

Figure 1.2 p.2, illustrates that SE misses an opportunity to provide a true total view of product and process integration through the consideration of manufacturing as the consequence of design. Subsequent review of SE has confirmed the lack of a sufficiently timely consideration of manufacturing concerns. A modular design methodology will address this issue through the consideration of manufacturing issues up front in order to ensure efficient function and production of modules and modular products.

As modularity utilises SE as a framework, the methodology relates to many of the elements within a systems or concurrent engineering approach.

- Holonic manufacturing, the bionic factory, and the fractal factory all exhibit system elements that are autonomous, co-operative, and essentially modular in nature. The theory behind the holon (Koestler 1989) suggests that the key to a successful system, is the intermediate points or nodes, and their robustness and flexibility. These needs are met by a modular product and associated manufacturing system. The manufacturing system is grouped into individual module manufacturing cells. Each cell is independent allowing parallel manufacture, but is also part of the greater whole, feeding into the completed product, being able to respond to changes in design and co-operate to address interface issues.
- Fractal product design (Warnecke, Schneider and Kahmeyer 1994) exhibits a product structure composed of fractals, or effectively, independent modules with precisely defined functionality. Product fractals are self-similar, having standard mechanical and information interfaces. Though they may have dissimilar components and structures, but will maintain the same inputs and outputs. A point that must surely be addressed in order for a modular strategy to succeed.
- The mass customisation approach utilises a more conventional view of manufacturing in trying to deliver the same aims. Mass customisation utilises flexibility in the meeting of specific customer requirements for every product (Beaty 1996). It also highlights that such flexibility cannot be attained purely through a manufacturing solution. The flexibility of manufacturing must be met with product flexibility through modularity and a supporting system of information management between processes and also to and from the customer.
- DFMA practice is important in the development of modules to resist part proliferation and address assembly issues with increased assembly operations and interfaces, and the need to be able to assemble and disassemble modules easily for service and recyclability.
- The identification and appreciation of product functions is a key stage in allowing a product or system to be developed in a manner that is not tied to a physical preconception. The use of functional analysis at the outset of module development provides a basis for module definition.
- VE and FMEA act as valuable checks that development is optimising the quality of its product. VE and FMEA can be applied during various stages of module development in order to optimise individual and also combinations of modules.
- GT is useful to module development to minimise design duplication. GT also goes further by linking the shop floor machines with the modules they manufacture. Such organisation improves transfer times and material handling, and also the process of organisation and the flexibility of the facilities in producing product variety and order filling.
- Teamwork for module development is essential as the decomposition of product systems requires integrated and multidisciplinary co-operation.

Modularity is not new, though a review of the existing modular design processes and software engineering techniques presents an opportunity for a fresh approach. Through analysis of the modular development or related processes a number of considerations have been determined:

- Wherever possible a modular design process should facilitate integration with a company's existing development process, possibly through a widely-used or generic process.
- Modularity should also take account of its interaction with existing business processes and the strategic direction of the company.
- A modular process should act as part of a framework for product development and should be sympathetic to the use of other techniques when required.
- A process for modularity should also be backed by guidance on its use and implications.
- Modules are based upon functionality but also other system elements that are typically dedicated to a particular company or application e.g. standard power supply, user interface, etc.
- Module definition cannot be done efficiently purely by formulaic technique, but requires a team process of considering all aspects of element grouping in order to determine modules.
- Interactions and interfaces are a key. They should also be considered before and after module definition in order to influence the grouping of elements into modules.
- Modular design affects the whole product life cycle rather than just the design process.
- Functional and physical decomposition are linked, but it is not one to one. Functions can be split across physical modules and physical modules may contain more than one function.
- There is benefit in avoiding interaction of functions and the way in which they are met.
- Modules should have virtually all their functional interactions within the module.
- There is a lack of information as to impact of module architecture, combination, and variety.
- Graphical representation of a functional description of the products elements is a good basis for module definition. Schematics, function/means tree, FAST diagrams are all very useful.
- A physical representation of modules is useful for visualisation of complex 3D interactions.
- A natural modularity to products provides one possible basis for module definition.
- Modularity is suited but not exclusively, to a wide range of complex products. However there is no existing classification of products to which modularity is suited.
- Modularity is a basis for an efficient process as well as an efficient product.
- It is possible to determine modularity metrics that can be used as benchmarks for module numbers, assembly time and cost.
- A number of different modular design processes have proven useful within industry. This suggests that there are underlying principles of modularity that, regardless of the approach, still remain true. From this we can deduce that there is no single process for module development: what must be considered is the awareness and integration of the technique.

4.2.3 APPLICABILITY OF MODULARITY

The analysis of modularity revealed that it had a wide ranging applicability. This section reviews the extent of that applicability. The identification of the category of products to which modularity provides utility would be beneficial not only to the topic but also to the potential implementers of modularity in assessing their need for such a technique. Puttick and his manufacturing grids (PA Consulting Group 1989) provide a useful classification of both product and business with respect to the uncertainty and complexity of the sector in which they operate.

Sector Classification

Uncertainty \ Complexity	**High**	**Low**
High	Sophisticated capital equipment	Fashion
Low	Consumer durables	Commodities

Competitive Stance

Uncertainty \ Complexity	**High**	**Low**
High	1.product performance 2.delivery/availability 3.price	1.delivery/availability 2.product performance 3.price
Low	1.price 2.product performance 3.delivery/availability	1.price 2.delivery/availability 3.product performance

Critical Competence

Uncertainty \ Complexity	**High**	**Low**
High	Product design & development Information technology	Market vision Time to market
Low	Time to market Flexible manufacturing	Manufacturing productivity Logistics

Manufacturing Response

Uncertainty \ Complexity	**High**	**Low**
High	Engineering database Versatile production Central control	Rapid design Flexible automation Reactive scheduling
Low	Modular design Flexible manufacturing Just in time	Capacity planning Continuous production Delivery logistics

Figure 4.4. Manufacturing Grids.

Complexity refers to the variety of products, components, processes, sources of supply etc. Uncertainty is about the volume and stability of demand and the degree to which the product design is static. The grids identify major groups of products and the processes and strategies that accompany them.

A review of the case study material and literature reveals that the influential area of modularity is the high complexity half of the grids as the benefits of modularity are related to the complexity of the undertaking. The grids themselves specify modular design for the consumer durables, such as automotive, conventional machine tools, and both white and brown consumer products. However the products that comprise the capital equipment area, such as aerospace, defence, professional electronics, and railway equipment can also benefit greatly from the modular approach. In fact the boundary between the four grids is misleading as strict segregation is not possible. It is therefore proposed by the author that modularity occupies an area that overlaps the four areas with a different aspect of modularity being beneficial for each case.

Modularity Classification

Uncertainty \ Complexity	High	Low
High	Sophisticated capital equipment	Fashion
Low	Consumer durables	Commodities

Modularity Influence

Uncertainty \ Complexity	High	Low
High	1. Complexity 2. Variety	1. Variety 2. Recyclability
Low	1. Flexibility 2. Manufacturability 3. Variety	1. Manufacturability

Figure 4.5. Modularity Aspect Grid.

Figure 4.5 shows the beneficial aspects of modularity to each of the four classifications of product. If the grid is considered as a scale, the shaded area represents the beneficial impact of modularity. Capital equipment will benefit from the ability to use modularity as a means of complexity rationalisation and structuring, and the ability to incorporate product variety. Consumer durables benefit through the accommodation of flexibility, the manufacturability through standardisation, process organisation and simplified testing, and also through the increasing requirement for variety. The two high complexity areas are not covered in entirety, as a number of products will be suited to an integrated architecture. The fashion goods will not be greatly influenced due to the limited number of components used. However, the boundary area where there are potentially enough components and inherent functionality, may see modules implemented for the capability for product variety and the recyclability of highly changeable products. The same applies to the commodity products, but boundary items will benefit from the manufacturability of modular products.

In order to clarify the applicability of modularity it was aimed to develop a number of rules. However, the complex nature and number of variables for applicability prevent the generation of meaningful rules that clearly classify a product suited to modularity. The only rules that can be stated are based on the inference that the classification of a product suited to modularity can be derived from the classification of products not suited to modularity:

1. Products that require an integrated architecture.
2. Products that are sensitive to functional interfaces.
3. Products that are predominantly uniform in substance, e.g. powders, aggregates, textiles, or from continuous processes e.g. rod, pipe, film, etc.

These rules determine a binary application of modularity i.e. whether it can or can not be applied. To further refine the applicability of modularity it has been determined that there are a number of increments between a product ideally suited to modularity and one that is not. The following questions on more specific implementation aspects have been developed to provide an insight into this range.

Q What is the degree of possible commonality between the product and any other?
Product is modular for commonality through, or across a product range (rationalised variety).
Q To what extent is the product likely to be modified / updated in the future?
Product is modular for implementation of design change/upgrade with reduced effort and cost.
Q How complex is the product and project to be undertaken?
Product is modular to simplify the product, and for structuring and management of the project.
Q To what extent is the product constrained by manufacturing strategy and processes?
Product is modular for late introduction of variety, cells, mass customisation, simplified test.
Q To what extent will the product include elements requiring regular service or replacement?
Product is modular to simplify service or replacement of consumables elements.
Q What is the degree of possible recyclable / reuseable elements within the product?
Product is modular to group recyclable elements to simplify disassembly and reclamation.
Q To what extent will the user desire / require configurability of the product?
Product is modular to simplify product configuration to user specification.

Each of the questions relate to a different aspect of modularity's application. These aspects may also be combined. This highlights the breadth of classification possibilities and the difficulty in providing a simple determination of the applicability of modularity.

The fuzziness of the applicability of modularity is also mirrored by the nature of the modularity applied. The case studies of chapter 3 have shown for a modular product there are a number of dimensions to the implementation of modularity. A product modularised for variety requires a range of generic modules that can be configured in a number of combinations. Whereas a product developed to take advantage of a consumable module may only consist of two modules, one a generic consumable item, and one dedicated to each product. This application difference of modularity will be referred to as the level of modularity and is investigated in chapter 5.

The use of the manufacturing grids to determine product classifications for modularity fails to address the size of the company producing the products. The question is whether company size matters in this regard? The implications are likely to be relative. For large companies modules can be used to reduce work repetition and allow flexible production volumes and location. Large companies will see relatively small changes but they will be wide spread due to the volumes of production. To small companies the benefits will be of a more direct nature impacting time to market and responsiveness. The impact of modularity to a small company will be relatively large but less widespread due to the more modest production volumes. Thus corporate size and complexity have little impact on the overall applicability of modularity but they are likely to impact on the actual implementation of a modular strategy (Section 4.2.6).

The use of the manufacturing grids and the rules/questions have determined a broad applicability of modularity. This can be further supplemented by the use of a number of measures or metrics to provide a scale for the range of applicability. Three sets of metrics have been developed to reflect the qualification and advantage analysis where products are deemed suitable or not to modularity, and the business issues to be addressed. The third is an implementation analysis where the specific modularity level may be classified and the driver for modularity identified. The rules and questions provide one qualification metric, one implementation metric; and a single advantage metric is also derived from the four issues of chapter 3:

Qualifier	Advantage	Implementation
1. Integration	1. Requirements	1. Configurability
2. Interfaces	2. Upgrade	2. Commonality
3. Uniformity	3. Complexity	3. Modification
	4. Flexibility	4. Complexity
		5. Manufacture
		6. Service
		7. Recyclability

From these metrics simple analyses are to be later developed to aid a potential implementer in determining the possibility and also highlighting the potential for modularity in their product and production realisation processes. Chapter 5 carries forward these metrics and basis for analysis into a number of analyses based around the qualifier analysis and metric, the advantage analysis and metric, and the implementation analysis and its level of modularity metric and driver review.

4.2.4 QUESTIONNAIRES

To supplement evidence of modularity from case studies and the literature two questionnaires were developed. The questionnaires were tiered into two levels; corporate level and operational level (Appendix 3). The approach mirrored that of the Design Council's survey of current issues in design (Cully, Owen & Pugh 1996) and aimed to gauge any differences in perspective of those questioned. The two questionnaires had slightly different content but the same broad aims:

- To gauge the understanding of the term modularity and the concept of a modular product
- To identify individuals perspective on the pros and cons of modular product design
- To try to identify interest in a process for modular product design, and to identify the preferred format for guidance in such a process
- To establish company background to allow any conclusions to be drawn.

Questionnaires were sent to companies who had been contacted regarding their work or interest in modularity. The companies ranged from small to medium sized and were typically producers of relatively complex products. The employees targeted were from a range of positions including product engineering both electronic and mechanical, manufacturing, software engineering, and supplier liaison. They also included employees from operations manager to engineer.

Though the sample was modest (20), and the returns even more so (7), the responses provide some interesting conclusions even though they can not be taken as any true representation of general opinion. A full break down of responses is available in appendix 3. but a brief summary is presented here. The questions asked were split into two sections and included details on:

General Section	Modularity Section
Company & Position	Product configurability
Product	Interest in help / guidance
Competitiveness	Understanding
Design improvement drivers	Main benefits
Constraints	Main disadvantages
Standards / guidelines	Format of help / guidance
Introduction of new standards / guidelines	
Standardisation / flexibility	

1. In terms of the important aspects of a company's business strategy to retain competitiveness, reductions in overall time to market were consistently the most important (Appendix 3. Question 7 operational questionnaire (O) Q.11. corporate questionnaire (C) (General)).

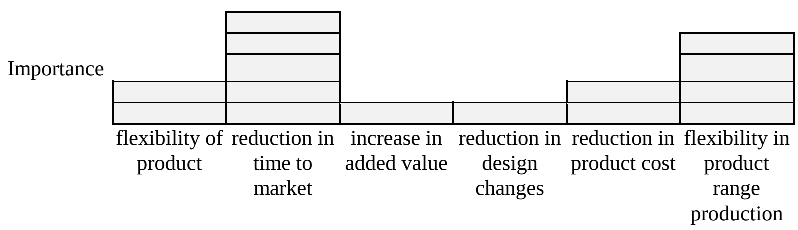

Figure 4.6. Business Strategy Aspects for Competitiveness (Q.7 / 11).

2. Constraints on the ability to meet desired aspects of the business strategy were product complexity, inadequate or inappropriate design tools and insufficient attention to up front design (Q.13 (C)).
3. Major drivers for design improvements were weighted towards reliability, cost, performance and improvement in the ease of manufacture (Figure 4.7). Less engineering based attributes such as aesthetics and ease of use were of lower priority, indicative of the non-consumer type of products targeted (Q.10 (O)).
4. Part / subassembly commonality or standardisation between products was an important factor for product design but there was an overall lack of formal requirement for this. This was also mirrored for the use of carry over parts (Q.17 (O) Q.18 (C)).

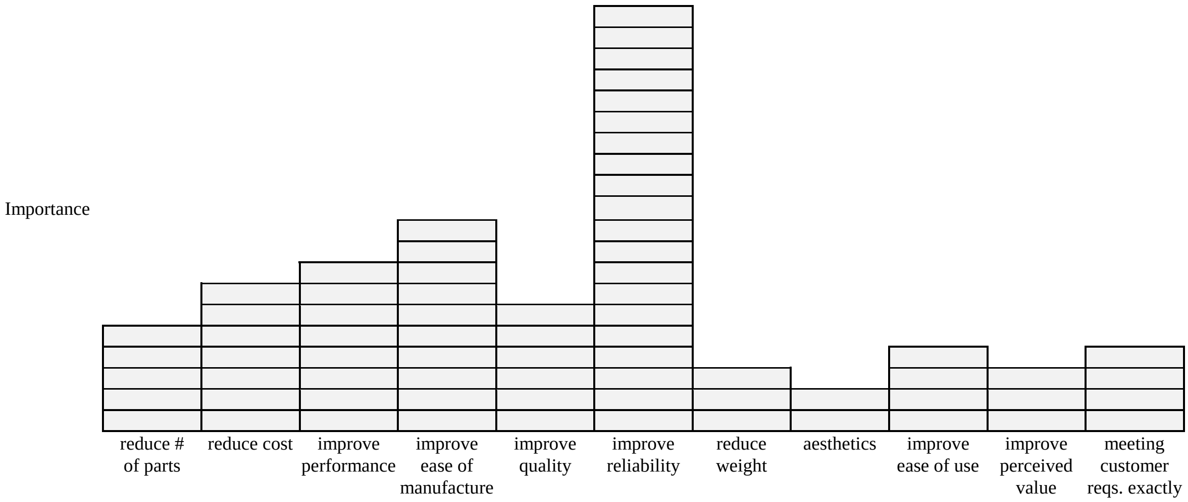

Figure 4.7. Design Improvement Drivers (Q.10).

5. Product and manufacturing flexibility were both important issues for the companies though little product flexibility existed. Flexibility was noted to be greater in electronics packages and in particular, software (Q.19 & 20).
6. The difficulty of implementing product flexibility was seen to be the mechanical and optical areas of products but could possibly be summed up by one comment that flexibility is most difficult to implement "if product and manufacturing process have not been originally designed to cope with the need." (Q.23).
7. Product configurability was seen to be important to all companies, accompanied by interest in a technique to aid in achieving configurability (Q.1 & 2 (Modularity)).
8. Definitions of the meaning of modular design were varied, though all respondents answered that they knew what it was (Q.3 & 4).
9. The main benefits of a modular product design were clearly a reduced repetition of work and a reduced lead time to market. Many of the other benefits even out and perhaps indicate that some benefits are universal whereas some are dependent on perspective. One general comment was made that modular design was, overall a more thorough process (Q.5).

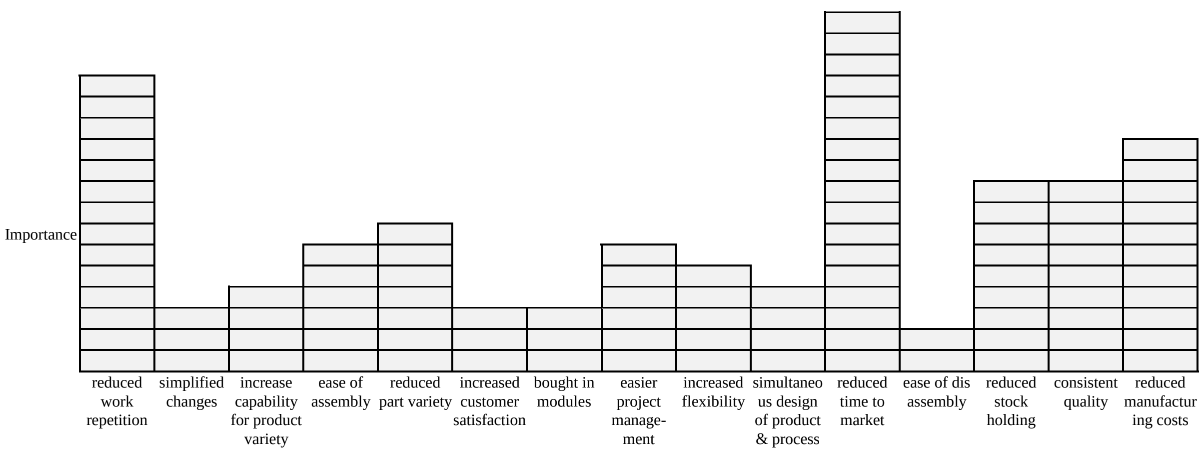

Figure 4.8. Main Benefits of Modularity (Q.5).

10. The main disadvantages of a modular product design were greater interface problems, and an increased perceived work load and cost. Though interestingly, two respondents from different companies believed that none of the possible disadvantages are applicable (Q.6).
11. Q.8. There was a fairly unanimous opinion that the benefits of modular design outweighed the disadvantages, both in general and for the respondents own products (Q.8).
12. Guidance on the principles and practice of modular design would be most appreciated in the form of regular team meetings, with software and paper based checklists / workbook a close second. It was also noted that this guidance would be beneficial in avoiding the pitfalls and repetition of mistakes of implementing a new process (Q.9 & 10).

The limited conclusions we can draw show that there was an appreciation that the important factors for competitiveness were quality, cost and time. It was also apparent that they could in part, be achieved or aided through standardisation and flexibility within the product design. Though these concepts were employed there was little formal requirement. Standardisation had no formal procedure for maintaining information and traceability to provide the designer with the required details. Flexibility was provided in the areas where change is relatively straightforward, such as software, but for mechanical design flexibility was very difficult.

Modular design provides a number of benefits, addressing issues such as quality, cost and time, and these outweigh any disadvantages. In conjunction with the lack of a structured approach to modularity this supports the need for a fresh approach concluded in chapter 3. The requirement for formal guidance was also clear and would be best disseminated and maintained through team meetings, supported by either software or paper based guidelines or a workbook.

4.2.5 THE ADVANTAGES AND DISADVANTAGES OF MODULARITY

This section reviews and summarises the positive and negative aspects of modularity taken from the case studies and literature. A more comprehensive list of advantages and disadvantages are available in appendix 7. It is important to note that modular design alone will not inherently provide all of the benefits outlined here. There needs to be the appropriate structure, facilities, tools and skills available to utilise modularity to its best advantage.

In development modularity encourages part standardisation simplifying and speeding the design process through a reduction in component design. At a module level standard modules allow commonisation across a range of products, or as carry over modules. The decomposition of the system into modules also simplifies and allows parallel development. The result is a structured, streamlined, and simplified process for development of new products and product updates.

Modularity facilitates the introduction of rationalised variety. Specific features requested by the customer can be developed into option modules that are combined to provide a tailored product for the customer. Thus the possibility exists to have a theoretically large product range from a small number of modules. This process combines the best features of standardisation, economies of scale and meeting customer requirements exactly. Variety of this kind also allows extended product life with simplified and faster upgrade development. Modules containing superseded technology can be directly replaced and modules containing new features and functions can be developed to enhance a product without redesign of the original.

To manufacturing modularity provides a system that can be JIT friendly and inherently leaner, through late introduction of variety, reduced parts, parallel manufacture of modules, less work in progress, and bought in complete and fully tested modules (Marshall & Leaney 1995b). In house testing can be performed on modules rather than finished products, detecting quality issues earlier and simplifying final assembly. The use of standard modules allows mass production benefits to be realised for products that exhibit the variety of tailored one-off production. Thus products have improved levels of quality, reliability, are produced faster and at lower cost.

A modular product will be easier to assemble, with fewer part numbers and part variety, modules that are self contained and robust, thus easy to handle, and are identical within each type, that is, they will require no adjustment to fit. Modules can be designed to allow assembly in a number of assembly sequences, or provide features that dictate a specific assembly sequence. Final assembly is simpler, faster, and more responsive to order fulfilment. These features increase the possibilities for automation of the assembly process possibly providing even greater advantages.

Maintenance and service is facilitated through simplified fault finding, access and disassembly of modules. Consumables (toner, paper, fuel, lubricant...) or service modules allow simple refilling or replenishing of a product. Simplified maintenance and service lead to a greater proportion of tasks being performed by the operator, saving on costs and time for producer and operator.

Management and plant considerations benefit from simplified product and project planning through standard modules, decomposition of product and project, and the rational introduction of variety and subsequent configuration control. Factory layouts can be simplified and floor space requirements greatly reduced. The necessity of considering modularisation as both a design and manufacturing issue, and tackling the development problems at an early stage also leads to a reduced downstream activity overhead.

To address environmental issues modularisation allows grouping of consumable or recyclable materials for removal on disassembly or for replacement in the field. Elements that have the ability to be re used or that can be refurbished may also be easily removed and integrated into a new product. Simplicity is an important factor especially in public recycling schemes, as the ease of performing the desired task will have a direct influence on the number of participants.

There are also a number of trade-offs. The disadvantages of a modular strategy include:

- Increase in number and complexity of interfaces.
- Possible increase in part numbers due to redundancy requirements, and extra interfaces.
- Possible increase in assembly operations. (A 6 part product requires 12 operations if assembled serially, three modules of 2 parts require 16 operations plus more fixtures.)
- An increased 'perceived' work load and cost through greater resource requirement up front.
- The management of change to the modular strategy.
- Possible increases in weight and size due to interfaces and redundancy.
- Lack of guidance on the application of modularity.

The majority of modularity disadvantages can be lessened or removed by careful consideration and implementation of the surrounding framework and support. For example, modularity may cause an increase in part numbers, though is likely to be quite low and could easily be negated by use of DFA techniques. Size and weight also fall into this category, overall reduction in part numbers, and closer product tailoring to user requirements potentially realise a product of equivalent or reduced size and weight. Also, due to the front loaded effort required for modularity, initial project costings and time commitments may look discouraging. However this increased 'perceived' work load is easily outweighed by the downstream benefits of such an approach.

The increase in interfaces should be seen as a key opportunity rather than purely a disadvantage. By modularising and thus decomposing the system, module interfaces will become a priority. This priority will force consideration of the function of the system as a whole. Novel interface solutions and standardisation will aid the assembly and configurability of the modular product.

There will be situations when the application of modularity comes into question. However, it can be argued that no matter the constraint it is likely that modularity will not adversely effect the product or its development, as a modularity process is inherently a combination of best practices. This confirms the earlier conclusion that the application of modularity is not a black and white decision. Instead modularity will provide benefit to almost any application no matter what the constraints, the issue that must be addressed is the level to which the product is modularised.

4.2.6 MANAGEMENT OF CHANGE

Regardless of the specific details of the process to be implemented it is likely to have significant impact upon the company. Of course implementation is likely to be an extremely specific task relative to the organisation in question. However a starting point for change management is the degree of intensity of the change at hand. Incremental (quality programmes) and anticipatory change is much less intense than discontinuous (BPR) and reactionary change. The approach is therefore to integrate the new philosophy into the existing processes in advance of the critical need to react to market forces. A further factor for consideration is the complexity of the organisation. As an organisation becomes more complex the task of managing change becomes more difficult. The intensity and complexity of change can be represented in figure 4.9 to identify the different strategies required.

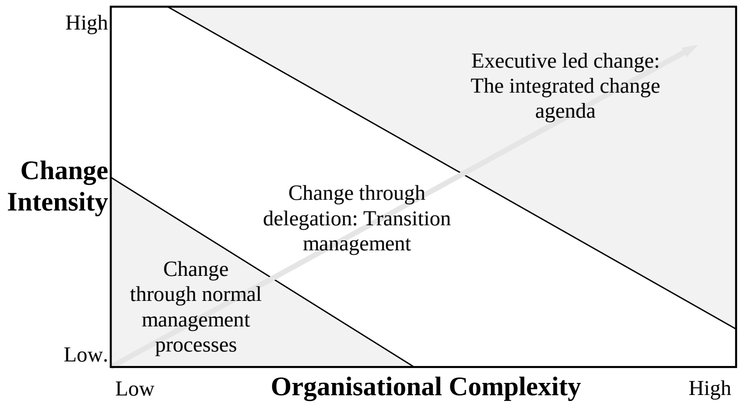

Figure 4.9. Types of Change Management (Nadler & Tushman 1995).

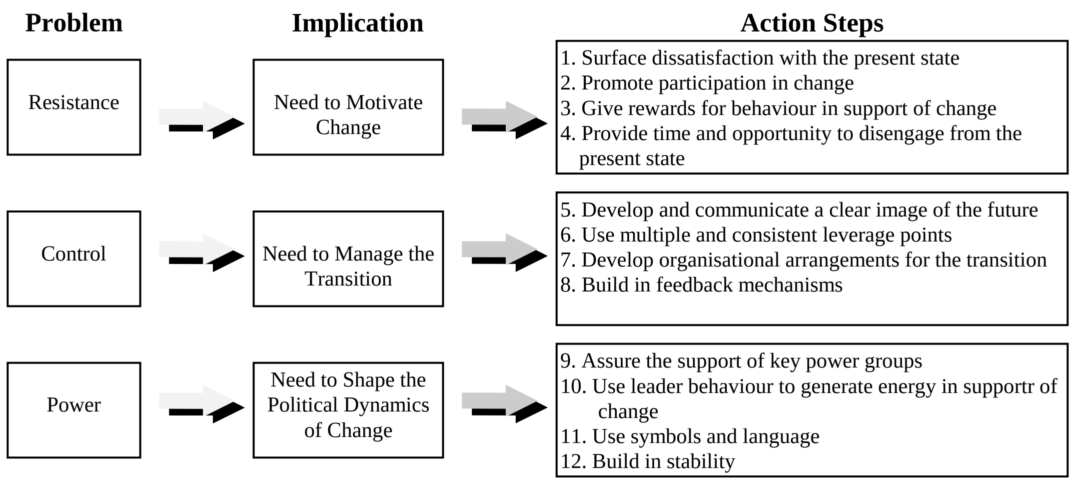

Figure 4.10. An Overview of Large Scale Change (Morris & Raben 1995).

For a potential fundamental change such as moving from an integrated product architecture to a modular architecture and associated processes three factors must be considered. The first is the resistance to change and the motivation that the change is worthwhile, the second is the management of the transition from the current to the future state, and the third is shaping of the political dynamics of the change. Figure 4.10 summarises the main considerations of such change.

All of these actions will be more or less critical and more or less feasible depending on the organisational situation. Thus leaders will have to be diagnostic in their approach to the problems of managing change tuning their efforts to meet the requirements of the situation. These concerns are addressed in the development of a process for modularity (Chapter 5) and modelling (Chapter 7) through the consideration of guidance and its tailoring and integration into existing systems.

4.3 THEORY FOR MODULAR PRODUCT DESIGN

Modular product design or modularity presents an opportunity to the developers of predominantly complex products to meet market pressures in a way that does not impose penalties upon the company. Exponents of the concept of modularity (Smith & Reinertsen 1991; Shirley 1992; Rampersad 1994; Ulrich & Eppinger 1995; Pahl & Beitz 1996; Erixon 1996) have realised the potential of the modular product and some have defined appropriate guidelines and processes for its application. Their analysis highlighted an opportunity to further the overall concept through clarification and the provision of a more comprehensive process and support mechanism to provide a truly fresh approach to product realisation.

Modularity is more than just a design technique. It impacts upon the whole of the product life cycle though its application is biased towards the early phases of design. In the same way that QFD can provide a linking mechanism between the various stages of this cycle. Modularity is developed as a linking methodology supported by a systems level framework for product realisation to provide an integrated and structured product modularisation process (Figure 4.11). The process relates to the specific application of modularity to a product, but through the methodology and framework also embodies the support of the product and its processes.

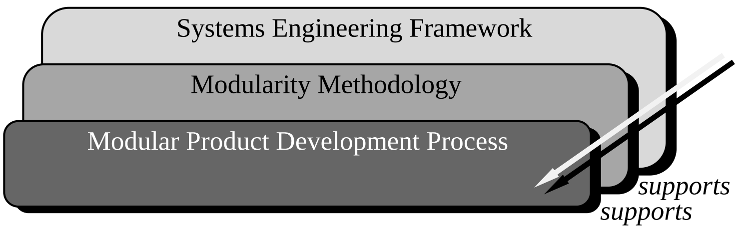

Figure 4.11. The Modularity Paradigm.

The methodology for modularity must cover a number of key aspects. It must be translucent and flexible in that it must be able to overlay an existing product introduction process without undue re-engineering and without masking any successful aspects of the existing process. Consideration will be given to the details of implementation and how the material may be best presented to maximise the clarity of the message, the ease of use, and the support of industrial concerns. Guidance in this regard can be taken from the questionnaire responses and balanced with the needs to provide a neutral format and the constraints of the research. However it cannot be transparent as it must make definite changes and highlight key processes. The methodology through its framework must relate actions to customer requirements, and consider the implications that any element is always going to function as part of a higher integrated system. This framework will support the needs of the whole organisation equally through the importance of: corporate strategies and goals, the need for efficient and effective requirements management, integrated product and process development (IPPD – Blanchard 1998), provision and enhancement of product support, and implications for product takeback, recycling and disposal. In addition the framework acts as a carrier for other techniques, such as DFMA, QFD, FA, VE etc., that are beneficial to specific issues within modularity and also to product realisation in general.

Within the methodology, modularity must be developed into a process that continues the aims of the methodology and ultimately the framework. This new process will be based upon existing best practice and share a level of commonality that facilitates its integration into industry. The process must be generic but take account of all of the diverse factors to which modularity may be applied. Based upon the findings that modularity is applicable at a number of levels and that each implementation scenario will be unique, a form of self analysis is required to allow the process to be analysed for applicability and tailored to suit the individual circumstances of the user. The analysis in 4.2 also identifies a number of specific issues to address. The opportunity presented by manufacturing as an integral part of the design process and the competitive advantage the use of modular product and manufacturing processes presents. The attention to module interfaces and their timing to ensure that interface details can be used for module definition. The acknowledgement of manufacturing paradigms such as holonic manufacturing and the fractal factory and the mutual benefit that may be drawn from their ties to a modular product architecture.

Finally, all of the elements of this chapter (the definition of modularity, analysis of case study and review material, and the requirements for a fresh approach) are carried forward through the development of a modular product development process presented in chapter 5. The resulting methodology is implemented and evaluated in chapter 6 and provides industrial assessment. Chapter 7 analyses the methodology for its impact within a broader framework and examines the underlying principles of modularity.

Chapter 5
The Modular Product Development Process

5

Objectives: This chapter outlines a fresh approach to achieve modularity, in response to the need identified in chapter 4. The approach is embodied through the development of a modularity methodology and modular product development process. The process takes an industrial view and reflects their needs and working practices, focusing upon:

- The consideration of all life cycle processes within a SE framework
- Integration with, rather than replacement of, existing processes
- Self analysis to address suitability and aid implementation
- Support of the methodology.

5.1 DEVELOPMENT OF A GENERIC PRODUCT INTRODUCTION PROCESS

The initial aspect of the methodology was the development of a generic product introduction process (PIP) shown in figure 5.3. This generic PIP provides two key elements to the modular design process. Firstly it provides a basis from which to build the new development process, allowing a company to develop as the process develops. The building process will then provide an end result that will be thoroughly and correctly implemented and understood. Secondly it will provide a common link to all companies in all industries. The generic PIP will provide a number of elements to which any company can relate their own processes. These links can then be used to superimpose the modularity methodology through the generic PIP to their own individual development processes.

There are numerous sources of product introduction processes. Pugh's (1990) design core presents one of the most widely accepted PIPs. Parnaby (1995) highlights the issues within automotive electronics systems, such as those faced by Ford (Chapter 3), of demanding performance, cost and quality requirements. With such product sophistication and the numerous skills required, traditional organisational approaches cannot be competitive for the product development process. A generic PIP developed within a SE framework to meet such requirements was applied within Lucas Electronics Systems.

However all PIPs share a common spine (Figure 5.1) with a greater or lesser degree of detail shown about each major stage, and minor differences about the boundaries of the development process many ending with product launch. However it is now vitally important that a holistic view be taken of product introduction, accepting that morally and increasingly legally the manufacturer has a responsibility for their products right through to disposal. To this end, a total view as promoted by SE is explored in due course.

Figure 5.1. The Common Product Life Cycle Spine. (Adapted from Syan (1994))

British Standard 7000 Part 1, Guide to managing product design (1989) presents an idealised product evolution (Figure 5.2) that was later enhanced by BS 7000 Part 2's model of the design process (Figure 5.3).

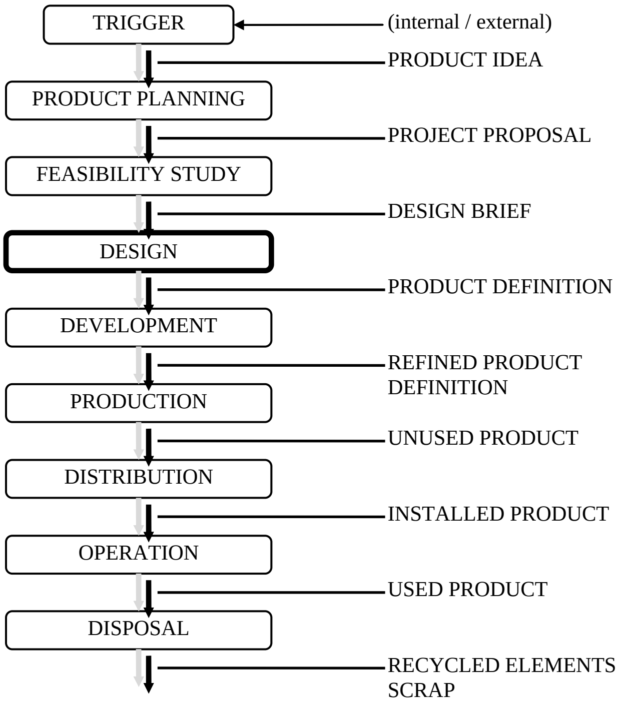

Figure 5.2. Idealised Product Evolution (BS7000 Part 1. 1989).

For the methodology the British Standard provides the best basis for a generic PIP for a number of reasons. BS 7000 Part 2, was recently (i.e. March 1997) launched to the considerable interest of British industry and academia, highlighting its topicality and relevancy. The standard embodies the current best practice within the design of manufactured products taking into account the work of respected names in this field such as Stuart Pugh and Bill Hollins. Potentially a considerable number of companies will use or at least be familiar with this standard and thus make it an ideal basis upon which to build.

Phase of project	Process	Output
Concept phase	Trigger for the design project	Perceived opportunities
	Analysis of opportunities	Alternative business concepts
	Analysis of business concepts and product identification	Identification and selection of preferred business concept and product characteristics
	Formulation of the project, objectives and strategies	Preliminary definition and project proposal
	Preliminary evaluation and approval of the project by the corporate body	Permission to proceed
Feasibility phase	Planning, research and feasibility studies leading to the formulation of a project proposal	Criteria of acceptability to organisation
	Refine characteristics. Development of a functional specification	Product design brief
	Development of project configuration and work programme	Project plan. Resource plan
	Evaluation and sanctioning of project by corporate body and commitment of resources	Project approval
Implementation phase	Bringing together of a multi-disciplinary team of specialists to realise the project	Roles and responsibility matrix
	Design concept development. Rehearsing the customer-product experience	Preferred option
	Outline design (embodiment design or general arrangement design)	Product resolution
	Detail design	Specifications for product
	Construction and testing of pre-production prototypes	Confirmation of performance and reliability
	Finalisation of the completed design ready for manufacture. Design support for manufacture.	Product package
	Provisions for manufacture and delivery	
	Product launch	Product availability

Figure 5.3. Model of the Design Process for Manufactured Products (BS7000 Part 2. 1997).

In order to address the modularity paradigm (Figure 4.11), the modularity methodology and subsequently the modular development process will be based within a framework provided by a modified version of the SE V of figure 2.14 p.29. The SE process is used in addition to the more conventional generic PIP to address the following:

- SE is a key element in the modularity paradigm (Section 4.3 p.84). However SE is not typically used for the development of products with which this thesis is concerned. It is therefore prudent to relate modularity to a generic PIP in addition to the SE framework.
- The cross references between modularity, the generic PIP and the systems framework can be used to highlight the integration of modularity to SE and more traditional development processes, in addition to the links between the PIP and the SE model. This methodology can also be used to bridge the gap between these perspectives.
- A SE approach deals with the elements that are key to modular product development, such as requirements management and system element interaction and integration in much greater depth than the more traditional PIP.

Figure 5.4 presents the SE process that will be used for the methodology and modular development process framework. The stages of the process are identical to the original with the addition of an implementation phase, and the content of each stage is augmented by manufacturing considerations (details in Appendix 4).

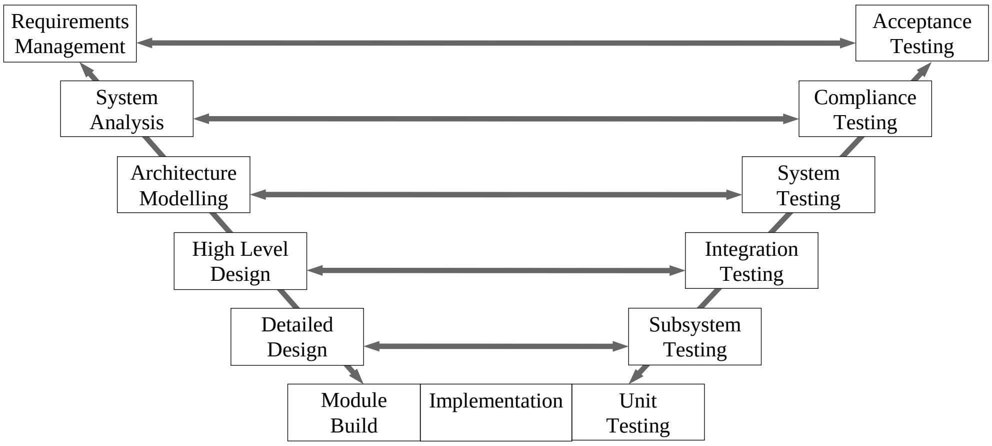

Figure 5.4. The Systems Engineering Process (Adapted from Walker 1997).

Though the product introduction process is fairly self explanatory a number of further points should be observed. The process of product introduction has to reflect on two aspects; the customer's needs and expectations, and the supplier's needs and interests. An organisation providing a product has to meet the customer needs and expectations fully but in the most economical way (meeting the suppliers needs) (BS 5750 Part 4 - 4.2.1 1990). BS 5750 Part 4 (1990) presents the design function as the ability to take the customer requirements and translate these in a systematic and controlled way into a specification which defines a product or service. This specification should be such that the product is producable, verifiable and controllable under the proposed production, installation, commissioning or operational conditions.

5.2 DEVELOPMENT OF HOLONIC PRODUCT DESIGN

This section documents the development of the relationship of a modular product development process to the basis established with the previously presented generic PIP model.

Modularity has a rather unfortunate legacy in that many companies and engineers believe, incorrectly, that they understand what modularity means and that they already utilise a form of modular product architecture. In addition modularity is often seen purely as a process of decomposition or demarcation. These preconceptions constrain the initial reception of a modular design process and thus effort was made to imply greater depth to the methodology developed through the selection of a new title. This lead to the use of holonic product design (HPD), where holonic is used for its representation of autonomous and co- operative elements. However, the term is still far from ideal as its use is uncommon and it has the unfortunate trappings of a fashionable and transient word. However, the term relates well to modular entities and their relationship to the environment and system in which they operate.

Such reasons caused the IMS to coin holonic manufacturing systems, taking the word holonic out of its original context. Holonic product design does the same but applies it to the process of product development rather than purely of manufacturing systems. To a degree, the limited proliferation of holonic also works in favour of its use. Interested engineers will pick up on such a title and the enquiry into its meaning can spark an interest into the application behind it.

Figure 5.5 illustrates the relationship of the HPD PIP (methodology) and the SE model (framework) to the generic PIP. 'Stages' (shaded boxes) are linked through three main 'phases' (left column). The diagram further integrates the detail of the modular design process necessary to actually design modular products (right column) which is covered in section 5.3. The following explanation details the impact of HPD upon the stages of the generic PIP (note: those stages largely unaffected are not considered here).

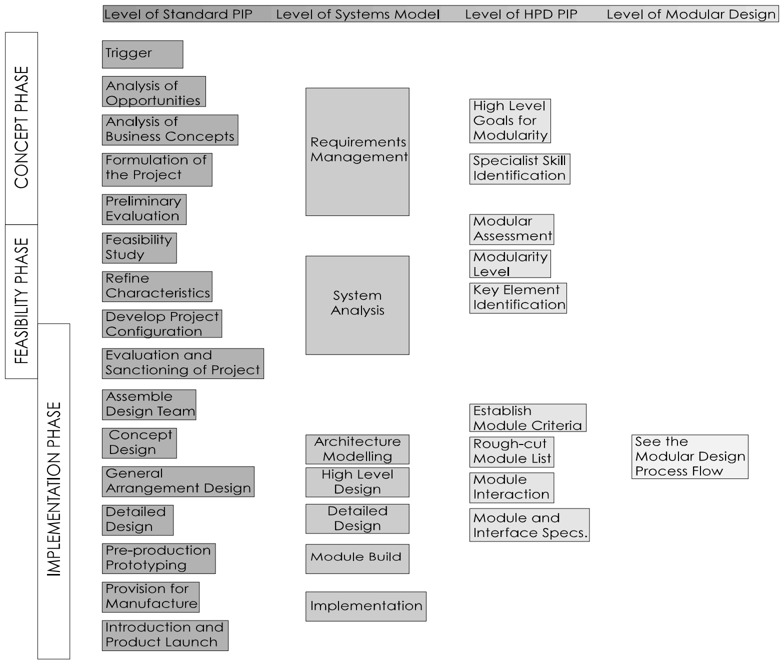

Figure 5.5. The Holonic Product Design Methodology and Relations.

The first phase of HPD is the 'concept phase' and relates to the generic PIP and SE model through the following processes. During the *analysis of opportunities* and *analysis of business concepts* additional consideration must be given to compatibility with corporate objectives and strategies. It is important that the corporate objectives should provide the foundation and main thrust of all activities, including design. Corporate strategies should be drawn up as prescriptions of approaches to be taken and how resources will be harnessed to achieve the corporate objectives set. These are fundamental company ideals and as such it is recommended that the appropriate corporate objectives and strategies be modified to include the company's wishes for modularity. Projects at this stage must then conform to these criteria.

The use of the corporate objectives and strategy in this way provides a universal platform for the integration of disciplines and the utilisation of resource in achieving business goals in an effective and efficient manner.

One aspect of the modularity process is it's inherent capability of dealing with variety. The project should be considered in relation to existing and future products with the view to the development of a family of products to maximise the potential for the modules. Though future products may not yet be defined the capability to add models that use common modules must be considered, if only to be ruled out.

During the *formulation of the project* a project team should be assembled. A project team will involve a multi-disciplinary approach including, for example; design, manufacturing, test, and service personnel, but also have senior management buy-in and be prepared to include specialist personnel whenever required to lend a particular perspective. This team will then oversee the development of the project and make the key decisions along the project life-cycle, whilst maintaining a clear focus on product requirements. Depending on the size and available resource of the company, this team may also be the module team detailed later, but could also be a high level body co-ordinating a number of module teams. During this phase specialist skills should be identified that can take a systems view of the design. Any bottlenecks to the change should be identified, such as poor communication channels and employees unused to the team environment.

The second phase is the 'feasibility phase'. During the *feasibility study* a product must be assessed as to whether it is suited to a modular architecture. If the project requires a highly integrated and refined design, where criteria such as weight, size, and functional interfaces are a key issue, a modular design may not be a suitable aim. At this stage an idea of the level of modularity (introduced in chapter 4) must also be agreed by the project team. Three levels have been identified by the author: complexity, resolution, and composition, which relate to the degree of functionality, the number, and the standardisation of modules (their development is detailed later). It is important that a benchmark be set in order for all modules to aim for this agreed level. Key elements of existing and planned products must also be identified to allow targeting of modules during the concept design phase. Key elements may include; specific electronics packages, power supplies, user interfaces, consumable items, and ease of access.

Though there are many benefits of defining certain characteristics toward modularity as early as possible, some companies may not be committed to having modular products that share modules to any large degree, it is therefore recommended that the previous stages be left to the concept design stage, where a modular architecture may form one of a number of options.

The *refine characteristics* stage is where the product design brief is developed. Included in the brief should be the information already gathered such as the level of modularity. It may also be useful, if possible, to assign key elements that that are important, to a module. This is especially true as regards legislated requirements or items related to product reliability. During the *development of the project configuration* project reviews should be assigned for each step of the design phase. This is especially important due to the added complexity that a modular product and modular processes may introduce.

The final phase of HPD is the ‘implementation phase’. This phase represents the main area of activity in developing modular products (detailed in the next section). In accordance with the generic PIP the modular design process will be developed to integrate with its processes, specifically those sections labelled as*: assembly of design team, concept design, general arrangement design* and *detail design*.

5.3 MODULAR PRODUCT DESIGN

This section aims to clearly define the process developed for designing a modular product and highlight the necessary steps to be taken to ensure a successful design. It also continues the process of building upon the generic PIP through the HPD. The process utilises concepts from the case studies and the literature on modular design, in addition to adhering to a number of basic concepts that were developed by the author as a series of preliminary modular development guidelines. The guidelines are shown in Appendix 4, and are a compilation of best practice for modular development that should be considered when undertaking a modular project.

The process (Figure 5.6) was developed to be a logical flow based around the formation of a module team and occurs during concept and general arrangement design, early on in the PIP (Figure 5.5). As an initial activity the team would accept or determine a number of key requirements for the module for which they are responsible. Level of modularity, key elements, and module criteria are all requirements upon the system for modular design. It is important that each requirement is determined very carefully as they will have significant impact upon the outcome of the modular design process. It is possible that the source of the requirements will come from many areas, such as; customers, the company’s corporate strategy, company departments, and the team itself, all requirements must be collected and considered for the module criteria. The result is a list of module criteria that function as a design specification.

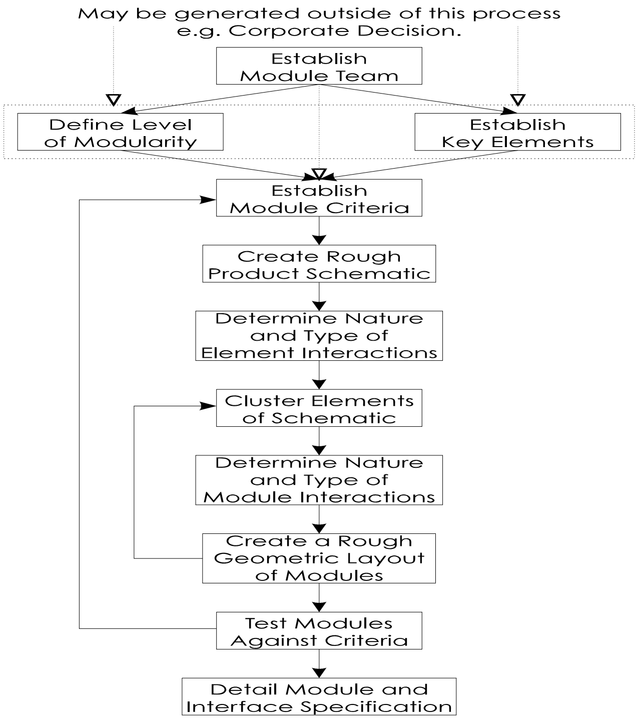

Figure 5.6. The Modular Design Process Flow.

5.3.1 TEAM FORMATION AND REQUIREMENT DETERMINATION

Team formation initiates the process and consideration must be given to familiarity of team members with the product, location of members, team resources, and team responsibilities. The module team may be a core project team but for large complex projects individual teams may be assigned to single or small groups of modules. Resulting in greater focus for team members and parallel development. Such teams each have a representative forming part of a main project team.

One of the requirements for the modular design process is the level to which the modular architecture is to be taken. The level of modularity (LOM) introduced in chapter 4, must be defined in order to provide a fundamental direction to the process. Three factors were determined (see earlier) that define the level of modularity:

1. *Complexity* - This is the functional level of modularity for each module. A module can contain anything from a single function to a combination of many functions.
2. *Resolution* - This is the number of modules in the product. The number of modules relate to the complexity, where high numbers of modules are likely to have low individual functionality.
3. *Composition* - This is the degree to which module complexity varies within a single product, and whether the product is a hybrid of an integrated common module and variant modules.

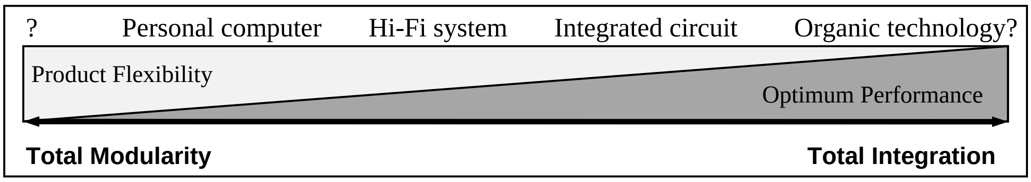

Figure 5.7. The Modularity Scale.

Where products with a high LOM exhibit benefits in terms of flexibility, those with a low LOM act as an integrated whole and tend to be products where optimum performance is critical. The affect of the LOM has been identified through a number of additional factors:

1. The LOM gives a basis for development to maximise the ability to utilise common modules. Products of greatly differing LOM are unlikely to be compatible due to the module interfaces.
2. The LOM will affect the flexibility and the performance of the product. Though highly flexible modular solutions can perform extremely well, they are unlikely to exhibit the optimal architecture and performance. It must be stressed that this only relates to examples of exacting performance, as non-integrated systems can also be designed to function to very high levels.
3. The LOM will affect the manufacturability of the modules, and subsequently the product. The more common modules that can be used the more efficient the manufacture. The more complex the individual modules the more complex the manufacture.
4. The LOM will also affect, complexity, robustness (both in quality and flexibility), and cost.

Once an LOM is determined other key elements should be documented. This is a process whereby any feature that is important or desired is noted, and may include a particular assembly, a brand, a standard, or legislation to be met. Though key elements may appear later in the product specification or concept designs, this early stage allows the elements to be considered in the modular scheme. Key elements may arise from team actions such as the analysis of existing products. However elements are likely to be presented as project requirements from earlier requirements management processes. These links between the module teams and other aspects of the business provide the opportunity to impose requirements upon the project, allowing strategic decisions, made independent of any one project, to shape the overall concepts for modularity.

Module criteria takes the LOM, the key elements, and adds to them specific module requirements. Module criteria are features and functions that are deemed necessary, or essential by the modularity team. Criteria act as a focus, a reminder and as a benchmark for the design of the modules. Module criteria will be analogous to system and design requirements. Traceability and weighting (e.g. mandatory, important, and desirable) should be indicated against requirements. Allowing actions to be traced to requirements and also trade-offs to be made if required.

5.3.2 MAPPING OF THE PRODUCT ARCHITECTURE

Having determined the requirements these are then translated into an initial form for the product. This is done through a diagrammatic representation of the product's functionality and any specific physical requirements. A schematic fulfils this purpose and can be developed using FAST diagrams, function-means trees or any other familiar representation. The schematic then allows elements to relate to physical concepts, to critical components, or to a functional element that may not yet be described such as 'deliver power'. The function representation is important, the verb+noun format allows a high degree of freedom for the design process. Schematics should avoid over complexity and may be related to the LOM if helpful. Several schematics should be produced to facilitate the consideration of several product feature and architecture types.

Having mapped out the product makeup the interactions between elements should be examined in more detail. Interactions will have significant affect upon modules and impact manufacture and the overall function of the product. The interactions are defined using the product element interaction chart based upon Crosfield's and Pimmler and Eppinger's (1994) work.

Modules		**1.**	**2.**	**3.**	**4.**	**5.**	**6.**
CCD	**1.**		S	-	E	S	EI
Carriage	**2.**			-	E	S	EI
Focus image	**3.**				E	-	EI
Provide power	**4.**					E	(E)
Position carriage	**5.**						E
Control process	**6.**						

Figure 5.8. The Product Element Interaction Chart.

Where:

M = Material Interaction. E = Energy Interaction. I = Information Interaction.

S = Spatial Interaction ◯ = Fundamental or critical interaction.

5.3.3 MODULE DEFINITION

Once the agreed schematic elements and interactions are finalised, the elements are ready to be assigned to a module. This process is one that is so case dependent that it must be done purely intuitively by the team. However the LOM should provide a guide to number and complexity of modules. The process is best approached by assigning one element to one module and then grouping where advantageous. A number of factors have been developed for the process of deciding if grouping is advantageous.

- Interactions: Interactions between elements that are critical may benefit from the elements being grouped as may interactions utilising mechanical movement which is not sympathetic to being made to function over long distances. Interactions that utilise digital signals can be easily separated and may benefit from being in separate modules, as in multiplexed systems.
- Geometric location: Integrating elements that require geometric alignment between them will benefit from being in the same module, as control of the alignment is done in a localised area or by a single component.
- Function deployment: When a single element can implement a number of functions the elements can be grouped. This may inhibit flexibility as not all of the integrated elements may be used in another product. However there is the possibility of redundancy if advantageous.
- Supplier capability: A regular supplier to the company may have a specific area of expertise, elements in this area may be grouped to utilise the capability of a supplier to the maximum.
- Natural Modules: Groups of elements that naturally complement each other and benefit little from being separate are termed natural modules, such as power supply units.
- Core Business: The grouping of elements into modules that contain features, functions and expertise that fall outside of the core business allows them to be provided by a supplier.
- Localisation of change: If change is anticipated in certain elements through, wear, use, obsolescence or fashion, then these elements should have their own modules, such that they may be altered, replaced or serviced without affecting the whole, as in toner cartridges.
- Configurability: Elements should be grouped such that the company may combine modules in differing ways to provide variety if desired.
- Standardisation: Elements useful to a range of products should be grouped so that modules can be common or form a generic platform or architecture. A generic architecture provides a standard proportion for each product, and introduces benefits through flexibility. Modules can then be developed that provide variety when configured with this generic architecture. In this regard designs should consider existing products in addition to possible future products and how they may be integrated with the current designs, components, processes, facilities etc.
- Manufacture: Elements may be grouped that require the same manufacturing processes or combined through the use of a manufacturing process such as injection moulding or casting. This can be further extended to the grouping of elements composed of similar materials, not only for ease of manufacture but also for recycling purposes. Groups can be formed to provide modules that encapsulate key features of the product these will aid manufacturing if the design allows for these to be introduced to the assembly process late on.
- Failure modes and effect analyses: If product or process FMEA studies are carried out early on, or previous data is available, the results may be used to group elements with a view to minimising the failures and their consequence.

Once a satisfactory grouping of elements into modules has been performed interactions between modules should be identified. It cannot be taken that the interactions will purely be combinations of those between elements determined previously. Module interactions are at a higher level than element interactions and will arise due to the physical implementation of the functional elements or due to the geometric arrangement of the modules. These interactions will probably not appear on the schematic and must be identified to ensure that any detrimental effects may be removed. The process follows the format presented previously for element interaction.

When determining interfaces it is beneficial to determine a set of standard interface types and standard interface locations to be used wherever possible through the product range, and in future products. Thus carry-over modules will have a set of defined interactions associated with them. Standard interfaces facilitate the compatability of new product modules. They also provide economies of scale, reduced stock holding, ease and flexibility of manufacture and assembly.

After module grouping and interaction analysis, a geometric layout should be created using drawings, CAD, or foam mock-ups. Though still in the concept phase of development it is useful to bring forward some arrangement design in order to aid the conceptualisation of the physical feasibility of the product. The model forces the team to consider if groupings can be realised geometrically, and to optimise modules with respect to interactions, and the grouping criteria. Depending on the results of these layout trials, the grouping of elements may have to be revised.

The final aspect of the process involves testing modules and interactions against the criteria defined earlier. This check ensures that all desirable criteria are included or considered in the module design. This is especially important in complex products where addressing the details may make the team loose sight of the overall desires. Modules not meeting the criteria must be looped back and the process performed again. Any particularly advantageous grouping that is in conflict with criteria, may also require the criteria to be addressed. If modules contradict a non-essential criteria there may be compromise in the interest of the overall product. The outcome of this process provides input for detail specifications to be drawn up for modules and interfaces.

These specifications will form part of the standard product design specification but will document the specific modular detail. Interactions documented in the specifications are very important and may be used to structure and manage the remaining development activities. Modules that have many interactions should be developed by groups that are closely tied, or even a single group. Modules that have few or no interactions can be developed by independent teams or outside suppliers. If a module is to be developed in isolation there must be a strict specification of the interface that it has with any other module, even if the interaction is low.

5.3.4 SOFTWARE

Software is increasingly a highly functional element of product design. Many products derive a high degree of functionality through their software. Reflecting this, there are a number of points that need to be considered when developing products that have a software element.

Software development should be addressed very carefully. It is often a feature that is considered to be effectively free, infinitely adjustable, changeable at the last minute and an ideal way to compensate for shortfalls in the basic design. In reality software complexity increases rapidly with the complexity of the problem and, due to temporal dependencies in real time systems, can have extremely complex failure mechanisms. This requires a very rigorous design and test philosophy based around software modularity and it is very important that software requirements are treated with as least as much care as mechanical or electronic systems (Loureiro 1998).

During the *document key elements* stage it should be ensured that any software considerations are included. These additional requirements will then become part of the *module criteria*. When *determining the nature and type of element interactions* it may be beneficial to highlight those interactions that are made or controlled by the software element. This will allow the domain of the software's influence to be clearly identified. This boundary can then be used during software development to indicate the interactions with the product modules and the personnel responsible.

When the process of *grouping elements of the schematic* is being carried out, a subset of the 'Interaction' factor may be the desirable feature of grouping elements that are controlled by software to do complimentary functions or to perform simultaneously. There is an advantage to be gained from linking the product architecture to the software architecture, such that changes to software functionality may be mirrored through localised changes to the product modules.

When product modules are determined any software requirements should be included as a module themselves. So that it may be developed in parallel, analysed for interaction with physical modules, and finally integrated with greater efficiency.

Though the software elements are very important they are generally beyond the scope of this process, to go into in greater depth. For further information users of the process will be guided to more comprehensive standards related to this area such as: BS 5750 Part 13. (1991): Guide to the application of BS 5750 Part1: to the development, supply and maintenance of software.

5.3.5 THE LEGACY FACTOR

It is unlikely that a company considering the use of a modular strategy for one of their products is embarking on their first product design project. The implications of this are that the company will have it's own experiences and their own existing products, preferred components, systems and suppliers. This section will briefly addresses the issues on dealing with the legacy of previous products and how to manage this legacy for future products.

From the outset the modular design process was developed to be integrated into an existing development process through the determination of a common PIP. The reasons for this are to combine the familiar and useful elements already in place with the Holonic Product Design process. This methodology is also applied to the product level where existing elements that are useful or desired are identified for the modular design.

Typically the product and manufacturing legacy presents two attributes. These attributes provide constraints and also possibilities. Existing products that have to be supported present constraints upon the development of a new product in order to achieve compatability between old and new systems. This attribute may also take a subtler form where direct compatibility is not required but there are so many resources invested in specific engineering and manufacturing capability that a product that is considerably different from the 'known' status of previous products is not viable. Backward compatability however, provides a possibility for success if the user does not have to completely upgrade their existing system purely on the basis of a new incompatible product. Backward and forward compatibility should always be considered whether a requirement or not. This will turn the constraint of backward compatibility into a possibility for a common element for new and future products. A number of guidelines have been identified that allow the maximum freedom for design whilst maintaining the all important backward compatibility.

- During the *document key elements* stage all compatibility issues should be documented fully. Modules should be developed that can be used to retro-fit older products and allow a step-change to a new feature for the products. Backward compatability may be further addressed through identification of any module criteria that will provide flexibility in the product range.
- When creating a product schematic elements that interface to older products should be high-lighted for attention. Interface interactions should also be identified to allow compatability modules to be formed during the element grouping process. This realises the possibility for products that do not need the compatibility, simplify changes to compatibility dependent areas, and ensure interaction is localised and thus easier to ensure full compatibility.

- It may also be prudent to try to break the dependency. By using the above suggestions or others that may be specific to a particular case, a move could be made away from being dependent on support of previous products. This will allow greater flexibility in development, reduced problems when there are issues with procurement difficulty, etc. and allow the possibly redundant but necessary for compatibility elements to be phased out at a later date.

Generic or common elements to products provide a constraint on product development, but with care turn the constraint into a possibility for savings in development time, work, space, and cost. The key to using this feature to advantage is getting it right early on, and also providing flexibility for the unpredictable situations that can, and do present themselves. Generic elements of the product build upon common features to provide a generic module, platform, or architecture that is a physical building block for all products within a range. It embodies the concepts of commonisation and rationalisation through reduction in the number and variety of parts. It provides economies of scale, eases and speeds development, production, and maintenance, by reducing the number of procedures and features that staff have to be comfortable with. It presents a philosophy that can meet the customers needs for variety, yet make the proposition economically viable for the developer.

The development of a product to take advantage of a generic element starts by defining a level of modularity that takes account of a generic platform. The concept for a generic element should form part of the key elements along with an indication if it is to be an existing module or new module. Module criteria must also give consideration to forward compatibility so that the generic element will have as long a life as possible before modification.

When creating the schematic the generic element must be included and carefully considered for the determination of interactions. If the nature of the generic element is known (i.e. being used from another product) the process will continue as though two products are being developed that must closely interact and only provide the overall function when combined. During geometric layout, geometry requirements for interfaces with the generic element should be flexible.

5.3.6 BALANCING IT OUT

It is possible that such a radical change from a conventional integrated architecture product to a modular one may have some disadvantages (see Section 4.2.5 p.80). There may also be situations when modularity is not always justified for a product or for a specific part of a product. Section 5.5 provides some guidance on determining suitability and lessening the impact of disadvantages, but first section 5.4 addresses the manufacturing perspective.

5.4 MANUFACTURING STRATEGY FOR MODULAR PRODUCTS

The aim of this section is to highlight the impact of modularity upon manufacturing. The methodology is maintained to promote integration of specific points into an existing manufacturing strategy to compliment the new design process for modular products.

Manufacturing is fundamental in providing a competitive advantage to the company. The influence of manufacturing is wide spread and often directly affects the customer. These influences include: high quality production, rapid order fulfilment, keeping delivery promises, the timely introduction of innovative new products, providing a range of products to satisfy customer requirements, flexible production volumes and delivery dates to customer demands, and the company's ability to offer products at the right price. The implications are that the manufacturing function should be seen as central to providing competitiveness, and that through a modular strategy, each of the influences of manufacturing may be facilitated in meeting five performance objectives of: quality, speed, dependability, flexibility and cost (Slack 1991; Sleath 1998).

Quality: Products must be produced that meet all of the known requirements and are free from errors. Many initiatives and techniques can be used to provide this capability such as Kaizen, 'right first time' and 'zero defects'. The influence of a modular product, and manufacturing's input into the design help to achieve a high level of quality through modular simplification and parts reduction, ease of assembly, buy in of non-core modules, simplified and reduced verification and test, and the structured approach to the design and manufacture of the product.

Speed: A modular approach aids the process of attaining the speed advantage through ease of assembly, reduced tooling requirements, reduced parts inventory, reduced part count, and a reduction in process operations. Modularity also improves the production time by allowing parallel production and test of modules, and also the possibility for late configuration.

Dependability: Not only should manufacturing be fast, but also be able to keep delivery promises. Thus, manufacturing should be able to meet customer or self imposed delivery dates with consistency. A modular approach has a number of characteristics that provide this consistency:

- Simplified and flexible assembly implies a consistent throughput
- Modules can be produced in parallel, and configured to an individual order in final assembly
- Modules can be tested prior to final assembly, moving the impact of test upstream
- Products are all analogous, thus production times are similar and new products will be relatively easy to plan, as they will typically be new modules on a common framework.

Flexibility: Manufacturing should be flexible in order to vary and adapt to changing customer needs, changes in the production process or supplier changes. Flexibility is a key feature in a modular approach. The use of modules facilitates manufacturing flexibility through the flexibility of the product. A modular design provides manufacturing with the ability to easily meet design changes for customer requirements by meeting specific requirements through a limited number of modules. Thus changes are limited to the manufacturing processes that deal with these modules leaving the rest of the process unaffected. In addition, planned redundancy in modules or interfaces allows for changes with no modification to manufacturing. Finally, a modular approach deals with flexibility up front in the life cycle so changes are anticipated and allowed for.

Cost: This means achieving a price that is lower than a competitor can manage. Meaning that resources must be obtained cheaper and they must be converted more efficiently than the competition. A modular approach can influence the cost of a product by allowing suppliers to produce modules that are not core business. Removing needless capability, the burden of investment in technological expertise, and the time and effort in production and test. Secondly, modular production allows the company to meet the previous four performance objectives and through improved quality, faster production and greater flexibility cost can be maintained at a low level.

5.4.1 A GENERIC MANUFACTURING STRATEGY STRUCTURE

Following the PIP a generic structure for a modular manufacturing strategy and its key elements has been developed (below). The process maps onto the three generic phases identified by Jouffroy and Tarondeau (1992) of analysis of the existing system, diagnosis of the projected system, and formulation of strategic orientation, and reflects the work of Voss (1992) and Greenhalgh (1991). The process aims to devise a strategy that connects performance objectives with manufacturing activities.

1. Background
a. Function definition
b. Current situation

2. Basis for competitive advantage
a. The key factors for success in the major markets in which the organisation competes
b. On the basis of the business key factors manufacturing will contribute to the success of the organisation through the following:

3. Key issues

4. Strategic aims
a. What must to be done to address the key issues.

5. Strategic initiatives
a. How the strategic aims are to be met.

The nature of a manufacturing strategy should essentially be dynamic, it must be updated regularly to meet the changing needs of the company, and the markets it serves. The strategy must also be given a time period over which the statements and assumptions are made.

Background: To provide a statement as to the precise role of manufacturing over the time period considered, and to provide a perspective for the strategic aims and objectives. The function definition and current situation sections should include specific references to the implementation of modular products and modular assembly processes.

Basis for Competitive Advantage: The basis for competitive advantage should include a list of key factors for success in each major market in which the company competes. The layout of these factors should highlight the influence of a modular product. Highlighting the influencing region provides a focus for defining the contribution of manufacturing to the success of the modular product and the success of the company. In addition the influence of the modular product allows the company to avoid allocating resources to the areas which have no real impact on its success.

Key Issues: Covers events, trends, facts or realities which are likely to have, or have had a significant impact on the company and manufacturing. They can be summarised as the issues that have to be dealt with to ensure the long term effectiveness of manufacturing. Identifying and defining the key issues is paramount and requires a very thorough and multi-disciplinary analysis. It is all too common for companies to hold beliefs that when the correct people are asked are incorrect. A number of key issues should include the management of the change to a modular approach and its implications for manufacturing and the company (Section 4.2.6, p.83). Furthermore key issues should be identified that may be influenced by modularity so that the appropriateness of the LOM and the commitment to this approach are at an optimum.

Strategic Aims: Strategic aims provide direction as to what must be achieved within the time period considered and are in direct response to the key issues. The aims are not necessarily a one-to-one correlation with the issues but it is important to a modular approach that there are a number of issues that must be dealt with. A number of strategic modular aims include:

- Ensure the maximum benefit from the possibility of parallel production of modules
- Provide an infrastructure and climate which encourages the work force to contribute to the development of the modular concepts and their production
- Ensure that module assembly is as simple, responsive and flexible as possible
- Investigate the possibilities for outsourcing all non-core modules
- Ensure manufacturing input into module development as early as possible.

Strategic Initiatives: The strategic initiatives are the statements as to how the relevant strategic aims are to be met. These statements must be qualified with an explanation and example of what is to be done. Examples of the initiatives relevant to a modular approach are:

- Elimination of non-value adding activities. This covers the need to address outsourcing of modules but also calls for a tightening and refining of operations in manufacturing
- Training of shop floor employees. This must be done to educate the workforce as to the new products and manufacturing processes associated with them.

5.4.2 MANUFACTURING ORGANISATION

This section briefly considers two further aspects of modularity's impact upon manufacture.

Cellular manufacturing (CM) provides an organisational framework that allows a modular approach to system design (Alford 1994) and facilitates the introduction of programmes such as CIM, JIT, and TQM. CM has advantages in both product and process based forms but the product based organisation is one that would be complementary to a modular product. A manufacturing system structured to a cellular form in which cells are linked to modules of the products it produces would maximise the benefit of parallel production, and aid in the planning of production and scheduling tasks. This manner of organisation also provides continuity throughout the enterprise where module design teams will relate to module production teams in the cells of the manufacturing system, and should provide greater links throughout the system and simplified organisation.

This system would be fast and responsive allowing generic products to be easily tailored with specific modules to meet customers need through the introduction of variety late on in the manufacturing process. The late introduction of variety, the ability to buy in complete, pre tested modules, together with simple final assembly all lead to an efficient manufacturing process.

To reflect a total view to product realisation it is also important to consider the impact of the product after it has been manufactured. Servicing and maintenance of products and also take-back, recycling and reuse all require serious consideration during the development phase. A modular design allows for the maximum utility to be made of these aspects. Modules can be specified that localise service or maintenance, allowing easy removal and replacement in the field. For the end of the life cycle, recyclable and reusable elements can again be grouped in a module. In fact, modules extend the possible life of a product by allowing common modules to be reused and upgraded, and new modules added that contain the new features or technology.

5.5 SELF ANALYSIS

This section develops a process which tailors the generic HPD process to individual requirements through analysis of the current situation, the clarification of aims, and the derivation of some metrics, in the form of goals or benchmarks. The aim is to present this process as a form of self assessment or analysis to complement the initiation of a modular product design project.

Section 4.2.3, p.74, identified three groups of analysis from which three metrics (qualifier, advantage, and LOM) and accompanying guidance would be determined. This chapter has also supplemented these analyses through further development of the LOM. This section carries these forward and adds additional analyses to address other modularity aspects. In total, seven analyses are developed that are summarised here but presented in full in appendix 4:

1. Qualification analysis - to ascertain if the product is suited to a modular architecture
2. Advantage analysis - to ascertain the key business issues to which modularity is to be used
3. Implementation analysis - to ascertain the LOM suited to the product and company
4. Groundwork analysis - to ascertain if basic groundwork requirements have been met
5. Driver analysis - to provide tailored guidance based on the reasons or drivers for modularity
6. Product analysis - to ascertain the possibilities for modularity, and highlight key elements
7. Manufacturing analysis -to ascertain how current facilities and processes effect modularity.

In order to provide a measure against the analyses a ranking scheme has been applied to analyses one to four, five to seven have a more complex measurement. The exact measurement against the questions is arbitrary but aimed to be simple and intuitive. Each question will be ranked as neutral, moderate, and strong, allowing conversion to 0, 1 and 3 respectively. This provides flexibility in the response to questions that are subject to interpretation

5.5.1 QUALIFICATION ANALYSIS

The qualification analysis determines if the company produces or aims to produce a product that will benefit from a modular architecture. This is done by analysing the three product philosophy rules developed in section 4.2.3, p.74. Totalling the responses from the three questions provides the metric. Any qualifier metric score of 0-3 will be acceptable as a modular product.

1. Does the product require an integrated architecture?
2. Is the product sensitive to functional interfaces?
3. Is the product uniform in substance or formed through continuous processing?

5.5.2 ADVANTAGE ANALYSIS

The advantage analysis further addresses the ambiguity in the applicability of modularity. It identifies the reasons for applying modularity and determines the opportunity for modularity in the form of the advantage metric. This is done by analysing the four issues presented in section 3.2 through the questions below. Determining the metric as before and based upon an analysis of the case review (Section 3.2, p.64), any advantage metric score of 8-12 presents an excellent opportunity for advantage through modularity, 3-7 an opportunity, and 0-2 little opportunity.

1. Is the efficient deployment of customer requirements an important issue for your company?
2. Is the rationalised introduction of new technology an important issue for your company?
3. Is a structured approach to dealing with complexity an important issue for your company?
4. Is flexible or agile manufacture an important issue for your company?

5.5.3 IMPLEMENTATION ANALYSIS

The implementation analysis identifies a guideline for an appropriate level of modularity. This is done through the analysis of the seven questions developed in section 4.2.3, p.74:

1. To what extent will the user desire / require configurability of the product?
2. What is the degree of possible commonality between the product and any other?
3. To what extent is the product likely to be modified / updated in the future?
4. How complex is the product and project to be undertaken?
5. To what extent is the product constrained by manufacturing strategy and processes?
6. To what extent will the product include elements requiring regular service or replacement?
7. What is the degree of possible recyclable / reuseable elements within the product?

For a level of modularity metric a score of 17-21 is a very high level of modularity, 11-16 a high level, 5-10 a moderate level, and 0-4 a low level. The metric value can then be used to determine a broad level of complexity, resolution, and composition (the three classifications of LOM) using figure 5.9 as guidance. An additional aid to the determination of the LOM is the permutation chart. The permutation chart is based on a morphological matrix (Cross 1989) and has been developed as a simple graphical method of exploring the possibilities for the levels of modularity. Possible solutions are marked in each column and the desired combination is built up by linking solutions from row to row and thus deciding on the suitable level for each of the three factors. However this particular analysis is very subjective and should only form part of an important discussion on the level of modularity suited to the company’s products.

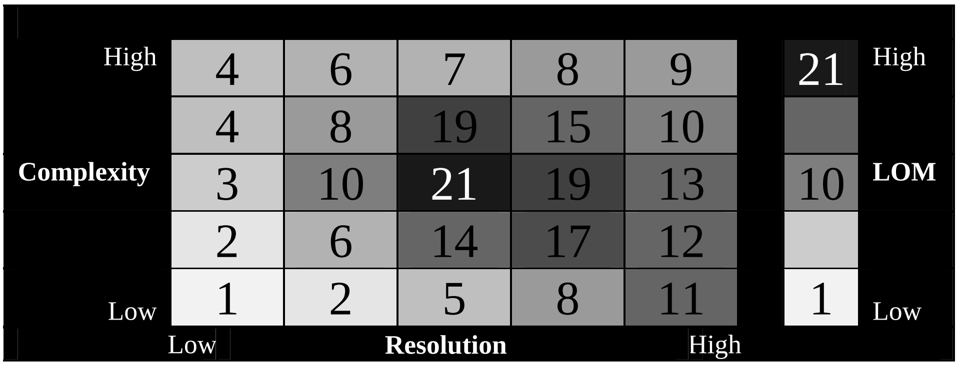

Figure 5.9. Level of Modularity Graph.

Classifications \ Solutions	1	2	3	4
Composition	No common element, all variant modules	Integrated common element	Modular common element	Only a common layout principle
Complexity	Low level of complexity in all modules	Medium level of complexity in all modules	High level of complexity in all modules	Mixed complexity levels in modules
Resolution	Only a small number (2-4) of variant modules	A medium number (5-10) of variant modules	A high number (10+) of variant modules	A variable number of modules to meet requirements

Figure 5.10. Permutation Chart.

5.5.4 GROUNDWORK ANALYSIS

The groundwork analysis is a relatively straightforward checklist for determining if some specific and some general issues have been considered or acted upon. 10 questions are asked in total (Appendix 4.) and measured consistent with the other analyses. For the groundwork metric a top score of 30 is desired however 25 - 30 is acceptable though all individual answers less than 3 should be addressed before any further action is taken. Example analysis questions include:

- Does your company have a clear product plan?
- Does your company know its reasons for developing a modular product?

5.5.5 DRIVER ANALYSIS

The driver analysis begins the customisation the HPD process to specific user needs. The analysis uses the questions in the implementation analysis as a list of major drivers for modularity (as Section 4.2.3) and asks for them to be ranked in order of priority. For the driver analysis total score is not relevant, the results relate to a list of pertinent points and guidelines that embody the specific considerations with respect to the driver chosen (see Appendix 4). The review does not restrict the user to a few drivers and therefore restricted guidance. The user is free to take guidance as far down the priority list as is seen fit.

As an example, a response of commonality as the main driver for modularity refers to the following considerations:

2. Commonality: Common modules, common interfaces, generic architectures.

- A generic 'platform' module or modules.
- Redundancy to provide the degree of functionality to meet all requirements from a standard.
- Standardising from the bottom up; look at part standardisation, service standardisation, configuration and architecture standardisation.
- Guideline numbers: 8, 10-13, 19, 20, 24, are especially pertinent (see Appendix 4. for full list)

5.5.6 PRODUCT ANALYSIS

The product analysis has been developed as a small process in its own right to identify possibilities for modularity within the template of the original or precursor product. The process leads through a series of steps similar to the modularisation process to identify possible modules for a new project. The basic steps include:

- Draw a schematic of the product and relate functional blocks with physical blocks
- Analyse functional blocks for relevancy to the new product
- Analyse the possible modularity of these functional blocks
- Determine any possible modules, generic or backward compatability elements.

Modules determined can then be used in the new product with varying degrees of modification. The goal is to use as many modules as possible with minimum modifications. Opportunities should be sought to standardise on interfaces which are likely to be poor on the identified blocks.

5.5.7 MANUFACTURING ANALYSIS

The manufacturing analysis is another small process. Aimed at manufacturing, the process relates the blocks determined in the product review to the manufacturing process structure. The process considers the grouping of processes with the blocks (modules), the partitioning of generic element processes, and the determination of non-core modules for procurement.

The review outcome will allow the existing facilities and processes to be adapted to maximise the benefit from a modular product architecture. The degree to which this can be done is related to the size of manufacturing operation.

Large organisations can aim to mirror the modules by manufacturing cells such that changes to the product are localised in manufacturing and will not effect other parts of the product. Smaller organisations must look toward identifying modules that can be procured totally from one vendor, and to rationalising vendor usage by grouping similar components and materials for procurement.

5.6 MAINTAINING THE PROCESS

Having implemented the HPD and begun development of a modular product there is still one final consideration. Industry works within severe constraints. The continuous referral to an in-depth process such as the one presented would represent an overhead to anyone without a particular strategic overview. For this case a series of checklists and guidelines have been developed to simplify the process of determining if the process is being followed, and keeping track of who is responsible for what, and the timescales of the project.

The guidelines are a comprehensive series of single line recommendations with explanation (Appendix 4.). The checklists are presented fully in appendix 4 and draw inspiration from Bell's (1993) work. An example checklist is presented in figure 5.11.

Checklist 2.

Due Date	Date Complete.	Person Responsible	
			1. Modularity / Design reviews held per plan? % to plan?
			2. Key elements identified?
			3. Module criteria identified?
			4. Internal documentation on schedule?
			5. Hardware module design on schedule?
			6. Software module design on schedule?
			7. Manufacturing tasks on schedule?

Figure 5.11. HPD Schedule Timeliness Checklist.

It is important that these checklists are customised with user specific questions, and preferably linked with a number of further checklists that relate to product development stages not included in the process such as, marketing, and distribution. The implemented checklists should be completed and kept in a central location (database / server) to allow all employees involved access to their status.

Having developed the HPD methodology and supporting systems framework the following chapters 6 & 7 investigate the implementation and evaluation of the HPD methodology within an industrial development project, and the modularity paradigm through software modelling.

Chapter 6 Implementation and Evaluation

6

Objectives: This chapter investigates design modularisation through implementation and evaluation of the HPD methodology developed in chapter 5. Key aims are:

- To investigate the implementation of the design modularisation methodology (HPD)
- The evaluation of the efficacy of the HPD methodology and the form of its implementation.

6.1 IMPLEMENTATION

In order to aid businesses interested in DM guidance must be given on the methodology developed. This best practice guidance must be concise and easily accessible to a wide range of companies to avoid overhead in the application of the methodology.

The dissemination of best practice has traditionally been transferred by consultants to their clients in the form of advice or assistance in diagnosing company needs and identifying appropriate solutions to those needs. Unfortunately, whilst large businesses may already have, or be able to acquire the required expertise, small businesses are known to suffer from resource poverty. Resource poverty is characterised by immense constraints on financial resources, a lack of expertise, and a short range management perspective imposed by a volatile competitive environment. Other means by which small companies can acquire knowledge of best practice include attendance at seminars and conferences, television, trade and popular press, technology vendors, books and workbooks and software. The potential best of these are software applications, providing an interactive and flexible medium. However the lack of a generic platform and common application clearly limits the ability to ensure widespread acceptance. The most suitable solution in regard of these limitations is books, and in particular workbooks, characterised by their flexibility and their structured recipe format. Through their availability and relatively low cost can provide valuable awareness and instructional material. Methods and techniques may be transferred in the form of analytical frameworks and supported by relevant case studies (PSOC 1997). These facts are also supported by the questionnaire responses (Section 4.2.4, p.77) that highlight that guidance would be a valuable asset when embarking upon a modular product design project and that a workbook would a suitable medium for that guidance.

6.1.1 THE WORKBOOK

The workbook (Appendix 4) has been developed to embody the holonic product design methodology developed in chapter 5 in a clear, concise and accessible manner. This HPD workbook is presented as a framework and methodology to enable companies to address the four broad business issues determined in chapter 3. Its development stems from an early set of guidelines that were themselves developed from a comprehensive list of pros and cons. The formatting of the guidelines generated a number of sections related to the stage of development at which they needed to be considered. These stages were then expanded upon to provide an easy to use format for the presentation of the methodology. Where possible the workbook was partitioned into small chunks to aid with implementation and intake of the new material. Checklists and guidelines were collated in separate sections to aid reference, copying, and to allow them to be used separately from the rest of the workbook. Attention was paid to presentation and layout to ensure that the content would be put across as effectively as possible. The workbook is formatted into 7 main sections listed here and then expanded upon below:

1. The product introduction process
2. The holonic product design methodology
3. Designing for modular products
4. Manufacturing strategy for modular products
5. Self Analysis
6. Checklists
7. Guidelines

The workbook begins *(Section 1)* by introducing the product introduction process (PIP) based on BS EN ISO 9000 and BS 7000 Part 2 in order to establish a baseline for integration of the workbook methodology. Detail of the generic processes is kept to a minimum focusing on key points that can be extracted to relate to a company's existing process. *Section 2* relates the generic product introduction process to the holonic product design (HPD) methodology, highlighting the influences of HPD at various stages throughout the generic PIP. The format of three phases presented by BS 7000 Part 2 is maintained to allow companies to partition the process into the broad steps of product introduction for simplified integration and to allow personnel responsible for each area to have ownership of the respective changes.

Having introduced the PIP the workbook goes on to provide detail on the mechanics of designing for modular products *(Section 3),* and how this process fits into the HPD methodology and subsequently the generic PIP. The detail of designing for modular products provides guidance on the each stage of the process and the new issues that must be dealt with for a successful modular design. Material is presented in a neutral and flexible way wherever possible in order to allow the process to be adapted and integrated into a wide range of industrial scenarios.

Section 4 provides detail on the manufacturing strategy for modular products. As before, a generic basis is established and modular specific considerations related to this basis for ease of integration into an existing strategy. Specific attention is given to cellular manufacture and its relationship of cells to modules and the implications for lifecycle stages beyond manufacture.

The next section *(Section 5)* presents a self assessment to allow the HPD technique to be integrated into current practice within the company. The self assessment provides simple evaluations to aid companies to:

- Clarify the reasons for the change to modular product architectures.
- Clarify the business strategy and corporate objectives.
- Define the required company organisation and working practices.
- Provide a platform on which to base the framework of the new HPD methodology.
- Examine existing and future products and their features for suitability to modularity.
- Provide guidance on the level of modularity suited to the product and the company.

The results from *section 5* provide a clear understanding of what is wanted in terms of company goals and a modular product. In addition, the self analysis provides a list of benchmarks, priorities and relevant guidelines to the specific needs of the company in question.

Sections 6 & 7 of the workbook address maintaining the HPD methodology through a series of checklists and relating guidelines. The aim of these is to ensure that the HPD process is followed and to provide guidance to the employees embarking on a new process and dealing with product architecture in an unfamiliar manner. The guidance ensures that the best practice of HPD is instilled within the employees and yet does not try to adhere them to rules which are not always practical. These sections also present the underlying essence of modularity in highly accessible and user friendly elements that facilitate integration and acceptance. Again, the checklists and guidelines are company customisable to allow beneficial aspects to be adopted where appropriate.

The workbook is rounded off by a glossary, references and further reading material for additional detail. A revision history is also provided to allow companies to easily identify changes to a document that is undergoing rapid change during its ongoing development.

6.2 EVALUATION

This section deals with the evaluation of modularity and in particular the developed modularity methodology of HPD. The evaluation processes are targeted at two aims. To evaluate the implementation of the HPD methodology within the HPD workbook, and to evaluate its efficacy within a company development environment and its reception by potential users.

6.2.1 WORKBOOK FORMAT AND CONTENT EVALUATION

The workbook presented in Appendix 4 has undergone a process of enhancement and refinement as a result of an evaluation. Though the workbook has been continuously refined by the author, feedback from industry and peer review has influenced the workbook to meet the needs of the user to a greater extent. The evaluation was carried out through the company links established for the case studies of chapter 3. Workbooks in various versions were sent to Crosfield Electronics, Sperry-Sun Drilling Services (SSDS), British United Shoe Machinery (BUSM) , PIOS Ag, Willett Systems, and Ford Motor Co, in addition to various other contacts and known researchers in modularity. Appendix 2 shows some of the feedback obtained from these evaluations.

Evaluators were asked to provide feedback on a number of elements but were given flexibility in the depth of feedback to reflect the work pressures upon those involved and the time available for the task. The elements to be evaluated were the overall content or message, the accessibility and clarity of the format of the workbook in terms of process, checklists, guidelines etc., and finally the relevancy and value of the document.

The evaluation became very dynamic through the range of levels and timescales of responses. Some evaluators such as Ford, chose to provide in depth review of all aspects of the workbook whereas many chose to purely provide evaluation through verbal feedback. What follows is a summary of the evaluation data from the persons asked to provide feedback on the workbook.

- All feedback suggested that the overall content of the workbook was good. The workbook represented a considerable depth of material in a concise manner. A broad range of considerations and business aspects were covered throughout the product lifecycle and thus closely represented the scale of the undertaking. The legacy factor considerations were seen to be a valuable resource by a number of companies who have considerable investment tied to support of existing products, facilities / tooling and standards. However, a number of specific comments / requests were received for modification or further coverage:

    - Specific consideration could be given to software functionality and its importance in many of today's products (done in v0.3 - a complete revision history is available in Appendix 4).
    - Consideration of the negative aspects of modularity or possible areas of concern to allow a balanced view of implementing the process (done in v0.5).
    - The provision of some basic metrics / benchmarks to provide some guidance on various aspects of modularity (done in v1.2).
- The workbook was seen to be presented in a clear, concise and structured manner though the content was potentially too concise. There was however recognition of the trade off between detail and user friendliness and that the guidelines provided a powerful tool for meeting the needs of engineers without over complexity. The checklists were a familiar tool and thus were widely welcomed with respect to ease of use and potential for integration into existing processes. A number of further comments / requests included:
    - The self analysis section should be refined for ease of use such that all questions are in positive logic (done in v0.5).
    - The guidelines would benefit from being subdivided into key aspects to aid ease of use (done in v0.5).
- The relevancy of the document was clear. The presentation of guidance on the topic of modularity was widely welcomed. Regardless of product and business every company recognised value in at least one aspect of the workbook.

Overall comments were very positive and that given the opportunity many companies would investigate implementing aspects of the workbook. Those who explicitly suggested interested in using the workbook included: Crosfield Electronics, BUSM, and SSDS.

6.2.2 WORKBOOK USAGE EVALUATION

The actual use or implementation of the workbook upon a development project was largely constrained by the capability of the companies contacted to adopt aspects of the workbook within the timescales of the research. Though a number of possibilities existed there were no fixed commitments or dates. The actual implementation of the workbook content presented in this section relates to the work done with Sperry-Sun Drilling Services (SSDS), as reported in the case studies of chapter 3. However at this time the workbook was being developed in parallel with the SSDS strategy. Thus this evaluation cannot be said to reflect the implementation of the workbook in its refined form, only the workbook concept in its infancy and the developing methodology that resulted in both the Sperry-Sun product development strategy and the HPD workbook.

Sperry-Sun Drilling Services provides the ideal example of a company who recognised the benefit of product modularisation but lacked a structured approach to its implementation. SSDS had utilised modularity at a high level to provide them with flexibility in the configuration of their sensor tools. However they had not taken the philosophy any further and had duly suffered from parts proliferation and compatability issues. SSDS recognised the need for an overhaul to their product development strategy and began the process of addressing corporate objectives, strategic targets and the facilitation of CE and a TQM philosophy.

To coincide with these changes the company also addressed some specific product difficulties through the development of two core product replacements. The PCD (pressure case directional) and PCG (pressure case gamma) probes were planned to improve existing products, implement a number of new ideas, provide a future upgrade path for the whole product range and set a benchmark for future product developments within the company.

Section 3.1.2.1, p.51 and Appendix 1, detail the process followed by SSDS in the development of the PCD and PCG. The implementation of this structured approach to modularity was an iterative process that evolved over the development period. It combines the authors ideas for modular development and application specific details important to SSDS. This process was finally developed by the author into the generic process presented in chapter 5 and adapted for SSDS' product development strategy. Largely, the process maps onto the modular design process flow (Figure 5.6, p.93) and it is the application of this to the PCD and PCG that is to be examined.

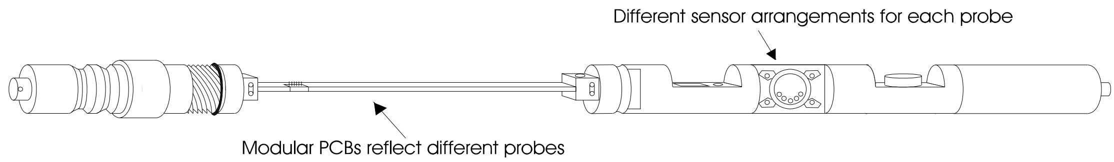

Figure 6.1. Pressure Case Directional / Gamma (PCD/G) Probes.

The process, after project team formation and other administration, involved meeting two requirements suggested by the author, definition of level of modularity (LOM) and a casual application of the self analyses (Section 5.5, p.105). The self analyses were experimentally applied due to their early developmental nature. The LOM at this stage was seen as separate to the remainder of the self analysis as qualification and advantage were largely redundant. SSDS knew that modularity suited their products and that it provided benefits from their experience of high level application. However SSDS completed all of the self analysis sections at the authors request. The results of SSDS' work are shown in detail in Appendix 1. and are summarised here:

Analysis name	Current equivalent	SSDS result
Suitability Analysis	Qualification and Advantage Analysis	Highly suited to modularity
Level Analysis	Implementation Analysis	3 to 4 ~ a moderately high level
Groundwork Analysis	Groundwork Analysis	All groundwork in place
Driver Analysis	Driver Analysis	Consistent quality, reduced lead time, and standardisation most important
Product Analysis	Product Analysis	Not fully developed at the time.
Manufacturing Analysis	Manufacturing Analysis	Not fully developed at the time.

Figure 6.2. SSDS Analysis Results Summary.

It can be seen from the results table that the analyses at the time have subsequently been refined for the process presented in chapter 5 and the workbook in Appendix 4. Though the latest analyses have been developed to be more useful they are still based on the same reasoning and largely the same line of questioning as the originals.

The suitability analysis indicated that SSDS produced products that were highly suited to modularity. In reality this was true. SSDS had implemented modularity at a high level enabling them to provide a level of flexibility that ensured customers requirements were met effectively and efficiently. Figure 6.3 highlights the way in which a set of modules / probes are combined for different customer requirements. There was also a general consensus that there was potential for modularity to be utilised to greater degree through a lower level implementation.

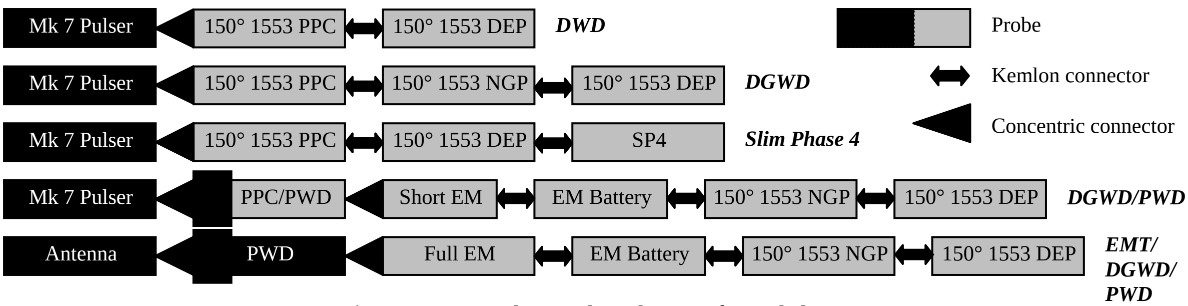

Figure 6.3. High Level Probe Configurability.

The level analysis proposed a moderately high level of modularity for SSDS products. Though interpretation of 'moderately high' is subjective, it mapped onto the case of SSDS and indicated the potential for further implementation of modularity. (note: high LOM refers to depth and breadth, SSDS' high level refers to a shallow/product level). The main point taken from the level analysis and subsequent discussion was to investigate the possibility for modularity within and across existing modules (probes). Figure 6.4 illustrates how modules have become common within the PCD and PCG. The value of this particular analysis was its ability to elicit the discussion of modularity level rather than propose strict solutions for modularity architecture concepts. It was also noted that there was more to LOM than that covered by the simple analysis. However it was considered that there was sufficient detail to give a broad introduction to the complexities of modularity level without undue detail and confusion.

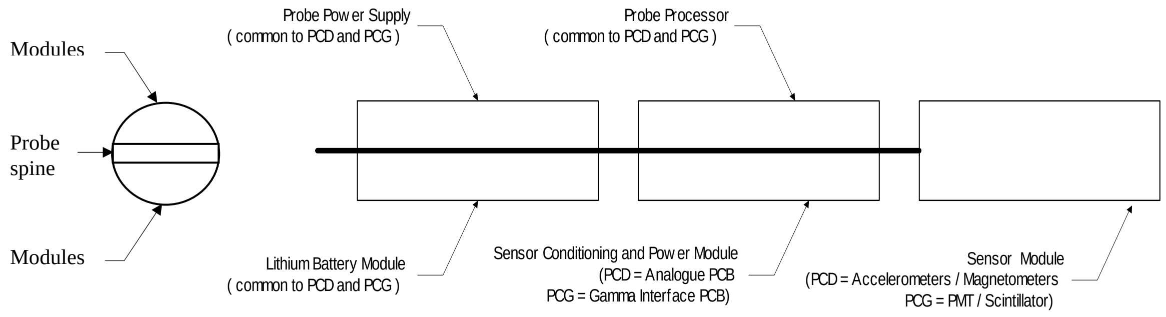

Figure 6.4. PCD / PCG Module Organisation.

The groundwork analysis highlighted that SSDS had all of the important facilitators for modular design in place. This was to be partly expected due to their previous involvement, but also indicated that the analysis was addressing the key areas with respect to success with modularity. Though groundwork is proposed as an analysis it acts as more of a checklist to ensure various actions have been performed or procedures put in place. However it also indirectly suggests the benefit of examining other areas of development through the need for them to be in place to support modularity implementation.

The driver analysis guided SSDS towards the areas of quality, time and standardisation. These corresponded to a number of guidelines and considerations. The analysis again indicated the need to address modularity at a low level building upon part standardisation up to complete generic modules. The driver analysis was a popular tool within the development team as it pointed to concise and highly relevant guidance on the aspects of modularity that were most important. This improved the efficiency of development from planning out the goals for modularity, to monitoring the progress of modularity development during all life cycle stages, and the ability to further checklist the items that require consideration. It was noted that some of the driver sections were effectively subsets of the same driver (e.g. standardisation and carry over both belong to commonality) and that the list may need to be revised.

Though the product analysis had not been developed at this point, an analysis in the form of a team examination of existing products was performed in anticipation of a product analysis. At the authors request the analysis focused on examination of functional decomposition versus physical decomposition. The findings of the analysis generated the points summarised in section 3.1.2.1, p.51 and provided the basis for the later developed product analysis presented in chapter 5 and Appendix 4. The results maintain the case for SSDS to implement modularity at a lower level simultaneously utilising that modularity across a range of probes and also establishing a generic platform module for future products.

From these analyses and the surrounding discussions, the requirements generated were fed into the development process and used to guide the development of the PCD and PCG through a comprehensive technical specification.

After signing-off of the specification a layout schematic was generated and used as a discussion point for the assigning of modules and interfaces. The criteria for module definition were broad but included a list generated by the author that is presented in section 5.3.3, p.95. From these criteria it was found that standardisation, manufacture, localisation of change, and supplier capability dominated the decisions and determined the modules and interfaces to be developed. This procedure was a key stage of the process as its findings not only determined what would be incorporated into modules but also the key interface requirements between modules and the personnel responsible for those modules.

The findings also highlighted other concerns such as backward compatability and thus generated possibilities to implement new ideas and also include upgrade and retro-fit features. Overall the process was largely allowed to adapt to the situation but it was found that the criteria for module grouping were relevant and helped focus on the possibilities and concerns for grouping of features and functions. The process also spawned ideas that had not been previously considered by the consideration of functions isolated from their current form. One concern that did arise was the decision of what to include and exclude from the schematic. However it was rapidly resolved by concentrating primarily upon all functions, then including any specific elements that were desired and using multiple layers of schematics for extra detail.

After module concepts were agreed they were given a final geometric check through the generation of a simple CAD model of the modules. This process served to check that the concept modules could be realised as physical elements that had to integrate together but also to fit into the constraints imposed by the operating environment and compatability requirements of existing products. This stage formed a simple but valuable process to ensure that important issues of realisation and fit were covered, albeit briefly, at a stage where change would be straightforward in comparison to later in the process.

The final aspect of the process was a check for correlation to the technical specification to ensure that requirements were being met and that no obvious areas had been overlooked. Another simple exercise but important in insuring the meeting of business and customer requirements in the most effective and efficient way. From this stage the modules went into detail development.

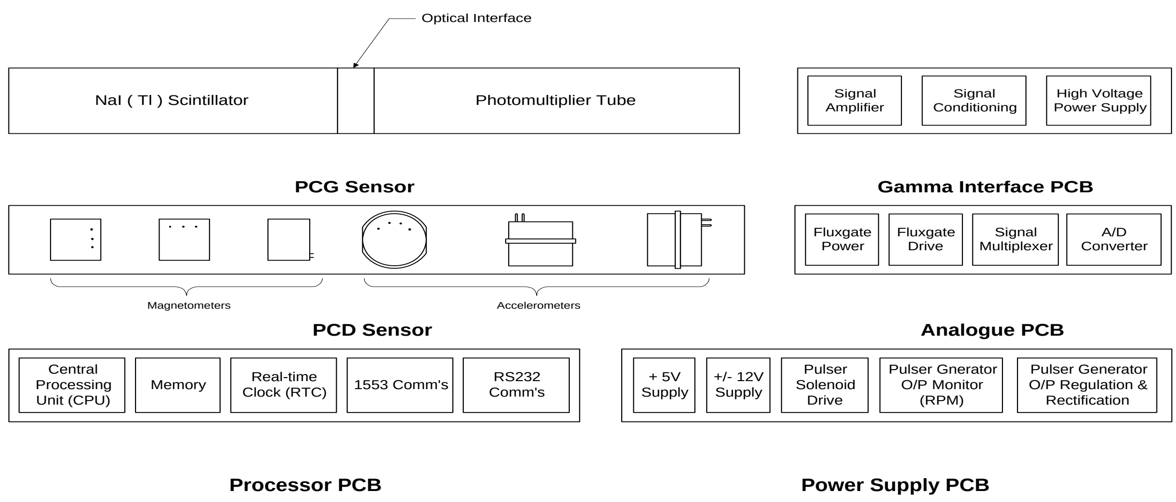

Figure 6.5. Completed PCD / PCG Module Detail.

Overall views of the modularity process during the development and implementation period realised that though the process was still in development, its framework nature lent itself to application in an industrial context where working processes and preferred methods are largely established. A requirement for a formal version of this process would be to provide a concise and flexible framework that could direct the user to detailed guidance when and where necessary.

The process concept as it stood was accepted as being a usable methodology within a larger development process. The basic stages of requirement definition through analyses and capture of other needs was a valuable starting point and mapped readily onto the already accepted generation of detailed design specifications. The generation of a schematic / layout and clustering of elements into modules was a simple overview of an involved process but provided the necessary framework to begin the process of module definition and provided support where necessary with detail consideration of clustering criteria, interface analysis, and individual guidelines. Geometrical considerations were obvious features of detail design but consideration at this early stage provided a valuable check to ensure that concepts did not progress too far before compatability between modules and with the environment were considered. A suggestion that did occur was to ground this process within a generic development process through explicit links that aided the integration of the useful features of the process into a company's own process.

The process also benefited greatly from multifunctional team involvement. Many of the process steps, self analyses, and guidance sections are deliberately free of specifics to maintain relevancy across a broad range of applications. Thus most recommendations and guidance require careful consideration and discussion in order to extract the valuable aspects of the message in relation to the individual needs of the company and its plans.

Though this requires a greater resource commitment than a pre-laid out process it ensures that the appropriate steps are taken at the appropriate time. Important decisions are discussed thoroughly by those personnel who are likely to be effected by the outcome, and that the implications and company direction to the process can be carefully planned and implemented whilst still moving toward the modularity goal.

6.3 CONCLUSIONS

The HPD methodology presented in chapter 5 represents the embodiment of the research into DM. This methodology was subsequently implemented in the form of a workbook aimed directly at addressing the needs of industry for guidance on the topic. The following conclusions can be drawn from this document:

- Though many applications are tending toward software implementation this option was avoided due to the numerous issues with compatibility, and the trade off between developing the interface and developing the content. The result was a workbook to which the effort could be devoted to content and its ease of use and accessibility.
- The workbook has a basic premiss to build upon existing processes rather than replace them. This approach was welcomed within industry where any facilitator to change is beneficial. This premiss is initiated through the presentation of a generic product introduction process (PIP), used as an intermediary between the new and the existing techniques, based upon BS 7000 and BS EN ISO 9000. In addition to the integration aspects of the PIP the use of British standards further provides familiarity and also highlights the value of the guidance and best practice embodied within the documents.
- The format of the workbook aids accessibility but also allows targeting of guidance to the appropriate company areas and personnel. This shares the task and also facilitates a multifunctional approach. The most valuable aspect of this approach is the guidelines which appeared to be universally popular.
- The use of self analysis was a valuable addition as it addresses aspects of tailoring to further improve implementation within an existing development process, but also serves to provide further guidance and target values and concepts at which to aim. The self analysis section also serves to lessen the passivity of such a document and provide a degree of underlying science to the approach.
- The implementation and evaluation process highlighted areas of possible refinement for the workbook which have subsequently been addressed. Overall the workbook presents a balanced package to address the needs of a company wishing to implement modularity.

Though opinion of the usefulness of the workbook is valuable it cannot replace the evaluation of the methodology through application to a development process within industry. This aspect of the overall evaluation process presents the following conclusions:

- The methodology has proven to be beneficial if only in one specific case and under the guidance of the author. However the generic efficacy can be extrapolated through the reaction of the company personnel and their experiences with the workbook guidance.
- The importance of the level of modularity (LOM) became apparent. Largely modularity is beneficial to product development from both customer and developer perspectives. However it is the level to which the product is modularised that is a key to its success. The evaluation at SSDS flagged the importance in investigating modularity beyond their current level, the exact approach they had considered themselves.
- The generic level approach and lack of detailed rules is not optimal but necessary. The specific implementation details are dedicated to every application thus an extrapolation has to be made from the generic to the specific. This then allows interpretation but also provides value in the discussion of the interpretation through clarification and extraction of the important aspects for that case. Where possible ties to universally applicable elements have been made and values provided through self analysis.
- The methodology derives a great deal of benefit for application within industry from its framework nature. The stance of guides rather than rules, the need for multidisciplinary involvement, the need to thoroughly discuss the development decisions, and the benefit of broader considerations and techniques from the potential of manufacture to the need for DFA.

The SSDS work provided valuable insight into the working of the methodology within a development process. However the evaluation does not represent the potentially true test of workbook, that of implementation within a company in a non interventionist manner. What the evaluation does provide, is evidence of the efficacy of the concept, the relevance and appropriate targeting of the material. In addition it provides another element in the package of evaluation that together with case studies and the modelling work (Chapter 7) provides a complete picture of DM as an approach to the industrial needs of today.

Having examined the methodology for DM through industrial implementation and evaluation the following chapter 7 examines the broader implication of the methodology within the SE framework. Through modelling, specific details of the methodology are also investigated in relation to the concept of attributes that will be introduced.

Chapter 7 Modelling

7

Objectives: Having developed and evaluated the modular design methodology in the form of HPD, this chapter examines the methodology within a systems engineering framework and also investigates the detail mechanics of the methodology. This is performed through:

- Modelling of the systems framework, clarification of terms and orientation of modularity
- Investigation of manufacturing attributes to complement engineering attributes
- A systems model highlighting the impact of modularity upon the customer
- Demonstration of the traceability of requirements throughout the model
- A performance model to evaluate an assemblability metric of modularity.

7.1 FRAMEWORK MODELLING

This section examines the SE framework for the modularity methodology. It maps out the taxonomy of a system and clarifies the view of SE, how it embodies DM within the total view that encompasses manufacture. The purpose of the taxonomy is to highlight the impact of modularity upon the customer through attributes. Attributes are used as system characteristics that reflect customers needs within the product realisation environment. Firstly, a number of definitions are required:

- Though a number of system definitions were provided in chapter 2, a system can be simply defined as ‘an organised set of components that fulfil a purpose’. This definition is used in preference as it is open to interpretation and so can embody all system concepts, rather than attempt to define all cases to which it refers.
- Product realisation refers to the processes of systems. Within product realisation no distinction is made between the process of development and process of manufacture. A seamless combination is required to fulfil the premiss of a total view and to deliver the product.
- The process element of a system subsumes methods, tools and the environment (Martin 1997).
- Functions refer to the activities or purpose that are performed or fulfilled by the entity to which they are applied (e.g. deliver power)
- Attributes are qualities or characteristics that are perceived by the customer of the entity to which they are applied (e.g. power).
- System properties are synonymous with attributes.

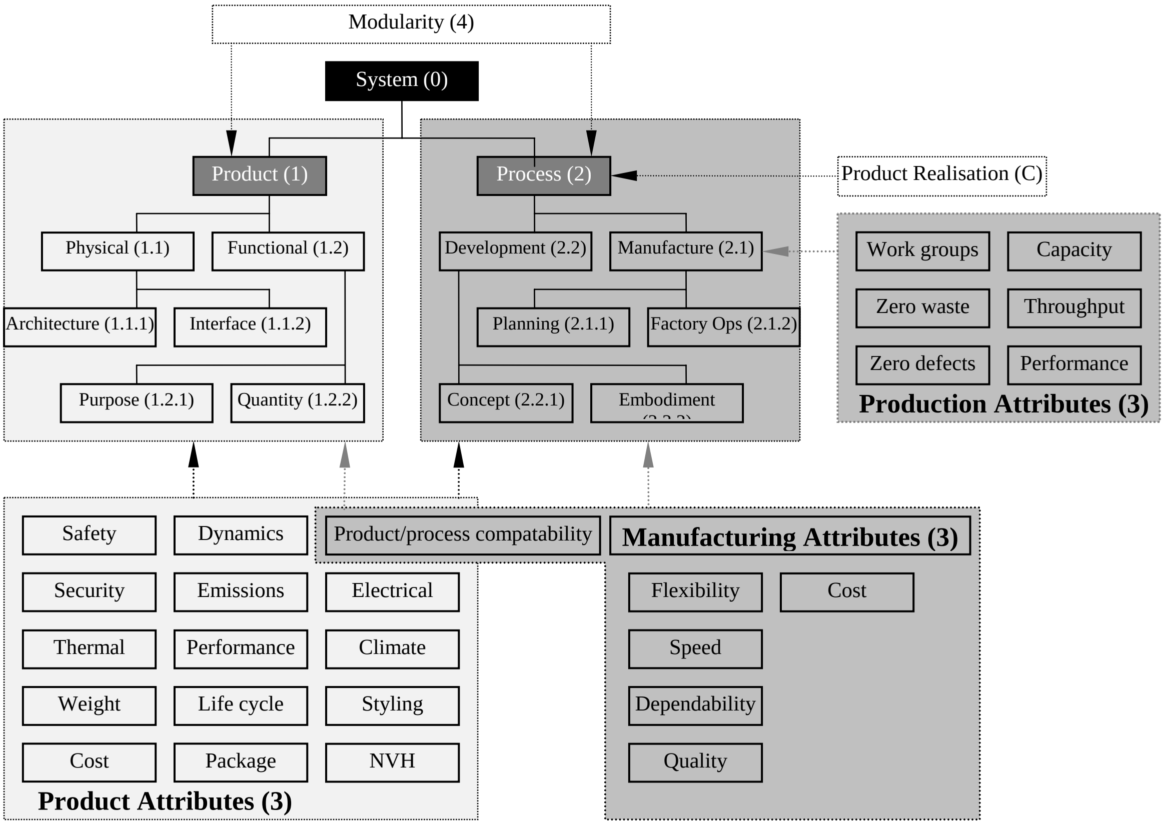

Figure 7.1. The System Taxonomy and Relations.

Figure 7.1 maps out the taxonomy of a system developed by the author based upon the system definitions and with respect to the literature review. The premiss is that a system is a combination of the product and its processes. These can then be further subdivided into their main constituent elements. The product into a physical and functional decomposition. The (realisation) process into development and manufacture. The taxonomy also includes the broad relationships of the various system attributes and modularity.

Three sets of attributes are defined, taken from Ford Motor Co.'s SE development, part of the Ford product development system (FPDS) and Ford production system (FPS) (Everitt 1997; FTEP 1997). Ford's attributes are used as they represent considerable contemporaneous research into customer attributes and allow the impact of modularity to be related to real world system attributes. Though these attributes are Ford specific they do represent a more generic application. As this work is not examining the determination and analysis of attributes, any dedication is overlooked in this regard.

Attributes are presented in two broad categories. Product attributes that relate to product aspects of development are design concerns and are covered comprehensively. Process attributes have two areas of influence and thus are divided into manufacturing and production attributes. The difference is that manufacturing attributes are also design concerns relating to the design of the product for manufacture and assembly. Production attributes relate to planning and operation of the production system. The distinction is made to reflect the relative lack of attention to manufacturing attributes for design. This lack of manufacturing attributes mirrors the earlier concerns with SE as a whole, missing the opportunity of manufacturing to product realisation and thus the realisation of manufacturing as a competitive weapon and not simply as a service to be bought or sold. In order to realise this potential, manufacturing attributes are considered in greater detail to integrate manufacturing into the single systems process and provide a truly total-view framework for the HPD methodology.

7.1.1 MANUFACTURING ATTRIBUTES

If attributes are qualities or characteristics perceived by the customer, then manufacturing attributes must address two customers. Manufacturing attributes relate to the product user or customer through manufacturing's impact upon the products realisation. Manufacturing attributes also relate to the manufacturing company/department as a customer of the processes developed to produce the product.

A number of manufacturing attributes have been determined with respect to the performance objectives of section 5.4, for the purposes of the DM system model covered later. It is noted that these attributes may not be comprehensive or developed to the level necessary for use but are sufficient for the model considered. Manufacturing attributes are:

- Quality - fitness for purpose as seen by the end user. Includes reliability, specification conformance, control of dimensional variation, ease of test.
- Flexibility - the lack of dedication to manufacturing processes, volumes, facilities, tooling, location, suppliers, and customer needs, as seen by the manufacturer.
- Speed - the speed of the product delivered to the end user. Includes ease of assembly, tooling requirements, part numbers and variety, and process operations.
- Dependability - the meeting of orders on time and with consistency. Includes simplified assembly, parallel production, late introduction of variety.
- Cost - the cost of production to the manufacturer and its impact upon the user-seen price. Includes the obtaining of resources, efficient use of those resources, efficient supplier relationships, and appropriate capability.

These attributes now form part of the system taxonomy. This taxonomy is modelled in order to demonstrate the impact of modularity through the SE framework upon customer related attributes. The tool chosen for the modelling work is covered in the following section.

7.1.2 CRADLE

The modelling medium chosen is the software package Cradle as introduced in chapter 2. Cradle is a SE environment that presents a suite of tools and features from requirements management and system modelling to the support of a shared database and documenting tools. Cradle provides a number of characteristics that makes it suitable for application to a DM methodology and framework model:

- Cradle's SE environment is suited to investigation of systems such as products and product introduction.
- Cradle provides an integrated environment that includes the management of requirements, system design and analysis, lifecycle traceability and flexible support for data.
- Cradle is flexible and allows different representations for system design as appropriate.
- Cradle lends itself to the analysis of change management, factors can be altered and their impact traced throughout the system.
- Cradle can be used to demonstrate the linking mechanism of SE throughout the product life cycle.

7.1.3 DESIGN MODULARISATION SYSTEM MODEL

The model developed is based upon the HPD methodology detailed in chapter 5. The basic structure follows figure 5.5, p.90 that details the stages of product development with respect to SE, HPD and the process of modular design. These processes also link to product and process attributes and thus customer requirements, and the product itself. The product is also broken down into functional and physical representations. This allows a spectrum of cross references to be highlighted. This serves to show the interlinking nature of SE throughout the product life cycle, but also the impact of modularity. The basic representation of the system model is shown in figure 7.2.

The model is initiated through a generic set of customer requirements. These represent the desires and needs of the end user, and the desires and needs of company personnel, departments and suppliers. These requirements are translated into attributes that are specific benchmarks and metrics that can be utilised by the product realisation process to embody the customers needs. These attributes feed the realisation process throughout a number of early stages. The product realisation process then forms part of the product life cycle system embodying stages beyond realisation through use, support and disposal.

Two further aspects are highlighted through the model. The first is the relationship to the system of the product and its functional and physical decomposition. The second is the relationship of the DM process to the system. The model then maps out the links between modularity and the processes of product realisation and the system life cycle, the links to attributes and thus the customer and the links to the product architecture and thus modules through functional and physical relationships.

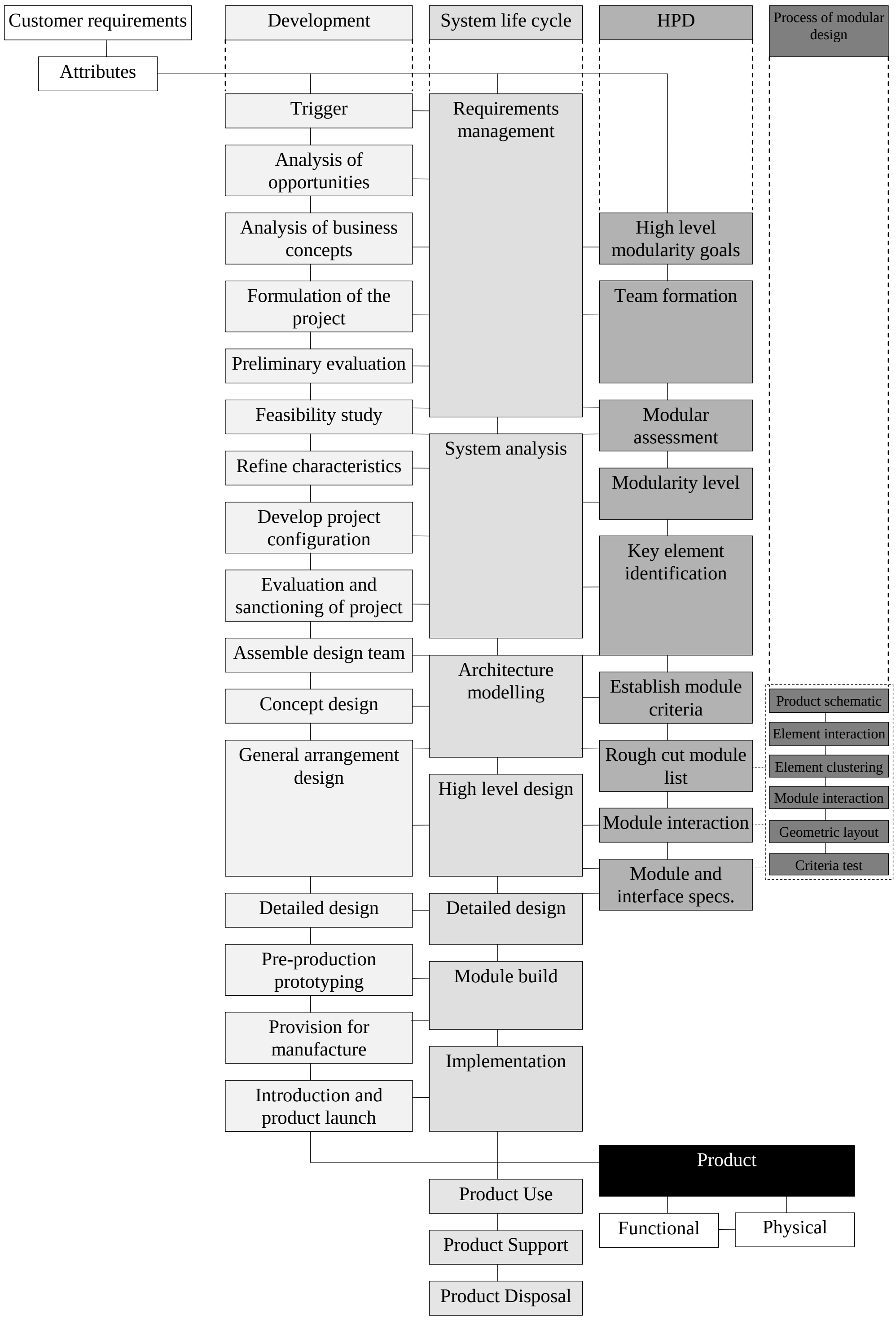

Figure 7.2. The System Life Cycle Relation Model.

7.1.3.1 System Model Construction

The system model has been developed following the Yourdon structured method. Though this is only one of a number of structured system design and analysis techniques, it is widely used, has had time to mature, and was fundamental to all structured methods in their infancy (Tudor & Tudor 1995). In addition, Cradle inherently encompasses the Yourdon method.

The Yourdon method consists of the development of two main models:

1. The essential model
2. The implementation model

In brief, the essential model represents what the system must do in order to satisfy the user's requirements, with as little as possible said about how this is to be implemented. The implementation model adds physical decisions to the essential model and thus begins to identify: how the system is to be implemented, allocated to hardware and software, and the organisation of the modules of the system (Yourdon 1989).

Before the models are developed the requirements upon the system are captured. This is performed through a generic set of requirements, developed to represent the needs for a new small car (see Appendix 9). The key requirement is that the model would focus upon the need for an innovative range of body styles and internal configurations combined with affordability. The individual requirements are extracted from source documents, engineered (a process of grouping and formatting) and then cross referenced to appropriate product and manufacturing attributes, namely Package (A3), Climate (A6), Styling (A7) and Flexibility (AM1 - Figure 7.3).

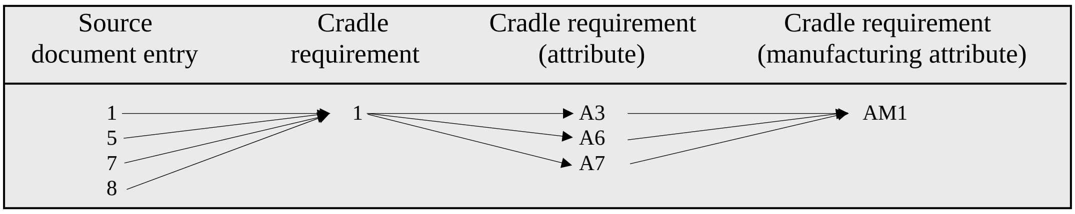

Figure 7.3. System Model Requirement Cross-references.

The first modelling process involves the development of the essential model. The first aspect of this is the context diagram (Figure 7.4) that defines the system's boundary with its environment. The diagram shows the very top level of the product realisation system and its links to real-world entities such as the customer and the business.

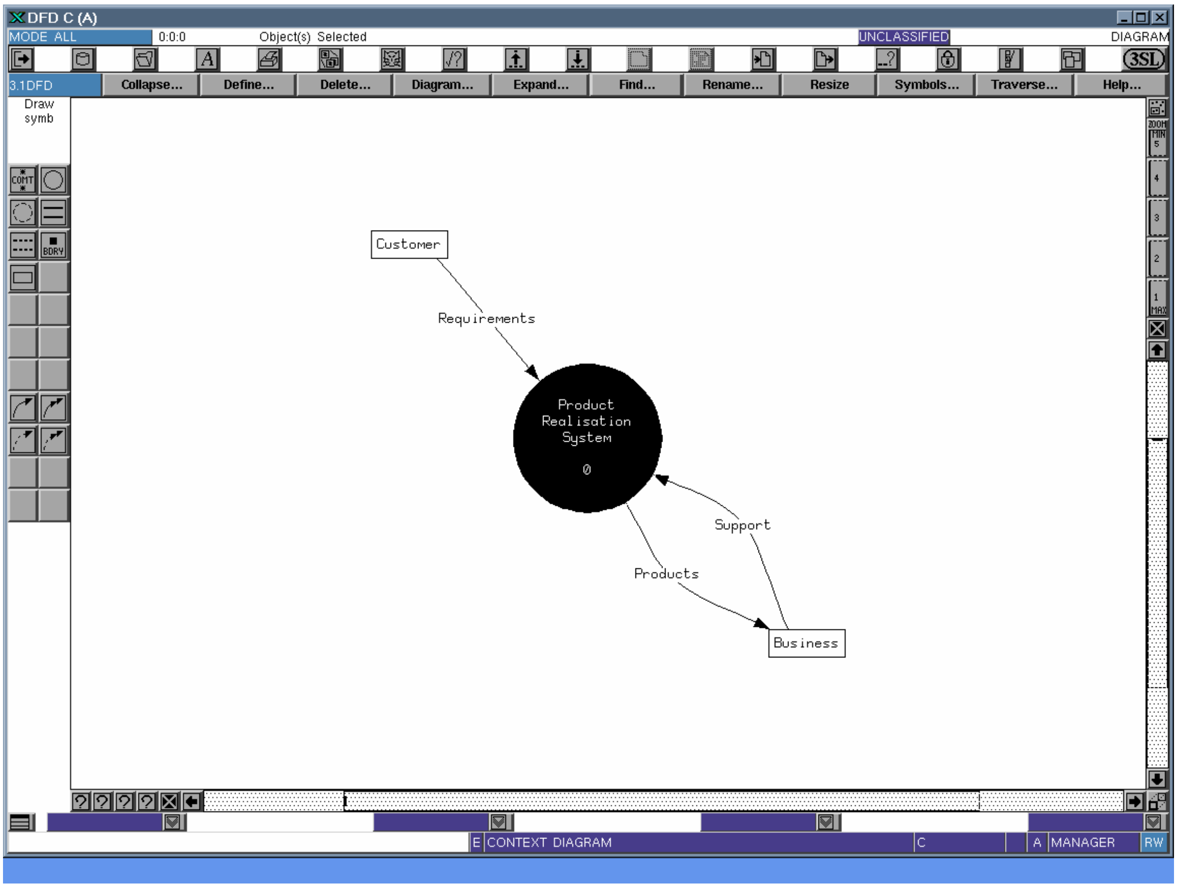

Figure 7.4. System Model Context Diagram.

The second aspect of the essential model is the event list (Figure 7.5) that defines all events which occur in the external environment and either require a system response or a system change. The requirements defined earlier are also cross referenced to these events.

Event number	Event stimulus	Event response
1	Customer requirements received Business support go-ahead	Begin realisation process
2	Realisation process ends	Product available to business

Figure 7.5. System Model Event List

These two elements effectively represent a simple environment model of the product realisation system. At this point, work on the essential model is complete for this particular exercise. Further model development involves the examination through the implementation model of the system as defined in the taxonomy and relations models (Figures 7.1 & 2).

The implementation model is decomposed from the context diagram and represents the next level of the realisation system hierarchy. For this particular model development, use was made of function block diagrams. These provided flexibility in using the constructs as physical elements that could represent the actual product or its enabling processes and the links between them.

The structure was based initially around the system taxonomy of figure 7.1 following the number classification (1= product system etc.) and showing the links between product, process and the two elements to be highlighted in the model, attributes and modularity (Figure 7.6).

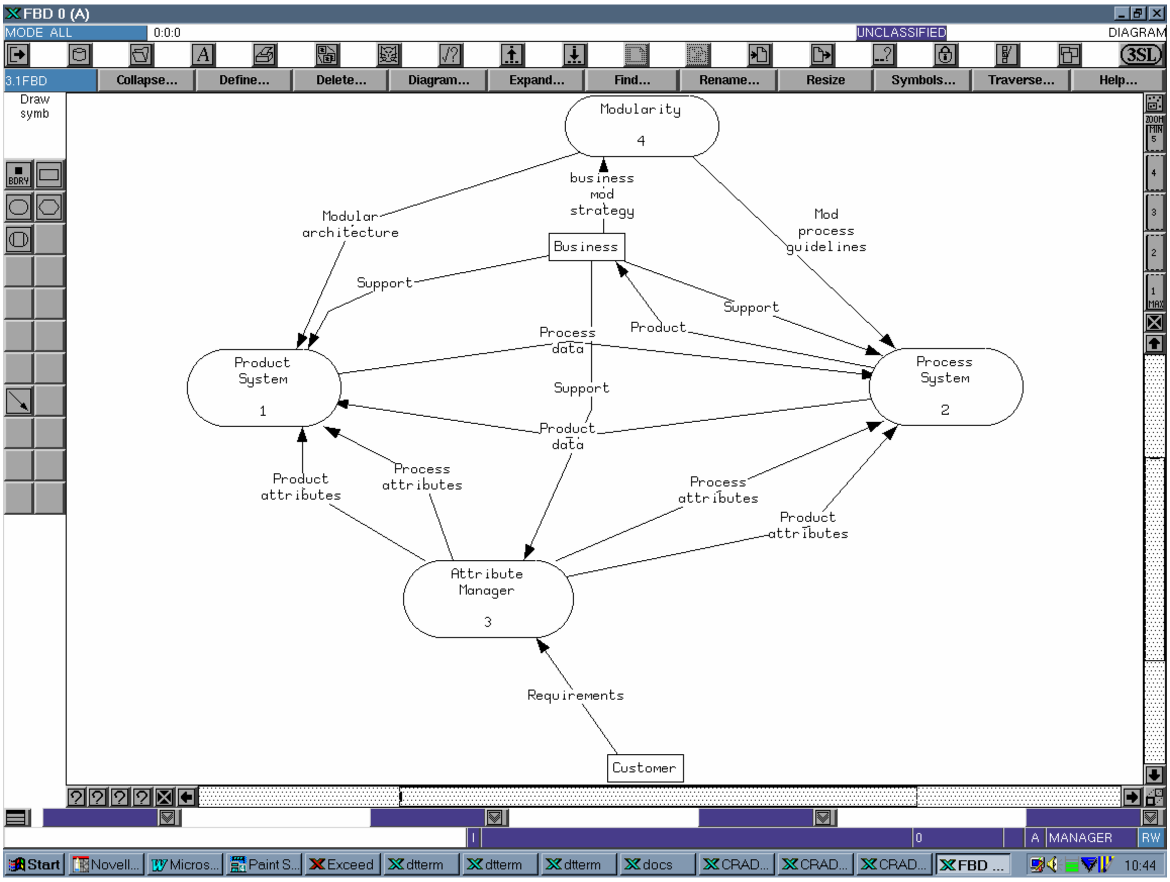

Figure 7.6. System Model Level 0.

The product and process elements are then further decomposed to the lowest level of the taxonomy whereupon the product elements are decomposed into vehicle related entities as per the requirements, and the process elements decomposed into the steps of product introduction from the relations model (Figure 7.2). Modularity is also decomposed into the stages of the HPD process. Figure 7.7 shows one of the key diagram levels highlighting the links between the generic process of development, modular design and the attributes that ultimately lead to the customer. This particular level (2.2.2) is the decomposition of Process (2), Development (2.2), and then Embodiment (A complete set of diagrams is shown in appendix 9).

To complete the implementation model a complex array of explicit cross references were established between the entities of the diagrams, the event list and subsequently the attributes, requirements and source statements.

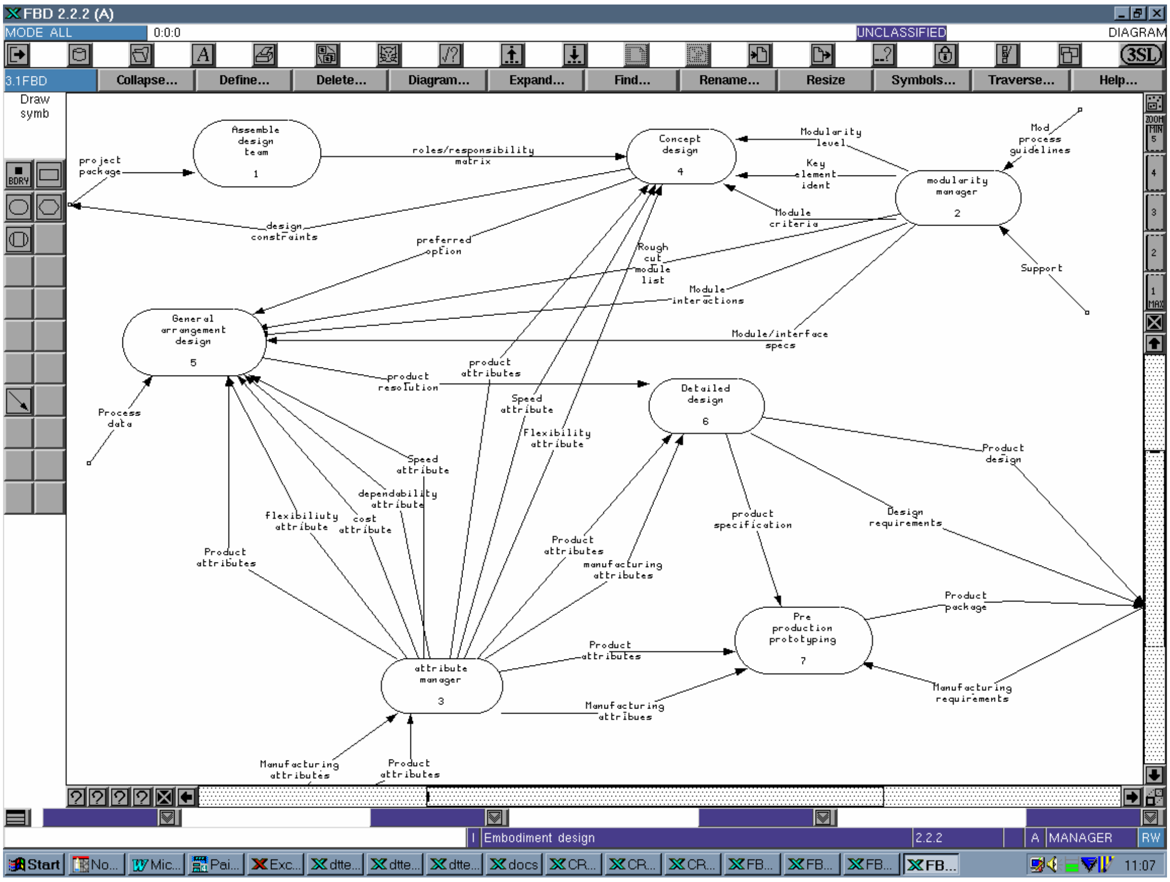

Figure 7.7. System Model Level 2.2.2

7.1.3.2 System Model Analysis

The system model developed within Cradle brings together a number of the chapter objectives. The model structures the actual system of product realisation from the perspective of the customer through the use of attributes, and from the perspective of DM. The model shows the processes of development, manufacture, and DM in conjunction with the breakdown of the actual product into functional and physical elements.

In addition the model highlights the links within that system. The links shown not only cover those between processes, but also all the elements shown in the matrix over (Figure 7.8). The matrix shows direct cross references, however transitive cross references would show a near perfect matrix of relationships of everything to everything. This clearly demonstrates how modularity impacts upon the whole of the product realisation system and thus requires a total view, as proposed by SE to provide a framework for its support. The matrix also shows how modular design affects the product and its processes and thus has a direct influence through attributes to customer requirements and provides a competitive advantage in meeting those requirements in the most efficient way possible.

Model elements	**No.**	S	R	A	E	1	1.1	1.1.1	1.1.2	1.2	1.2.2	1.2.1	2	2.2	2.2.1	2.2.2	3	4	4.12	4.4
Source statements	S																			
Requirements	R																			
Attributes	A																			
Events	E																			
Product	1																			
Physical	1.1																			
Architecture	1.1.1																			
Interface	1.1.2																			
Functional	1.2																			
Quantity	1.2.2																			
Purpose	1.2.1																			
Process	2																			
Development	2.2																			
Concept design	2.2.1																			
Embodiment des.	2.2.2																			
Attrib manager	3																			
Modularity	4																			
Mod/int specs	4.12																			
Key elements	4.4																			

Figure 7.8. System Model Cross-reference Matrix.

Though the model was developed at a generic level, a specific set of requirements introduced in section 7.1.3.1 were applied in order to highlight how the system would relate to a real-world realisation issue. Requirements for a flexible car body system could be traced through product and manufacturing attributes through to product and process elements. Product and process elements would be then decomposed until the level of architecture (1.1.1) or concept design (2.2.1) for example, where these specific requirements would be met. Figure 7.9 shows the decomposition of the Architecture element (1.1.1) into modular body elements and how this relates to the attributes, interfaces, functionality, modular design, realisation processes and the business.

The use of attributes contributes to the model in a highly useful manner. Rather than deploying customer requirements directly into the realisation process, the use of attributes structures their use into a form that facilitates their integration into all levels of the product realisation system. Attributes provide requirements that can be used within the process as benchmarks or metrics rather than ambiguous statements of need. Providing a similar role to QFD but ultimately subsuming it. In addition the lack of previous consideration of manufacturing attributes within SE is highlighted through the manufacturing attributes developed in section 7.1.1 linking heavily into the Embodiment design element (Figure 7.7).

Finally the model highlights the complexity of the realisation process and thus the need to manage the integration of DM with existing business processes. As modularity has such a broad range of links the adoption of the methodology is not just a process of following clearly defined steps to a modular product, but rather a framework of key considerations and activities that form a structured approach to the realisation of modular products.

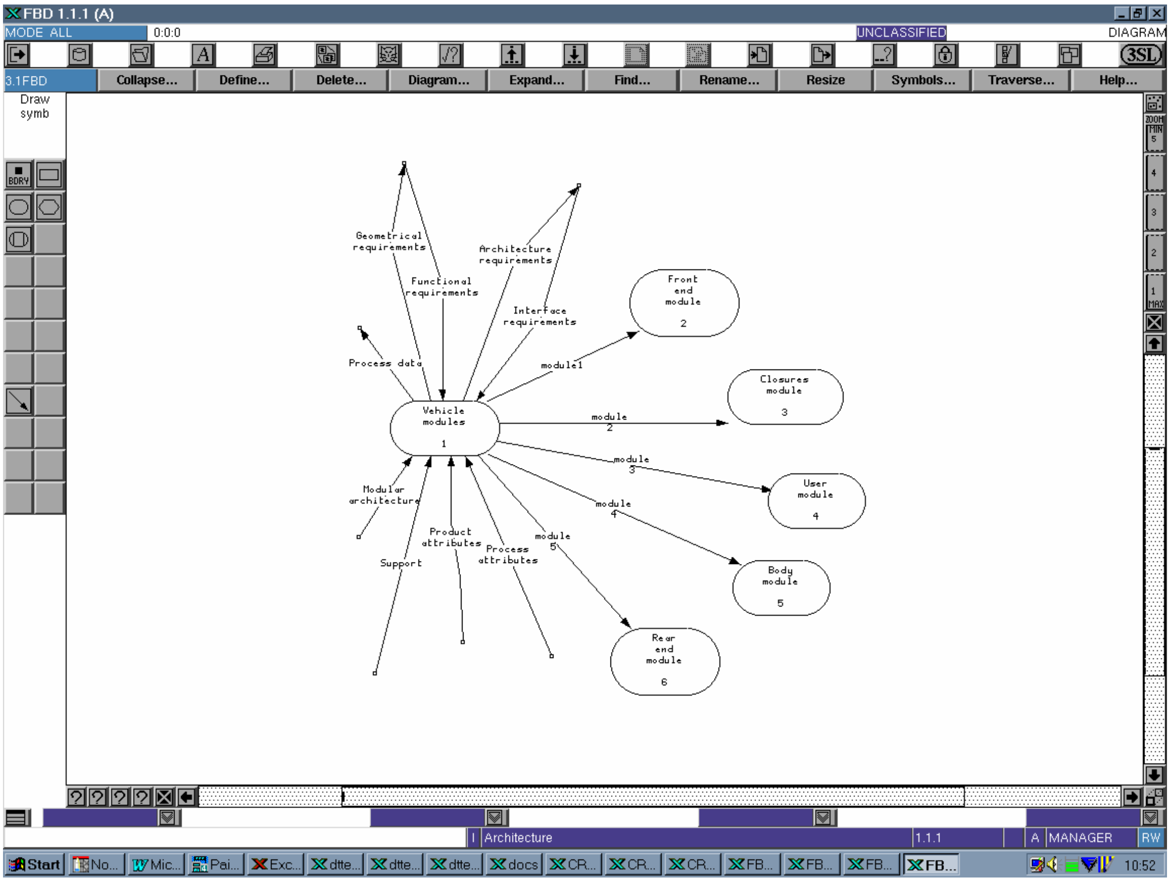

Figure 7.9 System Model Product Architecture Level 1.1.1.

This chapter now examines a more specific aspect of modelling, looking at the performance analysis of modular assembly.

7.2 PERFORMANCE MODELLING

The performance modelling investigates a measurable of DM's impact upon product realisation and in particular the manufacturing attributes. A single assemblability metric is analysed in order to demonstrate how modularity affects the assembly of an example product. This assemblability metric comprises two measurables, the first is the number of operations in the assembly process, the second is the number of fixtures required. The products examined are imaging scanners as manufactured by Crosfield Electronics. The Phoenix is used as an example of a modular product to be compared to the non-modular Magnascan product it replaced.

The assembly process reflects the difference between opposed situations. At one extreme is an entirely non-modular sequential assembly process. At the other is a product consisting of 20 self-contained modules that are built up in parallel and finally brought together as a completed product during final assembly.

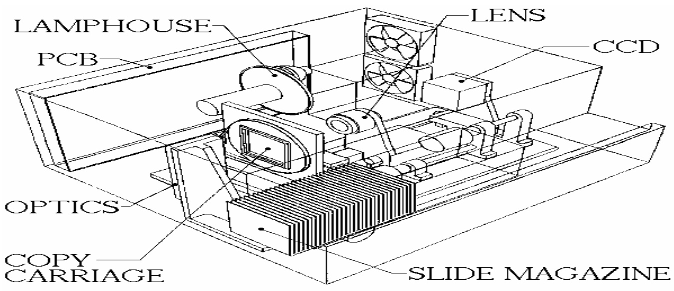

Figure 7.10. Crosfield Phoenix Scanner Module Detail.

The original, sequentially assembled product (Magnascan) consisted of a total of 6000 parts assembled in a line of 15 stations. However, only 4800 parts were assembled by Crosfields, the discrepancy being due to the component count of bought-in subassemblies. The Phoenix consists of 1500 parts assembled in 20 module workstations, though again only 1024 were assembled by Crosfields. The module – part breakdown is shown in figure 7.11.

Module Name and Number of Parts							
Top skin	10	Carriage drive	77	Lamphouse + filterwheel	53	Support packaging	14
Bottom skin	14	Lens and Focus drive	202	PSU	4	Magazines	22
System board	150	Camera head	64	Keyboard & display	52	Copy holder	16
Mag. drive & platform	45	Traverse carriage	51	Cable loom	15	Base casting and guides.	20
Fans	12	Copy load mech.	95	Core packaging	25	Illumination optics	83

Figure 7.11. Phoenix Module – Part Breakdown.

For this modelling activity an additional tool was chosen.

7.2.1 ITHINK

The modelling package chosen for the analysis was Ithink as introduced in chapter 2. Ithink is a generic systems modelling package that allows any system to be modelled through the use of flows to and from containers and various actions upon these flows and containers. Ithink was selected due to a number of characteristics that made it suitable for application to DM.

- Ithink provides an easy to use environment with a simple yet powerful representation.
- Ithink allows any process to be modelled to a complexity suited to the task.
- Ithink provides simple graphical tools to analyse definable parameters of the process.
- Ithink allows easy exploration and simulation of different test scenarios.

7.2.2 MODULAR ASSEMBLY PERFORMANCE MODEL

To represent the two assembly situations two models were developed within Ithink. Figure 7.12 shows the Ithink model for the original (prefix *o*) sequential assembly process. The model broadly consists of the flow of components (*o handling*) into a fixture (*o fixture*). When two components are in the fixture they can be fixed (*o fixer* loop) until the *o assy trigger* informs the process that the assembly is complete. Upon completion the assembly is unloaded (*o unloading*) into an area of completed assemblies (*o completed assemblies*). The two further elements of the *o null* and the *o fix trigger* flow are constructs purely for model function and do not affect the assembly concept.

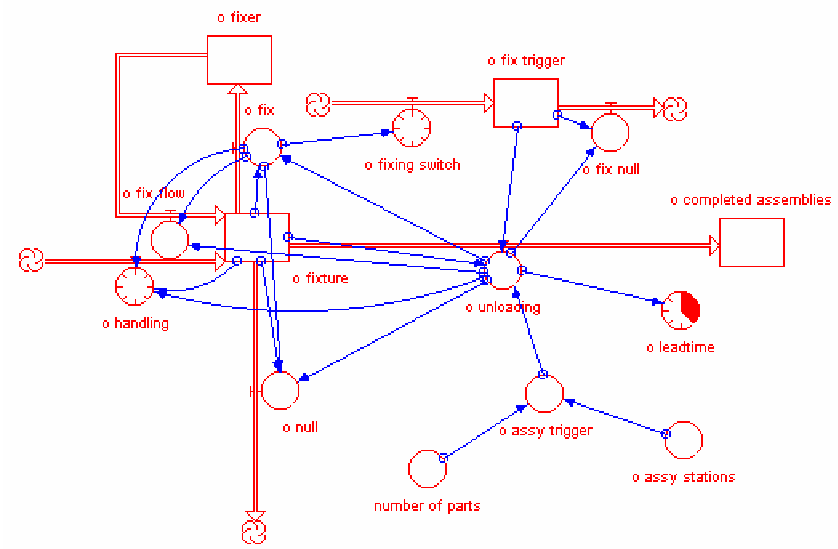

Figure 7.12. Original Sequential Assembly Process Model.

The second model is that of the Phoenix modular assembly sequence. Figure 7.13 shows the Ithink model for the modular assembly process (prefix *p*). To maintain consistency the model was constructed similarly to the sequential model but has an extra level for assembly of the modules. As before a flow of components are handled (*p handling*) and fixed (*p fixer*). However this time the parts are assembled until the module part total (*p max mod parts)* is reached. Completed module assemblies (*p completed modules*) then feed into a second process for assembling modules as oppose to parts. The process the modules go through is identical to the part process and this time results in completed assemblies (*p completed assemblies*). As before the *p (mod) null* and *p fix (mod) trigger* flows are purely for model function.

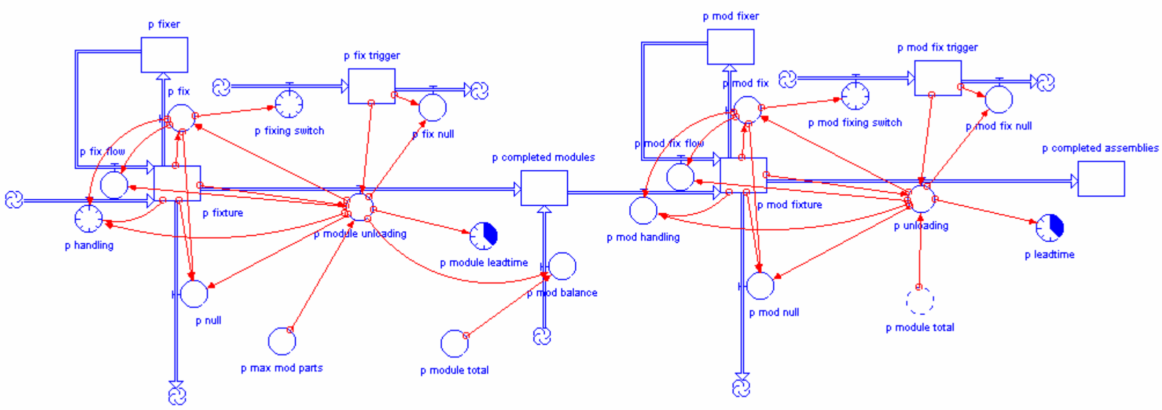

Figure 7.13. Phoenix Modular Assembly Process Model.

Both models have a number of operating parameters. The model of the original sequential process assembles parts until the *o assy trigger* is reached. However the assembly is done in stations, balanced such that each station assembles a number of parts approximately equal to the total number of parts (T) divided by the number of stations (n). After the initial run-up time, the line will therefore produce a completed product every ‘T/n’. Thus the two variables: *number of parts* and *o assy stations* can be used to influence the performance of the model.

The model of the Phoenix assembly process assembles parts until the modules are complete. However, as assembly of modules is done in parallel, the time of completion is constrained by the longest module’s assembly time (*p max mod parts*). Once this time is reached all the modules (*p module total*) are available for final assembly. Thus the two variables: *p max mod parts* and *module total* can be used to influence the performance of the model.

From these models various parameters can be monitored and graphed to analyse the performance of the model. In order to analyse the assemblability metric the performance of the two models were graphed.

Figure 7.14 shows the parameters of part loading (*o fixture*), assembly unloading (*o unloading*), part fixing (*o fix trigger*), and *o completed assemblies* for the sequential assembly of 4800 components at 15 assembly stations graphed over a period of 1000 cycles or operations. From the graph and results a number of points can be identified:

- After run-up, the time to produce one complete assembly (*o leadtime*) is 640 operations.
- Of those 640 operations, 319 are fixing and 321 are handling (320 loading, 1 unloading).
- 15 fixtures are required.
- The process produces 1 assembly in the allotted time.

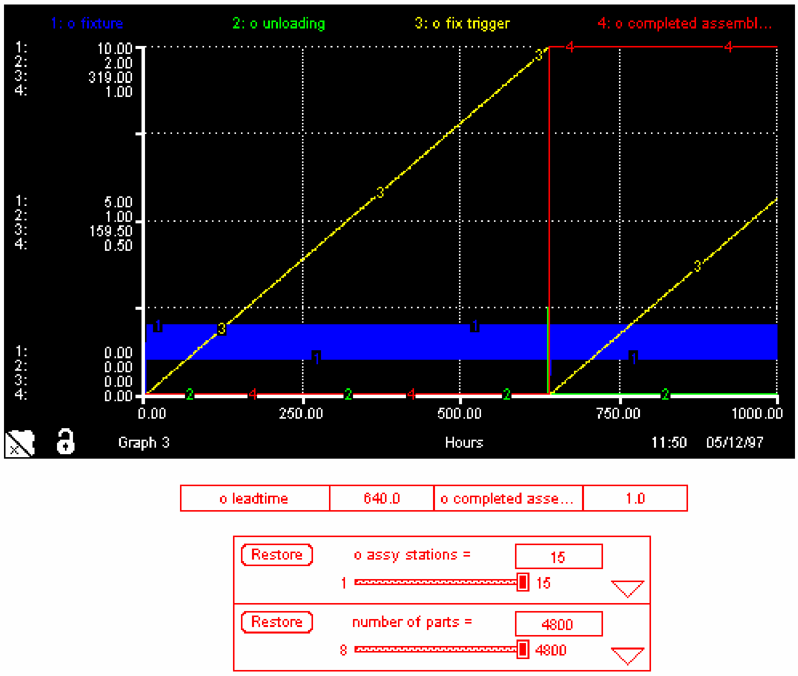

Figure 7.14. Sequential Assembly Process Graph.

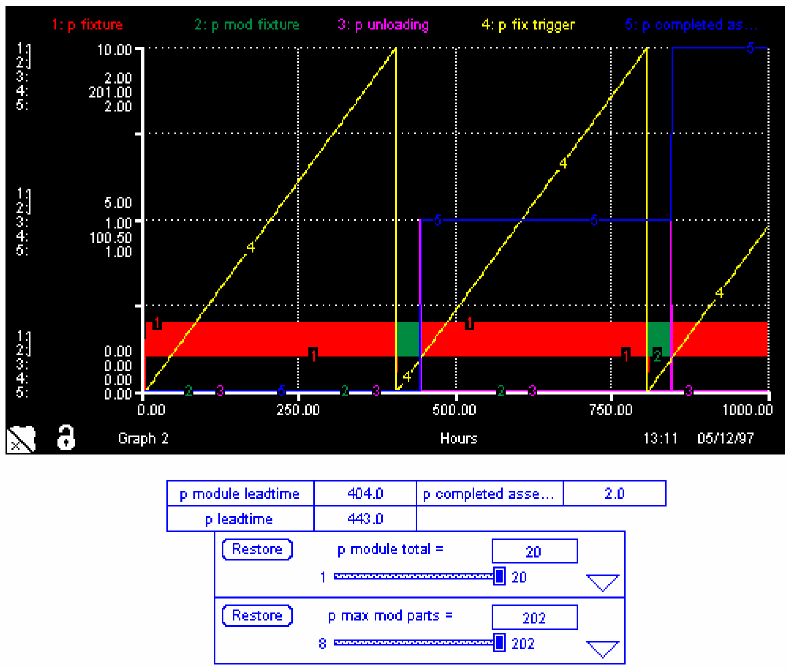

Figure 7.15. Modular Assembly Process Graph.

Figure 7.15 shows the parameters of part loading (*p fixture*), module loading (*p mod fixture*), assembly unloading (*p unloading*), part fixing (*p fix trigger*), and *p completed assemblies* for the modular assembly of 20 modules containing a maximum of 202 components graphed over a period of 1000 cycles or operations. From the graph and results a number of points can be identified:

- The time to produce one completed module is 404 operations, one assembly 443 operations.
- Of those 404 operations 201 are fixing and 203 are handling (202 loading, 1 unloading)
- Of the additional 39 operations, 19 are fixing and 20 are handling (19 loading, 1 unloading)
- 21 fixtures are required.
- The process produces 2 assemblies in the allotted time.

The models operate under a number of assumptions and constraints. All components require fixing operations. A fixture is required at each station and is sufficient to support all components within a sequential assembly station or module of the modular assembly. Finally it is assumed that all operations take an equal amount of time. Under these conditions comparing the results for assemblies consisting of a range of component numbers there are some general rules that apply to assembly:

- For parameters of equal part totals (T) and max module parts (M), a single module (m) and single assembly station (n), the results are of course identical, bar a single extra handling operation for the modular process.
- The number of fixing operations required is always equal to the number of parts minus one (T-1) per assembly. Thus as modular assembly is effectively two assemblies it is total minus two.
- The total number of operations for sequential assembly is always equal to double the number of parts divided by the number of assembly stations (2T/n). This breaks down as 1 operation for handling each part, the number of parts minus 1 fixing operations and 1 handling operation for unloading.
- The total number of operations for modular assembly is always equal to double the number of module parts minus 1 (2M-1) (basically the unloading operation becomes the first loading operation of the module assembly) plus double the number of modules (2m). Thus total = 2(M+m)-1
- Number of fixtures required is always equal to the number of assembly stations (n) for sequential assembly and equal to the number of modules plus 1 (m+1) for modular assemblies.

In terms of the assemblability metric these results show that modularity has a negative impact upon assembly operations and number of fixtures required. Though the number of assembly operations is reduced for the modular Phoenix over the sequential Magnascan, this is largely due to the parts reduction, an important benefit of modularity but not one we are considering directly for this model. For a modular product the number of operations is always increased by the need to re-handle and fix parts in the form of modules. The number of fixtures required is also increased to equal the number of modules, however the impact of this will depend on the number of sequential assembly stations.

With respect to the manufacturing attributes however the results are not so clear-cut. In terms of the speed attribute the increased number of assembly operations for a modular product would have a negative impact on assembly time. However these results assume a serial arrangement. From the model, if modules are assembled in parallel the actual time for assembly is significantly reduced. In addition, the sequential assembly has a number of other constraints:

- The sequential assembly process needs a run-up time. The first product will take the full 2T cycles to complete, only then are products produced every 2T/n. Whereas the modular process always takes 2(M+m)-1.
- The sequential process is prone to disruption. Any disruption to the line, halts all assembly. A disruption to the modular process only halts one module or final assembly, allowing other parallel processes to continue.

The parallel production of modules also affects the flexibility attribute. The modular assembly process provides flexibility within the scheduling of production and the meeting of urgent orders. The effective breaking of the links between the assembly stages allows assembly to be carried out independently where and when required. For the sequential assembly process, the process must either produce to stock or can only assemble on receipt of an order, dedicating the process to specific times and to a specific assembly sequence.

The modular assembly process also allows late configuration, affecting flexibility and speed. If the sequential process assembles to order, the full assembly time is included as part of the order to delivery lead-time. A modular assembly however can be assembled to a point that only includes the generic components of the assembly and thus only the operations required to assemble the dedicated components are included as part of the order to delivery lead-time. Of course the sequential assembly can also be partially assembled but it is unlikely that the generic components will be sequential in the assembly sequence.

Finally the modular assembly process has a positive affect upon dependability through easier and more consistent order fulfilment, and improves quality through ease of testing, and improved robustness. Figure 7.16 summarises these effects of DM.

Attribute / Metric	Modular vs. sequential assembly	Attribute / Metric	Modular vs. sequential assembly
Assemblability	-	Flexibility	+
Assy operations	-	Scheduling	+
Fixtures	-	Late configuration	+
Speed	+	Dependability	+
Run up time	+	Consistency	+
Disruption	+	Quality	+

Figure 7.16. Effects of Modular Product Assembly

7.3 CONCLUSIONS

This chapter examined the DM concept through a number of models. Firstly the systems framework element was examined and its relations to attributes, product realisation and DM itself. Secondly DM's performance was evaluated in terms of assembly. Examining the case of Crosfield Electronics, assembly metrics were compared for the modular Phoenix and the sequentially assembled Magnascan that it replaced. From the investigation of these models a number of conclusions can be drawn:

- A system is comprised of the product and its enabling processes and highlights the complexity of product realisation and the need for a total view as proposed by SE for overall trade off decisions.
- Attributes are a useful development for the efficient deployment of customer requirements. However requirements as investigated by companies such as Ford highlight the long standing problem with SE approaches, namely the lack of manufacturing consideration during development.
- To begin the process of addressing this shortfall a set of five manufacturing attributes were developed linking to the HPD performance objectives of chapter 5.
- A systems model of product realisation and its relations to attributes and DM has been developed within the SE environment Cradle. The model has highlighted the need for manufacturing attributes, the broad ranging impact of DM and attributes upon product realisation, and the traceability of requirements throughout the system.
- Modular product assembly presents a localised disadvantage to the assembly process through a greater number of assembly steps and an increase in the number of fixtures. The increases stem from having to re-handle and assemble parts in modules and the assembly of each module individually. However, taking a total view identifies that regardless of these disadvantages, assembly time is reduced from parallel assembly of modules, and attributes such as speed, flexibility and dependability are enhanced.
- Findings of the performance modelling are borne out through the Crosfields case study of chapter 3. The Phoenix takes advantage of parallel module assembly, late configuration, the potential for parts reduction and simplified assembly. The results were greatly reduced assembly times, flexibility in production and improved reliability (Section 3.1.3.2, p.58).

This chapter wraps up the scope of the research covered in the thesis. The following chapters draw together the wealth of issues presented thus far and then offer some final conclusions and suggestions for furthering the work into modularity and other closely related topics.

Chapter 8 Discussion

8

Objectives: This chapter draws together the issues presented within the thesis prior to the drawing of final conclusions. Discussion is broadly grouped to reflect the aims, including the systems framework, principles, and methodology. It also addresses the scope of the thesis, what was covered, what was not, and how this work complements other related research.

8.1 THE SYSTEMS FRAMEWORK AND PRINCIPLES OF MODULARITY

The case study material presented in chapter 3 highlights many aspects of the concept behind this thesis. The work with companies from a range of size and product sector generated a number of generic findings. The four broad industrial needs for; efficient deployment of customer requirements, a rationalised introduction of new technology, a structured approach to dealing with complexity, and flexible or agile manufacturing, showed the current pressures upon product manufacturers. What was also shown was that modularity provided a positive response to these pressures with the minimum of trade-off. However analysis of existing techniques and processes were found to lack an approach to modularity that would maximise its potential and that could be applied in a structured and accessible manner.

The approach to these concerns targeted key aims, investigating a broad framework for modularity through SE, developing a structured methodology for DM, and addressing the underlying principles of modularity through case study and modelling.

The potential for modularity across a range and scale of product industry is mirrored by its broad ranging impact across the spectrum of product realisation processes. In order to address this impact, SE is proposed as a framework that could provide both structure, an inter-disciplinary linking mechanism, and an opportunity to adapt generic systems philosophy to the development of modular product systems. SE also provides a valuable total view. This perspective manages localised issues against a broader framework, an important concern in meeting customer and business needs efficiently (Lorenz 1998).

Review of concurrent and SE highlighted a number of interesting aspects for the DM methodology:

- Modularity is a large and amorphous topic. It also promotes an approach that focuses on the integration of design and manufacture, highlighting links through SE with the breadth of processes, tools and techniques embodied within the product realisation system.
- SE provides a valuable premiss but misses the opportunity its concept provides through a lack of manufacturing integration.
- Modularity has a number of existing processes related to the generation of modular products. Though similarities are identified between philosophies, they all fail to address the specific concerns of product manufacturing organisations for a structured and accessible approach.

To embody the structure of the modularity concept, a paradigm (Figure 4.11, p.84) is presented, highlighting the hierarchy of a modular design process through to a systems framework and thus the linking mechanism of modularity throughout the product realisation process. Specific implementation issues are also discussed, examining the need to address accessibility, customisation of the process for flexibility, and crucially, the promotion of manufacturing within the realisation process as part of design to manufacture as a single process.

An investigation into the SE framework and aspects of the principles of modularity developed a number of models. Modelling through the use of the SE environment Cradle, highlights the impact of modularity throughout the product realisation process and the specific links from modules to attributes and thus customer needs and wants. In addition, the model also highlights the importance of the use of attributes themselves and confirms the traditional SE bias towards engineering. Attributes are a powerful tool in linking customer requirements to the product realisation process and in focussing activities. However, attributes identified only integrate manufacturing as a factory operations concern. Thus a valuable opportunity is missed to adopt manufacturing attributes for engineering activities and thus the view of design to manufacture as a single process.

In order to address this opportunity manufacturing attributes are determined with respect to the DM methodology. These attributes are then examined in a simple model of product assembly performance using the software package Ithink. A modular product assembly process is compared to sequential assembly and found to have a number of interesting features. Modular product assembly has a negative impact upon assembly if taken purely as a view of assembly operations and tooling requirements. However, when examined from an attribute perspective a modular assembly process provides a number of benefits through its ability for parallel production, flexibility and structured organisation. Though the example is a simple model it provides a clear demonstration of the impact of modularity upon manufacture but also the value of attributes in providing an alternate perspective, one that benefits from being customer oriented.

The model also highlights the benefit of a total view identifying that a localised assessment of modularity would miss the potential afforded by such an approach.

The concept of the principles of modularity is investigated in order to identify any generic elements of modularity that are always applicable, regardless of approach. The modelling, case and background work identifies an initial set of these elements. The first fact is that modularity concerns the mapping of functions to physical building blocks and that the way in which the mapping is done and the configuration of the mappings, effectively governs the whole concept of DM and the modular product. Modularity is also a widely implemented concept though much is by accident rather than design. Modular forms appear in industry through businesses, departments, products, manufacturing facilities and also within nature.

The function of modularity as a concept comes predominantly from its flexibility. Typically manufacturing flexibility is seen as a solution to the need to balance customer and business requirements in a manner that provides market advantage. However it has been highlighted that manufacturing flexibility is greatly enhanced by product flexibility. In products such as software, this is performed through modules, this can be repeated in so-called manufactured products and the benefits of product configuration adopted.

Having covered the framework and principles of modularity the discussion now addresses the methodology.

8.2 METHODOLOGY FOR DESIGN MODULARISATION

Upon examination, the wealth of material from literature and case study yielded a number of key elements within the development of a methodology for DM (Chapter 4). Modularity is used in a number of existing areas that share a few generic modular features, including; product design, software design, control systems, and manufacturing operations. However these applications lack a generic concept and approach to modularity. Thus to provide a basis for investigation the thesis defines the terminology of modularity. The need demonstrated by the case studies is analysed drawing out specific aspects of customer requirements, complexity, new technology and flexibility within the scope of DM. Modularity is also found to share goals and concepts with other research topics such as holonic manufacturing systems, fractal product design and factory organisation, mass customisation, the bionic factory, and also teamwork. In addition modularity has a synergy with popular techniques such as DFA, FMEA, GT, and FAST.

Other important aspects included the applicability of modularity. In a high-level examination modularity was found to be suited, though not exclusively, to the high uncertainty/high complexity areas of the market as defined by the Puttick grids (Section 4.2.3, p.74). It is further determined that the application of modularity to a particular product is not clear cut. Indeed, the aspect of concern is not if modularity can be beneficially applied but rather to what degree and in what manner should modularity be applied in order to achieve the optimum solution. A simple analysis was developed to determine products not suited to modularity, the advantage to be gained, and to identify the aspect of modularity that was required for a specific application. The range of applicability was also mirrored by the range of modular architecture possibilities. A modular product may have a the potential to be realised in a number of different physical structures and combinations. These possibilities are developed into an aspect of modularity known as the level of modularity, measured by three factors; complexity, resolution and composition.

The specific approach taken to a modular methodology is embodied in the Holonic Product Design (HPD) workbook (Chapter 5, Appendix 4). The workbook represents the need for a process for modularity that looks wider and yet more focussed in order to examine the far reaching impact of modularity upon an existing organisation.

HPD utilises the widespread standard BS EN ISO 9000 and the highly relevant BS 7000 Part 2: guide to managing the design of manufactured products, as a basis for a generic product introduction process. The adoption of this standard provides a number of advantages. Firstly BS7000 is a topical design standard embodying current best practice. Secondly it provides an advantage through familiarity, in the integration of modularity, through the ability to map the methodology onto an existing standard and thus onto an organisations own process. BS7000 also allows mapping of SE links further increasing the ‘hooks’ for integration.

From the consideration of lifecycle concerns through BS EN ISO 9000, BS 7000 and SE, the HPD workbook identifies modularity’s impact and requirements upon the product realisation process from corporate objectives to servicing and takeback. This approach provides a true total view of product realisation, considering and providing guidance on many real concerns for product manufacturing organisations.

The process of designing modular products is covered thoroughly in a flexible manner that avoids product or technology specifics. An organisation is guided through the processes of team formation, requirement management, and the process of defining product elements and grouping them for module definition. Throughout the process the user is aided by tools and self analysis worksheets to adapt the technique to existing working practices and to enhance the explanation of the activities. Powerful concepts include the identification and mapping of the modular architecture through the level of modularity (LOM), element and module interaction analysis, driver review and tailoring, and also existing product and process analysis.

Other pertinent considerations are highlighted to raise awareness of the impact of modularity upon products with a strong requirement for backward compatability, the increasing number of products with a software element, and also the possibilities within standardisation and the development of a generic product platform.

Beyond design, manufacturing strategy is covered in depth. Highlighting the need to consider manufacturing as a fundamental aspect of product realisation and include manufacturing concerns as part of the design activity of a modular product. Again, a generic structure is used for illustration and to allow tailoring of the modular concept to existing business practice. Manufacturing organisation is also briefly considered with respect to modular grouping of facilities in the form of cellular manufacture. Finally, the workbook provides further support and guidance to the organisation through checklists and single point guidelines allowing the process to be simply referred to and maintained beyond the initial project.

Though the workbook has not been implemented directly in its current form (version 1.2) a preliminary version containing many of the final concepts was developed and implemented within Sperry-Sun Drilling Services' PCD/PCG probe project (Section 6.2.2, p.114). Findings from this work illustrated the efficacy of the early concepts and specifically the LOM metric and guidelines. In addition the workbook was widely circulated throughout industry and was largely confirmed to be relevant, useful and well presented.

8.3 SCOPE

It is clear that this thesis has addressed many issues throughout a broad and amorphous area of research. Not only has the work developed the field of product modularity it has also addressed the impact of modularity throughout the entire product realisation process. This total view has been facilitated through the framework of SE. However an additional opportunity has also been addressed to enhance the traditional SE view through the concept of design to manufacture as a single process and the stance that a total view must of course include the perspective that manufacturing is more than just a consequence of product design.

However there are limits to many of the areas covered and also related areas excluded from the scope of the thesis. Though SE has been covered as a framework to the core DM, the examination of many of the detailed aspects of SE such as systems analysis techniques and tools have been only touched upon. This conscious decision was to avoid detailed analysis of another large area of research when the concept of the approach is the key element to this work rather than the specific implementation.

The work has also take a largely ‘design methodology’ approach to modularity examining processes, guidelines, and highly flexible models of application. However there are a number of opportunities in a more analytical approach to the principles of modularity that have only briefly been touched upon. Chapter 7 examines the modelling of the product realisation system and the process of modular and non-modular assembly. Though this only represents the highest level of the potential in this area. The examination of system models and the impact of modularity upon the system and its attributes provides an opportunity to isolate generic elements and provide a more scientific approach to modular development that still maintains a customer friendly aspect through the inclusion of attributes. Other opportunities also include the examination of clustering techniques for module function grouping (Hitchins 1992).   Again, the thesis did not aim to study in depth the underlying scientific basis of modularity, only identify that it exists and provides a further dimension and opportunity to the research.

Finally and possibly most importantly, the thesis does not sufficiently cover the implementation and analysis of the HPD methodology and its manifestation as the workbook. However the concept of the workbook has been implemented, and the process of its development and use is ongoing. It is not possible to include events that will occur in the future but the point can be noted that a number of companies have expressed interest in using the workbook in future projects that unfortunately are not timely for the writing of this work.

A further note is that this thesis represents one element of research under the broad umbrella of SE. Its combination with specific work into topics such as integrated product development, SE environments, and flexibility goes some way toward clarifying and furthering this truly total view of product realisation.

The issues highlighted and discussed are now carried forward in the following chapter 9: Conclusion.

Chapter 9 Conclusion

9

Objectives: This chapter provides a comprehensive list of conclusions drawn from the thesis and identifies opportunities for further work.

9.1 CONCLUSIONS

In light of the objectives of chapter 1 and discussion of chapter 8, the following main conclusions have been drawn from the research documented within this thesis:

1. **Need:** Case study and literature review have characterised the need for an approach to product realisation that utilises a concept for modular products and associated manufacturing systems.
2. **Nature:** The meaning, applicability, impact, and mechanics of modularity have been defined, and developed to clarify what modularity is, how it works, and to what it can be applied.
3. **Framework:** SE provides a structure, and approach to system (product and process) development that focuses upon meeting customer requirements that has the potential to integrate disciplines throughout the product realisation process. SE is therefore developed as a framework for DM.
4. **Methodology:** The need for a structured approach to modularity has been met through the development of a Holonic Product Design workbook. The workbook goes beyond the modular design process presenting guidance and support in all areas of product realisation, and providing tools for the integration and maintenance of the technique.
5. **Principles:** Regardless of approach DM exhibits underlying principles in its methodology. From the linking mechanism of a systems framework to the impact on specific attributes and metrics such as flexibility and assembly operations.

The conclusions are now expanded in the following sections.

9.1.1 THE NEED FOR A MODULAR PRODUCT APPROACH

- The approach to the research was developed around four main industrial case studies (see Chapter 3). The studies were undertaken to represent a range of company size and product in order to provide a broad base for analysis of generic needs. Industry covered includes: automotive, shoe manufacturing, and digital scanning and sensory equipment.

- The case study experience provides a view of current pressures faced by product manufacturing organisations, indicating the emergence of more discerning customers and the strive to meet their needs. These pressures can be broadly grouped into four main concerns:
    5. Efficient deployment of customer requirements
    6. A rationalised introduction of new technology
    7. A structured approach to dealing with complexity
    8. Flexible or agile manufacturing.
- Case study analysis highlights modularity as a means of addressing the above concerns that maximises the potential in each area for satisfaction of both customer and business needs.
- Case and literature review also highlight modularity as a topical approach, gaining momentum as a desirable concept for wide ranging applications from the Joint Strike Fighter to engineering system suppliers for the automotive industry such as Visteon.
- Though modularity sees use within industry, organisations have failed to take full advantage of the potential taking an ad hoc or localised approach. Techniques applied to manufactured products present an opportunity to address both broader (framework and links through product realisation), and narrower (application specific case details) aspects of implementation.
- A need to raise awareness of manufacturing concerns within the engineering aspect of product introduction is demonstrated through the concept of design to manufacture as a single process.

9.1.2 THE NATURE OF MODULARITY

- Case study and literature review have shown modularity to be a complex and amorphous topic. Also demonstrated are the links to many aspects of product realisation and thus the potential to positively impact product and process throughout development, manufacture, use and disposal.
- The definition of a module has a considerable impact on the interpretation of a modular product. The following definition was developed to define a module from which maximum advantage could be gained:

    A (sub)system that comprises a group of individual elements that form an independent, co-operative, self contained unit with one or more testable composite functions.

- Such a definition exhibits the following properties:
    - Modules are co-operative subsystems that form products or other such systems.
    - Modules have their main functional interactions within rather than between modules.
    - Modules have one or more well defined functions that can be tested in isolation from the system and are a composite of the components that form the module.
    - Modules are independent and self contained and may be combined and configured with similar units to achieve a different overall outcome.

- The applicability of modularity was investigated, and shown to be relevant to a wide range of products. However those products suited to modularity cannot be easily identified due to the number of influencing factors. Therefore a three element analysis has been defined to indicate a product not suited to modularity (Section 4.2.3, p.75, Section 5.5.1, p.105):
    4. Products that require an integrated architecture.
    5. Products that are sensitive to functional interfaces.
    6. Products that are predominantly uniform in substance or from continuous processes.
- Modularity has also been shown to have an increment of suitability. A seven question analysis has been developed to reflect the various implementation properties (Section 4.2.3, p.76, Section 5.5.3, p.106).
- In addition to analysis of applicability, the actual form of the application has been investigated. Case study work has shown modularity exhibits a level that reflects the nature of the architectural make-up of the product. This level of modularity (LOM) has three components:
    4. *Complexity* - the functional level of modularity for each module. A module can contain anything from a single function to a combination of many functions.
    5. *Resolution* - the number of modules in the product. *Resolution* and *complexity* are related e.g. high numbers of modules are likely to have low individual functionality.
    6. *Composition* - the degree to which module complexity varies within a single product, and the composition of a platform module and, common, or variant modules.
- From case study analysis modularity has been found to exhibit many wide ranging advantages (Section 4.2.5 p.80, Appendix 7.), and relatively few disadvantages that are largely removed through use of complementary techniques such as design for assembly.
- The case studies highlight a key element in a modular approach. Module interactions and interfaces form the core to a modularity methodology, requiring careful examination of module functions and their physical implementation. The management of interactions also links to the systems framework and a total view of trade off analysis.
- Case study and literature review has identified a number of different modular design processes proven useful within industry. This suggests underlying principles in modularity that remain true regardless of the approach. From this it is deduced that there is no single process for module development. What must be considered is awareness and integration of the technique.
- Case study and modelling has identified further aspects to the nature of modularity:
    - Modularity provides product variety to the customer. This variety is offered efficiently and flexibly through a number of common, variant, and potential upgrade modules.
    - Modularity presents an opportunity to manage process complexity and assign teams with the modules for which they are responsible.
    - Modularity addresses product complexity through decomposition of systems, partitioning of functions, analysis of interactions and modular assembly.

- Modularity facilitates a global perspective, allowing efficient logistical management and control for issues such as work share.
- Modularity allows more efficient and effective manufacture and assembly through part and module standardisation, and the structuring of processes around the product.
- Modularity also provides structure to the application of other related processes such as DFA, value engineering and group technology.

9.1.3 THE SYSTEMS ENGINEERING FRAMEWORK

- The review shows that SE promotes a total view. For the research a system was defined as a combination of both the product and its enabling processes. Therefore SE provides an excellent framework for a modular methodology that requires an encompassing support mechanism with links throughout product realisation.
- To provide structure and orientate the relationship of the framework to modularity a paradigm has been developed (Figure 4.11, p.84). The paradigm illustrates the important relationship between a process for modularity, its underlying methodology and the supporting framework provided by SE.
- Traditional views of SE neglect the opportunity that manufacturing presents. However an adapted SE is considered as a true total view for the purposes of DM (Figure 5.4, p.89, Figure 7.1, p.123).
- In order to investigate the SE framework a model was developed using the systems environment Cradle. The model shows that a SE framework for modularity provides strong links from the flexibility of a modular product to attributes and thus customer wants and needs (Section 7.1.3, p.125).
- The modelling work also illustrates how SE techniques and tools such as Cradle provide a valuable resource in examining the product realisation process and the links between aspects such as modularity, attributes, and the various stages of development.
- The use of attributes in a systems based approach provides an important tool in deploying customer requirements, ensuring an interdisciplinary approach, and in the management a complex project.
- Existing attributes confirm the engineering bias of traditional SE, predominantly relating to product engineering (Section 7.1.1, p.124). Existing manufacturing attributes are plant-based and thus only impact the setting up and running of factory operations.
- In order to enhance an attribute based systems approach, five manufacturing attributes of quality, flexibility, speed, dependability, and cost (Section 7.1.1, p.124) are presented that relate to manufacturing's impact upon the engineering process.

9.1.4 THE METHODOLOGY AND HOLONIC PRODUCT DESIGN

- The DM methodology has been developed as a Holonic Product Design (HPD) workbook (Appendix 4) to provide a complete package for those wishing to implement a modular approach.
- The workbook was developed to present a highly accessible framework for attaining a successful modular product realisation process. Addressing not only the detail of the process itself, the workbook examines all stages of product introduction including corporate and manufacturing strategy. Support is also provided in integrating the process into existing working practice, aiding the learning and maintenance of the process for future projects.
- In order to acknowledge current best practice and accredited standards HPD utilises elements of BS EN ISO 9000 and BS 7000 Part 2.
- The use of the standards was also implemented to reduce complexity of the modularity process, ensure topicality, and allow modularity to be integrated into existing company design management processes in a greatly simplified manner.
- HPD supports the modularity paradigm through presentation of the systems framework and how the links are formed through BS 7000 Part 2 and the SE V, to the modular process itself (Section 5.2, p.89, Figure 5.5, p.90).
- The development of HPD ensures the concerns and activities at all stages of development are comprehensively addressed in a clearly defined set of processes that are flexibly implemented to be product, process and scale independent.
- HPD is oriented toward guidance rather than the imposition of strict rules in order to maintain a wide applicability. Guidance is provided on topics such as backward compatability, software, and the potential concerns such as change management that will have to be carefully addressed.
- Within HPD a self analysis has been developed (Section 5.5, p.105). Based upon case study findings the self analysis is aimed at addressing implementation suitability, a groundwork check, an analysis of the level of modularity, an identification of specific drivers and associated tailoring of the process to suit, and finally, simple processes for examining existing products and processes for modularity compatible elements.
- In order to further facilitate integration and maintenance of the modularity process HPD provides a set of straightforward and accessible checklists and guidelines.
- The HPD workbook has been distributed for comment and partially implemented within industry. The partial implementation highlighted the efficacy of the approach and specific importance of the level of modularity (LOM) and guidelines. In addition the self analyses were a useful tool for clarification and tailoring of the information and guidance provided. Overall HPD has been favourably received and there are ongoing projects that are planned to utilise aspects of the workbook.

9.1.5 THE PRINCIPLES OF MODULARITY

- Modularity has been shown through modelling, case study and literature review to present a number of facts or rules that are applicable regardless of the specific approach taken:
  - Modularity is inherently based upon a mapping of functional aspects to physical entities. The way in which this is done and the impact of particular mapping configurations controls the modularity of a product and ultimately its ability to meet its requirements. Thus the development of measures such as the LOM and its associated analysis provide a valuable tool for structuring the application of modularity.
  - Eleven factors have been identified that influence the mapping of physical to functional elements e.g. interactions, geometry, core business and manufacture (Section 5.3.3, p.95).
  - Metrics have been developed to allow numerical measurement of advantage to be gained and suitable level of modularity (Section 5.5, p.105). Through case implementation of self analyses the metrics have provided valuable benchmarks for modular product development.
  - Modularity has a negative effect upon assembly when a localised view of total assembly operations and fixture requirements is taken. The modular assembly will always take an extra number of assembly operations equal to double the number of modules minus one.
  - However, taking a total view of assembly highlights the overall beneficial effects of modularity. Through the capability for parallel assembly, total assembly time is reduced and further positive impacts upon flexibility and dependability attributes are seen.
  - The power of a modular approach comes from its flexibility. Three modules provide a potential 7 products, an integrated architecture would require 7 individual products.
  - To meet changing needs in an effective and efficient way, flexibility must be introduced into the realisation process. Modularity provides a rational product flexibility to enhance existing manufacturing flexibility solutions.
  - Modularity provides a package of advantages that have seen its form replicated across a spectrum of research activity and even within nature. Holons, bionics, fractals, software development, control systems, and manufacturing operations, all revolve around modular elements and their application to manufacturing layout, the processes of engineering and manufacture, general business processes, departments, companies, and suppliers.
  - Modularity needs support of a total framework view in order to manage its complexity and broad ranging links. The Cradle system model shows the traceability of modularity's influence from development activity through requirements to the customer (Figure 7.8, p.131)

9.2 FURTHER WORK

Elements of research that could not be picked up on due to time constraints or due to lying outside of the scope of the thesis are now identified here in a list of possible future research activities:

- Examination of SE in detail, taking a modularity view of the links from customer requirements to completed modules and products. This would strengthen the framework aspect of the modularity paradigm.
- Further investigation of the principles of modularity. Identifying constant facts or rules would provide further insight into the underlying mechanics of a modular approach and thus provide an enhanced basis for a generic approach.
- Investigation of the attribute concept. Including detail research into a generic set of manufacturing and product attributes and how these may be best used to facilitate new product introduction. Attributes have the potential to provide a simple yet powerful tool for deploying customer requirements throughout product realisation.
- Examination of statistical techniques such as clustering algorithms (N^2 and simulated annealing) for the grouping of functions / elements into modules and the subsequent identification of modules for product families. This would provide an analytical approach to this activity, likely to be useful for particularly large and complex projects.
- Implementation of the HPD workbook to a range of companies in a controlled manner to identify strengths, weaknesses and any generic elements that may be utilised in the workbook or the generic concept of modularity itself. This would confirm the relevancy and efficacy of the approach and fine-tune application into a truly useful framework for modular product development.
- In light of any implementation experience the workbook should be revised and edited to follow general opinion and maintain links with current best practice. A software version may also be developed in line with the questionnaire responses of section 4.2.4, p.77. This would ensure that the technique stays relevant within industry and adapts to future trends in customer behaviour and business operation.
- Cradle provides an opportunity to combine a number of these suggestions through the investigation of the links from a SE process and the methodology embodied within HPD. This would address attributes, links, trade-off analysis and the software implementation of HPD. It would further allow for scenario testing and potentially provide an integrated and intuitive application of HPD.

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Appendices

A

APPENDICES

1 DETAILED CASE STUDY MATERIAL

Sperry-Sun Drilling Services - Cheltenham.
Product Development Strategy Report.
10/02/97

Introduction.

This document presents the product development strategy as proposed and implemented by Sperry-Sun Drilling Services (SSDS) Cheltenham. The strategy will be presented in conjunction with the reasoning for it's generation and implementation, and the benefits gained from it's inception.

The strategy is also presented in relation to the company's corporate objectives and goals.

Background.

SSDS Cheltenham design, manufacture, test, service and support a number of products that are used in an ever diversifying market, under increasingly harsh environmental conditions. The products are operated by a division of the company as a service to the customer. Over time the customer needs have grown as new applications have been envisaged and the requirements on performance have been increased.

In order to meet the needs of the customer the company has developed a range of products. These products exhibit a number of characteristics:

- They have been developed in response to specific customer needs,
- They have evolved to incorporate improved and / or new technologies,
- They can be used in combination to provide a variety of service,
- They are backwardly compatible with existing products already in service.

The development of this range of products directly met the needs of the customer but led to a situation that posed a number of difficulties to both SSDS Cheltenham and for the operators of their products. The constraint of providing backward compatibility to their product range, has, over time presented a problem with the number of interfaces required to ensure that the compatibility exists between products of differing ages. Of course this was not a problem when the number of product options was low, but with the increase in possible combinations and a likely continued increase in the future, the situation became prohibitive to both business and operator needs. Coupled with this was the traditional incremental and evolutionary design of products that would typically be unstructured and somewhat ad-hoc, presenting problems with poor standardisation of parts thus increased stock holding, and associated administration, considerable re-engineering of products to meet demands, poor time management, and continued 'fire-fighting'.

The solution to this, and a number of specific technical needs was the development and implementation of a new product development strategy that mapped out the needs of both the business and customer, and provided a framework for dealing with a number of issues:

- An efficient means of deploying customer requirements,
- A structured approach to dealing with product complexity,
- A rationalised introduction of new technology,
- Flexible or agile manufacturing.

The product development strategy was to be based on a modular product philosophy, and be linked with business objectives and a strong quality management process.

Cheltenham's Business Objectives.

The framework for a successful product development strategy was put in place by the definition of Cheltenham's business objectives and corporate mission statement. The focus was to be in understanding and exceeding the customer's expectations and providing benefit to the business as a whole in a continuous improvement culture. The objectives comprised of the following main points:

- To develop in a timely manner, reliable, cost-effective modular, products that provide SSDS with a competitive advantage in the market place.
- To assemble, test and calibrate premium quality products on time, and at a minimum cost.
- To encourage and optimise individual contribution to Cheltenham through training, empowerment and opportunity.
- To continuously improve the knowledge of our processes by encouraging a Company-wide learning culture.
- To instil the compelling need to continuously increase the value of Cheltenham for the benefit of SSDS and Cheltenham employees.

Cheltenham's Product Development Strategy.

Overview.
The strategy developed builds upon the modular nature of the product range supplied by SSDS Cheltenham where the products are developed as modules with a limited number of specific functions that can be combined by the operator to provide a variety of services to the customer. The modularity is taken to lower level where subassemblies within the products become modules. This then allows standardisation across the product range, reduced product development times, improved manufacturing efficiency, and an ability to upgrade old products still in service in a manner invisible to the customer.

Structure.
The strategy comprises of the following phases during development of a modular product.

Concept and Feasibility Phase.

- Identify Project team and specialist skills likely to be required.
- Capture requirements including key elements from existing products and possible future products.
- Loosely define a level of modularity to guide module development.
- Document product technical specification in a clear and concise manner. Include traceability of requirements.

Implementation Phase.

- Utilise parallel development of modules by assigning module teams.
- Develop rough layout / schematic of proposed product based on specification.
- Determine possible modules and interface concepts.
- Create a rough geometric layout to ensure fit and compatibility.
- Test modules against specification.
- Detail design.

Application.

Concept and Feasibility Phase.

This section details the implementation of the strategy to two core products in need of replacement. The 150º C D(G)WD system, or specifically the PCD and PCG probes.

The process truly began with the inclusion of the modularity goal as part of the corporate objectives. This step ensured that there was a company-wide 'buy-in' of the concept and that it provided a universal platform for the integration of disciplines and the utilisation of resource in achieving business goals in an effective and efficient manner.

A concurrent engineering environment was facilitated through a Total Quality Management (TQM) philosophy and the use of multi-disciplinary teams, the co-location of employees in related functions, the encouragement of co-operation and communication between all departments, and a general increase in employee awareness of the job issues of colleagues.

The detail implementation of a modular strategy was initiated with the analysis of the existing products and the documentation of key elements within them, such as (actual or possible) common functions and common components or assemblies. This analysis aimed to ensure backward compatibility with existing products to maintain high customer confidence but to also identify possibilities for standardisation and rationalisation.

The analysis identified a number of elements that required consideration.

1. A high degree of functional commonality, but low physical commonality between the two products. Both probes have a power supply (psu), a processor, some sensor electronics and the sensor stack itself. The power supply unit and the processor perform essentially the same functions on both probes but were implemented differently due to the legacy of earlier development by different engineers.
2. A distinct common and dedicated split of functional areas. The probes have an analogue and a digital section. The psu and the processor make up the digital portion and the sensor and associated electronics compose the analogue portion. These areas exhibited their own pcb's and discrete area of the probe.
3. No real justification for the low physical commonality. The lack of commonality in implementation was due to the previously mentioned historical influence. Often designs would be the responsibility of different engineers and would be developed in their own style, with little thought to commonality.
4. The possibilities for a number of novel design changes to improve performance and ease of manufacture. In order to improve vibration performance the traditional architecture of mounting the probe into an instrument case and then into a pressure case was modified to allow direct mounting of the probe into the pressure case. To further protect the probes from vibration it was also noted that they could be encapsulated in a potting compound to effectively dampen the forces seen at the component level.
5. A possibility to introduce a new standard to the product range whilst still maintaining backward compatibility. The probe to probe interfaces were traditionally performed by coil-cords which are effectively dedicated to the combination being assembled. A new standard (military standard 1553) was considered that would allow a single cord to be used for all combinations, compatibility with other SSDS equipment, and flexibility with the control protocol to be used with the interface. In addition it was considered that this could be introduced but also be available as a retro-fit option for existing coil-cord compatible products.
6. A starting point for a new company platform and philosophy. In addition to developing two improved core products, there was an opportunity to provide a generic platform for future products in order to maintain the benefits of commonality and reduce lead times for development. This coupled with the business changes and focus, presented itself as a new company philosophy for understanding and exceeding customer requirements.

In addition to the identification of key elements, a level of modularity was determined to include a generic platform element and to develop modules at a mechanical and electronic package level. Thus electronics packages could be developed within constraints by separate teams, in parallel to the mechanical design based around the same constraints. This provided a benchmark guide for product development, and allowed parallel development of the associated modules.

The culmination of this concept phase of development was the generation of a Technical Specification document. This document was refined to meet the needs of the new product development process. Original specification documents were often unclear and verbose and thus provided an additional overhead on the efficient development of new products. The new specifications showed a systems engineering influence by providing an up-front record of requirements on the new products, and traceability to who generated those requirements. The requirements were also formatted as single line statements to avoid confusion, aid ease of use, and avoid being prescriptive in the way they should be met.

Implementation Phase.

Once the requirements were signed off in the Technical Specification the requirements were used to develop a rough layout of the product. Due to the circumstances of replacing two key products simultaneously it was possible to use a large degree of freedom in the design of the products. This freedom encouraged the development of a number of novel ideas and solutions to existing problems to be tried.

- The traditional mounting of pcbs end to end could be replaced by back to back boards. This would reduce the overall length of the probe and allow a tighter radius of drilling to be achieved.
- The probe could be designed in such a way as to allow the boards to be placed in compression during final assembly. This constraining force would further improve the reliability of the probe under vibration and shock. This method could also be used to soak up any stack up of tolerances along the probes length.
- The probe could make use of flexi-circuit connectors to simplify the hard-wiring of board to board interfaces. This could also be expanded to include a connector tag that would protrude from the potted areas and allow testing and reprogramming without the need to remove the potting compound.
- The probes could be fitted with a keyway to ensure alignment with a known datum for probe calibration.

- The probe could be hinged to allow accommodation of any misalignment.

The layout provided information on key features, constraints and provided sufficient detail for the team to determine possibilities for modularity.

Module possibilities were determined from the layout and related to existing and future product requirements to ensure compatibility and extended life. The criteria used for module identification were primarily those of standardisation, manufacture, localisation of change, and supplier capability.

1. Standardisation was used to provide a generic element of the products that covered the common functional areas. This generic element could then be used as a platform for future products. The psu and processor boards and the spine would be common modules across the two products and be used in future products.
2. Manufacture was addressed through the commonality elements, complimenting the common areas of functionality with common areas of mechanical and electronic design. The commonisation of the modules would simplify manufacture and assembly.
3. Localisation of change was considered important in allowing existing products to be upgraded through the retro-fit of new modules. The psu and processor boards could be used in existing products and the 1553 capability could be retro-fitted into the existing coil-cord compatible designs.
4. Supplier capability allowed modules to be sourced completely from one supplier thus increasing economies of scale, reducing administration overheads, and providing a better working relationship with the suppliers. Boards are sourced complete from suppliers, so too are mechanical component packages.

In addition to module identification, interfaces were also identified and analysed. This was especially important between the generic element that would now become a platform for future products, and the dedicated elements for those products. The capability for a new interface standard was also included to enhance the flexibility of the design, improve ease of operator use, and reduce complexity and stockholding. This capability could also be retro-fitted to the existing products. In addition to the mechanical interface capability, a new protocol was considered that would further enhance the flexibility of product operation and integration of new products.

Once module concepts were agreed, a rough geometric layout was performed to ensure module fit, and compatibility with the existing equipment and products. This was especially important due to the constraint of probe diameter with respect to the pressure casing with which they must be compatible, and the need for new product modules to retro-fit existing products.

Finally the proposed modules were checked against the technical specification. It is important to ensure that the requirements are being met at an early stage when changes are relatively straight forward and economic.

Once signed-off the product went onto detail design.

Additional Strategy Influences.
In addition to the specific modular features of the strategy there were a number of complimentary initiatives to improve the development process.

Component standardisation was employed wherever possible to ease manufacture and assembly, reduce stock holding and part inventories, and provide greater economies of scale.

Total procurement was employed to source modules complete from individual suppliers. This often forces suppliers to secondary source components in order to deliver the complete package but ensures that the supplier will retain the business. This was accompanied by a rationalisation of the supplier base, and a shifting of responsibility of component quality from SSDS Cheltenham to the suppliers.

Manufacturing input in now much earlier in the development process, and manufacturing now manufactures the prototype products, as oppose to engineering, so that real production problems can be identified earlier.

Benefits.

The benefits gained from the implementation of this new modular strategy have been widespread. They are presented here in relation to the four areas introduced as issues to be addressed in the Background section.

Efficient Deployment of Customer Requirements.
New product development is much simplified. The reuse of modules reduces the engineering effort required to realise a new product.

Shorter development times are realised through the reusability of the modules in future products. This ensures that the customers needs are met quickly.

The modules have been designed with forward compatibility in mind and so allow for future upgrade with reduced engineering required. Thus future customer requirements are being addressed pre-emptively.

Existing products can be upgraded with greater efficiency and without trouble to the customer due to the ability to retro-fit modules with new features into old products.. Thus customer requirements can be met with the minimum of disruption.

Structured Approach to Dealing with Product Complexity.
A modular product allows the complexity of the product to be decomposed into more manageable portions.

The reduction in interfaces and provision of generic modules simplifies the use of the product by the operator.

A generic element helps manage complexity by partitioning areas of dedication and variety. This then simplifies engineering, manufacturing and service tasks.

Upgrades can be introduced in localised areas and thus reduce the complexity of the engineering and the associated replacement task.

Rationalised Introduction of New Technology.
The use of modules provides the capability to swiftly and economically replace existing technology with upgrades without the need to re-engineer the whole product.

New technology may also be introduced to existing equipment in this manner to upgrade products whilst maintaining backward compatibility.

Flexible or Agile Manufacturing.
A generic module reduces the part numbers and part variety, thus reducing stock holding and parts inventory.
A reduction in part variety increases the economies of scale for orders of parts that are required.

Assembly is simplified with reduced part numbers, reduced part variety, sub-assembly manufacture, a generic assembly to most products, and the introduction of variety late in the assembly process.

Simplified testing of products as modules can be tested separately and also by the supplier. There are also less varieties of products to test. The generic element also reduces the requirements for test tooling and facilities.

The build plan can be easily changed as the modular products have the variety introduced at a late stage and so are not dedicated to an order.

Supplier usage has been rationalised and their involvement increased. This new relationship allows for the sourcing of modules complete and pre-tested, reduces lead times as the supplier will hold stocks due the increased confidence for orders, and improves component quality and continuity.

Manufacturing are involved at an earlier stage and so manufacturing and assembly difficulties can be addressed well in advance of full production.

General.
Administration and documentation overheads are reduced through standardisation and generic modules. Thus one set of detail drawings, assembly drawings, and less component orders.

A closer knit and more motivated development operation with engineers more appreciative of functions outside their own.

An emphasis on finding and addressing problems early.

Future Opportunities.

Though this move has improved many aspects of the development process within SSDS Cheltenham there are a number of areas that are to be addressed in a process of continuous improvement.

1. The development and documentation of a formal development process and strategy. The process would detail the stages of the product life cycle including service and disposal. The process would clearly identify deliverables for each stage and consist of a number of formal reviews, that must be passed in order to move on. The process would be familiar to all employees and would aid in managing the time, quality, and cost of product development.
The strategy would be the objectives for future product development, and include the plans for proliferation of the 'platform' modules developed. New product timescales, detail idea feasibility periods and implementation dates, the introduction of procedures, a "what we aim to do and by when" document. These would ensure that development is at least partially pro-active rather than reactive.
2. It may be useful to set a life span for products to compromise on the backward compatibility vs. upgrade trade-off.
3. Some work should be done into improving the capturing of requirements. It is difficult to provide products that are meeting customer needs when it is not known what the customer really wants. In addition if the customers know that they have been formally consulted on a new product it is more difficult for them to justify that their needs have not been met. Questionnaires, interviews, group meetings, and operational experience will have to be combined in order to build up clear and applicable requirements lists.
4. The proliferation of standardisation practice to individual components. The development of a preferred components list is one proposal to deal with this in a convenient form. Standardising on components through put the product range would further increase the benefits seen for the standardisation between the PCD and PCG.
5. Increased and earlier involvement of suppliers in the development process. This is already in process and should be maintained.
6. Improved documentation management. If design processes, formal reviews, product strategies, and preferred components lists are to be successful there must be some way to efficiently manage the documentation. The documentation has to be maintained and reviewed itself periodically, it has to be disseminated to ensure all employees are familiar with their role and the overall picture, and it has to be conveniently accessible otherwise it will be all too easily ignored. The use of the companies own intranet provides a possible suitable medium, but could potentially do with someone who's sole responsibility is this function.
7. Further investigation into the possibilities for modularity within products. Could the power supply unit and processor be developed as a universal module in its own right. The number of connections was mentioned as a problem in this regard (24?) but it may offer further benefits if it could be achieved. Could this then be used with the Gyro-MWD tool? Will the Gyro MWD tool use the PCD / PCG spine and psu / processor boards?

The following series of tables represent the Sperry-Sun completion of the self-analysis section of the workbook concept in its infancy.

Sperry-Sun Drilling Services, Self Analysis Results.

R1. Suitability Review - to ascertain if the product is suited to a modular architecture.
R2. Level Review - to ascertain the level of modularity most suited to the product and company.
R3. Groundwork Review - to ascertain if some of the basic requirements have been met to provide the groundwork for modular design.
R4. Driver Review - to ascertain the reasons or drivers for moving to a modular design, and provide recommendations tailored to the results.
R5. Product Review - to ascertain the possibilities for modularity, and highlight key elements.
R6. Manufacturing Review -to ascertain how current facilities and practices may effect modularity.

Suitability Review (R1):

Please tick as appropriate.

Weighted as **Very Important**	yes	no
1. Does your product require a highly optimised functionality, such as that offered by an integrated design?		✓
2. Would an increase in functional interfaces in your product be a problem?		✓
Weighted as **Important**		
3. Do you usually manufacture products in a range (not one-offs) that may have possibilities for standardisation between them?	✓	
4. Is it likely that part of your product could go through an attribute change during its life cycle?	✓	
5. Is it likely that part of your product could be common throughout a range of products?	✓	
6. Is it likely that your product could be upgradeable through interchange of localised units?	✓	
7. Is it likely that your products could make use of carry over parts or sub assemblies?	✓	
Weighted as **Relevant**		
8. Is it likely that part of your product will go through a technology shift during its life cycle?	✓	
9. Is weight of relatively little importance in your products?		✓
10. Is size of relatively little importance in your products?		✓
11. Is it likely that trends or fashion will alter part of your product during it's life cycle?	✓	
12. Do all parts of your product have similar lead times?	✓	
13. Is it likely that any part of your product could be a bought-in assembly?	✓	
14. In Fig.7. below. Does your company fit into the left hand side of the grid?	✓	
15. Is it likely that any recyclable parts of your product could be located together?	✓	

Level Review (R2):

Please tick in order of magnitude. (5 is high)

	1	2	3	4	5
1. How often do parts of your product need to be reengineered due to new technology, trends, or specific customer requirements?				✓	
2. If parts are reengineered, how often, and how large are the changes?		✓			
3. To what extent is product configurability in terms of functionality to meet specific customer need important in your product?					✓
4. To what extent would any common elements between products need to be in different geometrical locations?				✓	
5. To what extent does the complexity of your product hinder it's design and manufacture?			✓		
6. To what extent are a number of functional interfaces acceptable in your product?			✓		
7. Does your product require a high degree of maintenance or service to many parts?		✓			
8. How much of an existing product would be carried over for use in the next model when a considerable architecture change is made?				✓	
9. Is modularity likely to be used as a major design methodology for your products, rather than for a few 'bits and pieces'.				✓	

Groundwork Review (R3):

Please tick as

	yes	no
1. Does your company run an active concurrent engineering programme, using multi-functional teams?	✓	
2. Does your company have a defined product introduction process in place?	✓	
3. Does your company have a clear view of their corporate strategy and objectives?	✓	
4. Does your company have a clear product plan?	✓	
5. Does your company organisation allow for easy; use of multi-functional teams, communication, adoption of ideas?	✓	
6. Does your company know it's reason for developing a modular product?	✓	
7. Is your companies product suited to a modular architecture? (See review R1.)	✓	
8. Is your company committed to providing upfront effort and accommodating the changes required for this process?	✓	
9. Have you an idea of the level of modularity suited to your product? (See review R2.)	✓	
10. Have you analysed your current situation in terms of products and future plans / corporate strategy and how they fit with a modular philosophy?	✓	

Driver Review (R4):.

Please place in order of preference.

1. Standardisation.	**3**
2. Carry over.	**10**
3. Ease of assembly.	**7**
4. Ease of upgrade.	**8**
5. Ease of service.	**4**
6. Reduction in reengineering.	**5**
7. Ease of project management.	**9**
8. Reduced lead time to market.	**2**
9. Ability to buy in modules.	**6**
10. Consistent quality.	**1**

2 COMPANY CORRESPONDENCE

Dave Haynie (VP Engineering, PIOS computer manufacturer) correspondence regarding modularity.

Date: Thu, 12 Jun 1997 11:15:55 -0400 (EDT)
To: Russell Marshall <R.Marshall@lboro.ac.uk>
From: Dave Haynie <dhaynie@jersey.net>
Subject: Re: Modularity.

On Thu, 12 Jun 1997 12:25:03 +0100, R.Marshall@lboro.ac.uk (Russell Marshall) yammered on about:

> I have been following various discussions on comp.sys.amiga.x newgroups and together with the Pios web pages it seems fairly obvious that the modularity of the One, and the concept in general is an important issue to you.

> The main reason that I'm mailing you is that I would appreciate your opinions on modularity, why you think it is important to your work and how you actually went about applying a modular philosophy, if I can call it that. I guess most of you work is working toward a concept you have in your head, but did you follow any kind of procedure or get any guidance from anywhere?

Nothing beyond observations. I started down the modular path back at Commodore. While it never was released, in 1991 I designed a new system architecture, internally called "Acutiator", to replace the Amiga 3000 architecture we had used in several machines over the years. I guess a good deal of these ideas at PIOS today came from this. The problem we had at Commodore was that we were just plain small, compared to Apple, much less the whole PC industry. And yet, every time the system architecture changed, we wound up reinventing most of it. And because (mainly due to cost concerns driven by the mid-to-late 80s technology we had to work with) our systems were so horizontally integrated, we necessarily had to make changes all over just to modify some small features. Or, more likely, we wound up kludging around the chip designs with expensive external parts (like the IDE port in the A4000).

So I started building a new system architecture, predicated on the idea that chip technology was advanced enough to support vertical integration. To help this along, I designed a low pin-count, CPU-independent, high performance 32-bit bus called the Amiga Modular Interconnect (AMI bus). A system motherboard would supply the basic I/O (most of which hadn't changed all that much since the C64 days) and an AMI bus backplane, which would take modules to provide the CPU, graphics, and other high performance pieces.

I guess I was influenced here by need -- we knew that the next generation systems (expected in the '94 timeframe, this was before C= really started its downward spiral) would necessarily ship with 680x0 CPUs, but would have to transition to some RISC processor along the way. This made it pretty clear we couldn't use a CPU bus to provide the modular interconnect. And the complexity of CPU bus modules in the A3000, which did base its local bus on a modified 68030 bus, also made this point fairly clear -- the needs of a CPU bus are not the same as the needs of a modular interconnect bus.

Alas, only small bits of work were done on this in 1991; I had several other projects, and the one engineer I had helping out was basically just helping out when he had nothing else to do. In mid-92 Intel released the PCI specs, which strangely enough set out to solve the same problems. So I started to switch the architecture specs, dropping AMI bus in favor of PCI. That's about where it was left, by the end of the year things weren't looking good for Commodore, and it was clear we weren't starting on any new projects.

The PIOS One design resurrects much of this basic concept. When you look at things that change in the computer business, the basic I/O is pretty stable over many CPU and graphics generations. So it's necessary to make the CPU modular, and that really has to incorporate the entire CPU subsystem to be effective in the long term (CPU, CPU bus specifications, main memory, cache, etc). One interesting benefit of this is that, just as in the AMI bus system, when you build a PCI machine this way, you get a PCI machine, independent of any specific CPU -- it's just as easy to build an Alpha or 80x86 modular as another flavor of PowerPC. The real important thing here is that we've factored out one of the pieces that changes most often, and since it's less work for us to build just this changed part than a whole new system, we can react faster, offer more variety, etc.

> Getting your opinion is very useful to me, as well as interesting, as evidence of the usefulness of modularity gives my work foundation.

It's providing flexibility in several dimensions. Graphics is another thing -- it changes constantly, I think the average life of a graphics chip at the high end of the marketplace is about a year (it may live on another few as a lower-end chip, unless its too expensive to make). Some people demand the fastest systems, others build them over time. Again, a highly modular system can react to changes faster.

The other thing is the bundling options. In a traditional system, maybe you can offer a high-end motherboard and a low-end motherboard, each with a range of CPUs. I can do that with one modular motherboard and two CPU modules. If I build a different motherboard, now I have four basic systems. One more CPU card, and I get six. That makes it easier for a small company to justify building a high-end system, for example (something Commodore was never comfortable with), and it makes it easier for us to meet consumer demand with less resource. It's good on the consumer end because they never have to upgrade the whole computer, just a piece at a time. It's likely we can even offer some kind of trade in, since the old CPU modules or motherboard could certainly be offered back, at least as refurbished units.

One of the problems with this model for the mainstream computer companies is that their business model doesn't mesh well with this. They have built their business based on the idea that systems get obsolete, and so they're not so likely to be offering modular machines (in fact, in the PC business, they've been moving slightly away from modularity, though in part thanks to cheap, highly integrated basic I/O).

At Commodore, we were basically forced to adopt this concept, though not always by design. The Amiga 2000 was sold for about five years, first unbundled, then in the Amiga 2000HD, Amiga 2500/20, and Amiga 2500/30 bundles. It went from 7MHz 68000 up to 25MHz 68030, and today you can go out and get 68060 boards at 50MHz for it. The implementation of this CPU module was fairly primitive (and I say that as the guy who designed the CPU-module features on the A2000), but the concept was valid.

Strangely enough, the industry seems to be flirting more and more with this concept, at least in their own special ways. PCI clearly caught wind in the industry as a better I/O bus, but the clear goal of Intel in my mind was "modular interconnect" at the get-go (both based on the functional similarities to the AMI bus, and the fact that PCI 1.0 didn't even define an expansion slot). And PCI 2.0's concept of multiple PCI buses was brilliant; it extends the modular metaphore into card design as well as backplane design -- back to the chip-to-chip idea PCI 1.0 spoke to.

Now the world's starting to "get it" with this. Intel themselves just introduced their own spin on a CPU module with "Slot 1" -- clearly a module designed to a chip company's tastes, not a system house's, but it makes some sense. At least there is a level of abstraction now between the connector and the CPU, you're no longer counting on supporting a particular packaging or a complete bus architecture. Motorola's offering a PowerPC upgrade socket standard that uses a PGA socket -- only Motorola doesn't make a PCI packaged PowerPC chip. This is designed to support a variety of different CPU modules, where, like with the Intel module, a PC board and small secondary logic address any changes in the CPU bus. In fact, these modules support two CPUs.

I guess I'm concentrating on CPU here, because that's the last real part of the modular puzzle that hasn't been adequately addressed by industry yet, in most consumer computers. The trick is to introduce a connector that's not going to affect performance or add significant cost. I went to PCI, since that adds the CPU independence. And really, PCI is shaping up nicely as the modular interconnect I wanted six years ago. A big part of that is, of course, that its widely accepted. We're getting very close to the point where a single chip does every function in the system. Already, I have the single chip controller for the CPU card: the MPC106 in the PowerPC case: it does memory, PCI bridge, cache, bus arbitration, etc. Intel makes a similar one for x86. There are plenty of single-chip graphics modules (just add memory), and already several sound chips, which use main memory. In my system, the "basic I/O" actually occupies two chips, but I just read about a new part that does virtually all of the basic I/O for motherboard stuff in one PCI module.

You see, once you get the modular concept, how it's applied everywhere. I'm designing in conceptual modules, and I can make a system different by changing what I include, or even roll my own if that makes sense. This carries up to the user, who's viewing "module" as "board" rather than "chip", though in many cases you're talking little else than "chip on board". One nice thing about PCI is that there's not logical difference in location -- module is module, whether on the motherboard or on a card.

> If you are interested I would be happy to send you a copy, and would be especially grateful for any feedback you could give.

Yeah, that sounds interesting. I think a good deal of this, conceptually, is just rehashing the old industrial revolution ideas. Once you didn't have to hand-produce parts for each gun, or each machine, but could stamp them out on a production line, modern industry became possible. I think the same things are taking form to create a similar revolution in information technology. This extends well beyond the computer, though rarely eliminates it. Look at the last two "bus" standards to gain big notice: USB and Firewire. Both of these automatically, dynamically configure themselves, support many devices (128 on USB, 64 on Firewire), and are as simple to connect as a telephone. This is what get computer- like things happening outside the computer, in terms of smart component modularity. Folks would scream about having to pop the VCR casetop off and install cards for some new feature, but they already know how to plug things.

Dave Haynie | V.P. Engineering, PIOS Computer | http://www.pios.de Be Dev #2024 |

Correspondence from Pete Leaney (Operations Manager, Sperry-Sun UK.) regarding the modularity process report.

Date:Fri, 4 Apr 1997 08:34:50 -0600
From: leaney@HOU.SPERRY-SUN.COM
To: R.Marshall@lboro.ac.uk (Russell Marshall)
Subject: Re: Modularity.

Russ,
Up to my neck in it, as usual. Read your document and it looks good. I've yet to pass it around for comment here, I'll do that and get back to you with any comments. I'll also get the questionnaires completed in the same time frame. About two weeks.

Regards,
Pete

Correspondence from John Elvidge (Ford Body Electronics Engineer) on the Systems engineering & HPD workbook.

Telephone conversation 5th Aug. 1996.

- The systems engineering that they follow has a world wide customer requirements document, that combines all the requirements for the electronics systems of the vehicle.
- They no longer consider components as such, but rather subsystems.
- They use what is known as the SDS subsystem design spec.
- The SDS defines all the inputs / outputs of a subsystem, and also the table of requirements for that subsystem, required form whom, by whom etc.
- There are no strict rules on how to fulfil the requirements, just that the requirements be met.
- The suppliers get involved very early in the programme (the Advanced Stage), 2-3 years prior to job 1.
- The requirements have widespread implementation and input from all departments, and suppliers etc.
- JE is currently working on the body system for Jaguar vehicles, specifically the 2dr coupe (6 modules) and 4dr saloon (8 modules) -XK8. The body systems includes, wipers, door mirrors, alarm and lights etc.
- Multiplexing is well established. It has been used by BMW and Mercedes in engine management etc for 4 years.
- Multiplexing is not so well established in less complex systems such as lighting, and door mirrors (that are easy to hardwire), and in vehicles of low specification, with minimal functionality. Jaguar, yes, Fiesta, no.
- Multiplexing’s main advantage is that it simplifies complexity.
- They try to use carry overs as much as possible but they are fairly poor at it. Raised the point at what level do you look at carry overs; standard components on a pcb, standard boards, standard modules, the further you go the harder it is to implement.
- The time savings and reduced engineering cost from the use of carry overs is considered valuable.

Date: Fri, 24 Jan 1997 06:28:46 EST
From: "John Elvidge
To: R.Marshall@lboro.ac.uk,
Subject: HPD Workbook Feedback (Part 1)

Russ,

Here is some feedback on the workbook that you provided to me. I hope that you find the notes useful - although in some cases I almost feel like I'm splitting hairs over wording! Please call if you have any further questions regarding my comments or if I can help you in any other way.

Regards,
John Elvidge

Version 0.6 16/12/96 Holonic Product Design

The term "Holonic" is only available as a definition to readers who make it to the Glossary (P36). It might be a useful "come-on" to give a flavour by putting a definition on the cover. It could also be quite "artistic" to pull a dictionary-definition-style block below the title but above the "crest" text.
Cover, Para 2
"and also the manufacturing system is designed" -->> "and the manufacturing system is also designed"
Cover, Para 3
"Building upon ... company's PIP."
- break this sentence after "... to individual situations".
Cover, Para 4
"Full benefit ... level of modularity."
- break the sentence (& para!) after "... and systematically".
Page 4, Para 1
"In addition this new way of product design and manufacture..."
- Beware of labelling something as NEW because readers will immediately become agitated if they find any component part that they recognise as not new or if they can equate the description to something with which they are already familiar.

Perhaps, "... an alternative perspective for product design & manufacture..."
Page 4, Para 2
"This provides a basis ..."
- You don't identify WHY many companies are accredited to BS5750. What does it provide? You tell me what BS7000 does for me!
Page 4, Para 2
"Once the generic PIP is established this then allows it to be related ..." --
>> "Once the generic PIP is established it is related ..."
Page 5, Para 2
"... new look ..."
- Better than "... new way ...". "... fresh ..."?
Page 7, Bullet 3
"... multi-disciplinary and is extremely ..." -->> "... multi-disciplinary and THIS is extremely ..."
Page 7, Bullet 7
"The use of techniques such as ... is encouraged in the design process."
There is a definite need to clearly, concisely, completely and correctly capture all customer requirements up front. These will form the basis of the product's success in the market and, after transformation into engineering parameters, will define the measurables of the product design. The design measurables must be available in time for concept selection from a number of possible product designs.
Page 8, Para 2
"During the Analysis of opportunities ..."
It might be useful to introduce some reasons why corporate strategy changes are necessary and the benefits that will be gained. Otherwise, corporate strategies have a terrible habit of not changing for the better!

Page 8, Para 3
"The project must also fit ..."
I would contend that modularity can be introduced purely to ease feasibility of design, manufacture, testing or serviceability and modules NEVER be re-used for any other purpose.
Page 9, Para 2
"... where such criteria as weight, size, and complexity are an issue, a modular design may not be suitable aim." (sic).
Complexity is one of those cases where modular design IS very important both at the design and the manufacturing levels. It also has a high impact on stock levels, tied investment, parts for service and serviceability. Modularity is one way to reduce complexity.
Page 9, Para 3
"At this stage a level of modularity must also be agreed. ... A decision must be made to the required level and then adhered to."
Yes but a little more elaboration would be useful. Who agrees to what? What are the necessary levels? Are we talking just design or should manufacturing be involved? What about corporate strategy "buy-in"? It's a little bound up in company structure and "politics" but it would be very interesting to have some guidelines in the text. Also, I don't think sentences end in "to"!
Page 9, Para 3
"to one module ... provides less flexibility but has less complexity"
A single module containing a number of functions is not a major detractor from flexibility if the module is generically applicable due to "universal" interface properties and internal re-configurability / programmability (viz. gearbox with replaceable ratio cogs, electronic control unit with programmable processor, CNC manufacturing rig with interchangeable tooling, etc.)
Page 9, Para 3
"... and would be more robust;"
Even replacing "robust" with "reliable" (they ARE two different ideas), I don't see the truth of this statement - the space shuttle has 3 separate systems voting to provide reliability. Robustness can only be designed in by producing a system that is insensitive to the noise factor against which it must be robust - irrespective of number of components.
Page 9, Para 6
"it may be useful, if possible, to ..."
Very true. This is especially important as regards legislated requirements or anything related to product liability.
Page 10, Para 1
"... to clearly define ..."
Where shall we boldly go when we have clearly defined?
Page 11, Para 1
It is also true that the team may change with time. The initial team must focus on product requirements - both customer wants and the business case for the company. These will be familiar with the product function as seen by the customer. Later the team may change to include experts in attributes of the various modules i.e. experts in power, plastics, mechanics, electronics, aerodynamics, packaging, fasteners, etc. These design attributes may not be immediately apparent at product conception.
Page 11, Para 4
"Where products with a high LOM ..." and following bullets.
Beware of pushing for a collection of re-useable modules over a small number of optimised components. The balance is OK so far.
Page 11, Para 5
"The documenting of key elements ..."
Again, legislated requirements (both current and predicted) can have high impact on partitioning and hence product design.
Page 12, Para 2
"The team must produce a diagram ..."
In the majority of cases it is useful to run with multiple concepts in the early stages of the product lifetime. It may be possible to create a generic schematic as you suggest and I especially like the idea of desribing costituent elements using only two words (verb + noun) such as "provide electricity", "generate heat", "rotate wheel", "increase torque". This leaves the design process wide open to innovation.
Page 13, Para 6
"... are termed natural modules, those such as power supply units and electronic packages.."
Page 13, Para 6
"... fall outside of the core business to be ..."
Core business considerations are as important as supplier capability. You might want to elevate this point.
Page 13, Para 8
"Re-configurability" is also very important. If a single module is re- configurable then it may be used over & over in the SAME product (i.e. a microprocessor instead of logic circuits or multiple identical CNC machines instead of many different bespoke machines) even if one or more individual instances incur higher cost.
Page 13, Additions
Other factors that you might wish to include are:
- Testability / serviceability have major impact on modularisation / partitioning decisions. There is a need to minimise scrap or component replacements, increase diagnostic capability, reduce the number and cost of spare parts inventory, reduce "service items" bills, etc.
- Cost, a big hitter in it's own right.
- Failure modes and effects analyses - enough said!
Page 14 - to be continued.
Regards,
John Elvidge, Jag SCP Sys Eng, |

Date: Tue, 04 Feb 1997 09:07:19 EST
From: "John Elvidge
To: R.Marshall@lboro.ac.uk
Subject: More Workbook Notes

Page 14, Figure 6
It may be useful to indicate that carry-over modules should have interactions already defined.
Page 14, Para 7
In "Create a Rough..." you talk about physical entities. You might like to consider how HPD could be applied to modular processes i.e. an administration system. This would make it a truely generic process. On the other hand, it may be beyond your envisaged scope: your call.
Page 15, Para 1
Note that in many cases (if your recommendations are followed) the modules will be carry-over with existing specs. It is necessary to check that there are no incongruities pulled in.

Page 15, Bullet 6
Ease of manufacture and assembly are always considerations irrespective of modularity but it doesn't harm to mention it here.
Page 15, Bullet 7
"assemblable"?
Page 15, Bullet Addition
Another good practice is to use existing standards. (Modular standards?)
Page 15, Para 3
Software Considerations are many and varied. They are also too complex address significantly here. Some references to good practice standards or standards bodies would be useful. It might be useful also to highlight some of the pitfalls that software can create: Many people consider software to be effectively free, infinitely adjustable, changeable at the last minute and an ideal way to compensate for shortfalls in the basic design. The truth is that software complexity increases dramatically as the problem complexity goes up and, particularly due to temporal dependancies in real time systems, can have extremely complex failure mechanisms that appear to be randomly rather than deterministically (as all digital software must be). This can thwart traditional debugging techniques (single stepping, etc) unless operated with a specific view to time dependancies. Also, as the number of decision points in the software increases, the number of paths to be tested can increase exponentially. This requires a very rigorous design and test philosophy based around, you guessed it, software modularity. Suffice to say that software requirements must be handled at least as, if not even more, carefully than requirements for complex mechanical or electronic system.

Page 16, Para 1
"... that can easily or economically forgotten, ..." -->> "... that can BE easily or economically forgotten, ..."
Page 16, Para 1
"synergy" rather than "sympathy"?
Page 16, Bullet 1
"... associated features; redundancy ..." -->> "... associated features: redundancy ..."
Page 17, Para 2
Sentence 3, beginning "Some of these influences ..." doe not appear to be correctly written.
Page 17, Para 4
"Making things right." -->> "Making things CORRECTLY." surely! It might be worth mentioning some of the tecniques / buzz words like "zero defects", "right first time", "kaisen", etc.
Page 17, Para 5
Smaller modules with fewer parts are usually easier to make correctly.
Page 17, Para 6
"Making things fast." -->> "Making things QUICKLY." ?
Page 17, Para 7
"... Speed Advantage through the ease of assembly..."
There should potentially be speed advantages from reduced tooling, reduced parts inventory, reduced part count, reduced number of process operations, .etc.
Page 18, Para 1
"Changing what is made." -->> "Changing THE PRODUCT."!
Changing a product that consists of many repetitions of basic blocks or processes does not rely upon checking each repetition of the basic element. The element can be verified once. This is also an advantage for "Making things correctly".
Page 18, Para 3
"... lower than competitor ..." -->> "... lower than A competitor "
Page 18, Para 4
A component cost increase (due to buying components externally rather than making in-house) is often more than offset by the savings of investment and manufacturing expenses associated with making that component in-house. Also, it may also be beneficial to place the burden of investment in technological expertise onto suppliers and pay increased piece cost.
Page 18, Para 6
"... (Greenhalgh 1991), and it's key ..." -->> "... (Greenhalgh 1991), and ITS key ..."
Page 19, Para 3
... over the time horizon considered ..." -->> "... over the time PERIOD considered ..." "horizon" implies an event; period implies a duration.

Regards,
John Elvidge, Jag SCP Sys Eng, |

FROM: John Elvidge
Subject: HPD Workbook Feedback.

Russ,

Thanks for sending the latest version of your HPD Workbook; I had no problems extracting the file back to Word format.
My perceptions / overall assessment of the workbook is as follows:

The workbook takes a very realistic approach to recommending product modularity that avoids the pitfalls one might associate with "trends" or “fads" being touted by consultancies for profit.
The workbook addresses key business aspects in order to ensure that the user has suitably questioned whether modularity is a suitable approach for a particular business situation.

It addresses "The Legacy Factor" in a straightforward manner that is unlikely to alienate personnel who might be associated with such factors - important if their buy-in is to be gained for future actions.

The checklist approach will be familiar to most company process champions and will be easily integrated with existing reporting formats. Indeed, it bears resemblance to some APQP (Advanced Product Quality Planning) formats in Ford. And this supports one of the main aims of the workbook - easy integration into a companies existing Product Introduction Process.

However, key to the success of the workbook is the "Guidelines" section that provides a summary of the critical detail in easily identified, digestible nuggets. Not scary at all!

Congratulations and every success with your thesis.

Regards, John Elvidge,¦EMail:jelvidge@ford.com
Systems Engineer, Ford ACD, ¦PROFS:jelvidge

Correspondence from Harry Longman (Manufacturing Manager, BUSM) regarding the HPD Workbook.

Date: Thu, 12 Dec 1996 05:48:09 -0500
From: Harry Longman <106221.452@compuserve.com>
Subject: HPD workbook
To: Russell Marshall <R.Marshall@lboro.ac.uk>

Thank you for the latest version. I think much of it is very valuable.

My only comments are on the checklist which I found confusing: "Is it unlikely that..." Could this be turned into positive logic?

Can the implementation guidelines be collected in sections rather than 38 individual items?

Can you advise on the DISadvantages of HPD, and where these may override the modular route, eg by imposing extra costs of interfaces or of redundant elements in modules to handle unused options?

Regards, Harry Longman

Date: Fri, 31 Jan 1997 07:29:04 -0500
From: Harry Longman <106221.452@compuserve.com>
Subject: HPD
To: Russell Marshall <R.Marshall@lboro.ac.uk>

Thank you for the workbook which arrived today, and for the improvements you have made. I will attempt to use this on the next project, but this does not yet have a start date.

Date: Thu, 20 Mar 1997 11:49:12 -0500
From: Harry Longman <hlongman@compuserve.com>
Subject: Any progress?
To: Russell Marshall <R.Marshall@lboro.ac.uk>

Dear Russell,

We have not started the LSH project and I cannot give a date to start. We have started some cost reduction work which will give us some directions for the main machine. I cannot promise to give you much feedback for September!

I have looked through the book again, and have noted a general improvement in structure, layout and content. I believe that what you are saying is extremely valuable and you have said it in a thorough and systematic way. You have considered the implications right through from business and marketing strategy to manufacturing and beyond.

You refer to a number of design methodologies such as DFA, Pugh and QFD. How do you see HPD being integrated with these? The problem for design teams is information overload. Where do they all fit together? HPD could be applied as a "filter" for design concepts, but would lose some of its impact. Can you build it into existing techniques so that it becomes a core part of the process? I am trying to work out how HPD can be taught, learned and applied in practice.

Hope this is helpful.

Regards, Harry Longman

Correspondence from David Bygrave (Principal product engineer - Crosfield Electonics) regarding the HPD workbook.

Return-path: <david.bygrave@ffei.co.uk>
Envelope-to: enrm6@sun-cc201.lboro.ac.uk
Delivery-date: Wed, 1 Oct 1997 16:37:01 +0100
From: David Bygrave <david.bygrave@ffei.co.uk>
To: Russell Marshall <R.Marshall@lboro.ac.uk>
Subject: Workbook
Date: Wed, 1 Oct 1997 16:31:00 +0100

Hi Russell,

Yes, you are right, we have changed our company name!

FujiFilm (yes, the photo film makers) bought us outright last March. We are now called FujiFilm Electronic Imaging Ltd., or FFEI for short. If you want to find out more, we have a Web Site:

http://www.ffei.co.uk

We are continuing to manufacture some of the old Crosfield products, but badged FujiFilm. What is exciting though, we are the European Manufacturing site, with R&D based at Hemel Hempstead. This implies that we can look foreword to bringing over to the UK for manufacture some existing FujiFilm products from Japan as well as developing our own!

Maybe influenced by the our Japanese bosses, but Engineers generally are now just starting to use well known tools like Pugh, QFD and indeed Taguchi! This leads me into the Workbook....

Well done, clearly there has been a lot of work in this. There are areas in the book that are relevant to the work I used to do, but as you know, I was effectively a one man band in what was a very difficult organization to influence for other applications. I think there will be an appetite to use these in the future, but I think our people are trying to get their minds around QFD, Taguchi and so on first. I would predict that maybe in 6-12 mths time we will be mature enough to want some HDP.

In the meantime, I have sent a copy to my colleague working on a new product - if there is any feedback I will let you know.

By the way, I am now working not so much on new products, but more on Supply Chain Engineering.

All the best

David

E-mail: david.bygrave@ffei.co.uk

From: David Bygrave <david.bygrave@ffei.co.uk>
Subject: RE: Phoenix modules.
Date: Thu, 4 Dec 1997 16:20:00 -0000

Russell,

Sorry about delay in replying, but you know what it's like.....

We defined a total of 20 Modules for Phoenix, but at the end of the day, those that were the major contributors to the product I've identified with '*' , as follows:

Top Skin
Bottom Skin
System PCB*
PSU*
Fans
Magazine Drive*
Base Casting and Guides*
Carriage Drive*
Lens and Focus Drive*
Traverse Carriage*
Camera Head*
Copy Load Mechanism*
Filterwheel + Lamphouse*
llumination Optics*
Keyboard & Display
Cable Loom*
Core Packaging*
Support Packaging
Magazines (Not paper type!)
Copy Holders

I have a crude picture which I'll fax - what's your Fax No?

The forerunner was called the Magnascan Scanner.

Business is looking very much better now we are totally FujiFilm. I guess the biggest impact is the very strong corporate drive for Quality. Both internally and our Suppliers have gone through hell and back in the demand to have product to specification. It has been worth it though - the orders are now rolling in!

When do you complete your Ph.D., I'd like to see your Thesis?

All the best.

David

P.S. We are looking for well qualified graduates - interested?

Design Modularisation Survey

Russell Marshall. 16/04/96

Department of Manufacturing Engineering,
Loughborough University.

Operational Questionnaire

This questionnaire concerns research being done into the topic of modular design, where a product is developed from self contained assemblies to; allow easy configuration and modification, and be friendly to agile manufacturing practice. This questionnaire is aimed at the technical / implementation level employees within your company and is related to a second questionnaire aimed at a corporate level and is an attempt to identify if there is a need for modular design, and how this need may be addressed. The questionnaire is part of research being performed into this topic leading to a PhD currently being taken in the Department of Manufacturing Engineering at Loughborough University. I would appreciate it if you could take the time to complete the questions and return the questionnaire directly to the address below, as it should only take a couple of minutes.

I will also provide a breakdown of the responses to all replies received.

Thanks,

Russell Marshall.

Please post to:
Russell Marshall
Department of Manufacturing Engineering,
Loughborough University,
Loughborough, Leicestershire,
England, LE11 3TU.
Tel : +44 (0)1509 222929, Fax : +44 (0)1509 267725
email : R.Marshall@lboro.ac.uk

General Section

Q1. Please fill in the details below.

Your Name	Address for correspondence ....
Job Title	....
Organisation	....
Department	....
Telephone	....
Fax	Country .... Postcode..................
E-mail	Date completed ....

Q2. Please describe your job content and responsibilities.

....

....

Q3. In what type of industry is your company involved?

....

....

Q4. What mode of production does your company employ?

please tick one

One offs	☐	<u>Any Comments :</u>
Small batch	☐	
Large batch	☐	....
Large volume	☐	

Q5. How many products do you have in development at any one time?

please tick one

1	☐	<u>Any Comments :</u>
2	☐	
3	☐	....
4	☐	
5 or more	☐	....

Q6. How many of your current products share the same or similar features but have probably been repackaged due to modifications?

please tick one

1	☐	Any Comments :
2	☐	
3	☐	....
4	☐	
5 or more	☐	....

Q7. What is the importance of the following aspects of your business strategy in order to retain competitiveness?

	Very Important	Important	Desirable	Not Important
Flexibility of product	☐	☐	☐	☐
Reduction in overall time to market	☐	☐	☐	☐
Increase in added value	☐	☐	☐	☐
Reduction in design changes during development	☐	☐	☐	☐
Reduction in product cost	☐	☐	☐	☐
Flexibility in product range production	☐	☐	☐	☐
Other (please specify)				
....	☐	☐	☐	☐
....	☐	☐	☐	☐

Q8. Do you work on a single project at a time, or are you responsible for a particular area over several projects?

....

....

....

Q9. What experience / knowledge do you have of manufacturing or design issues?

....

....

....

Q10. What do you think are the major drivers in terms of design improvements within your company? Please rank them in order or priority (1 for the highest through to 11 for the lowest)

Reducing the number of parts	☐
Reducing cost	☐
Improving performance	☐
Improving ease of manufacture	☐
Improving quality	☐
Improving reliability	☐
Reducing weight	☐
Aesthetics	☐
Improving ease of use	☐
Improving perceived value	☐
Meeting customer requirements exactly	☐

Q11. Please summarise the main constraints on your ability to meet the desired improvements in Q.10?

....

....

....

Q12. Do you practice any form of design for assembly? e.g. reduction of parts, ease of assembly.

....

....

....

Q13. What standards / guidelines do you follow whilst working on a new product?

....

....

....

Q14. In what way are these standards / guidelines communicated to you, and is the method effective?

....

....

....

Q15. In what way are these standards / guidelines monitored to ensure that they are followed?

....
....
....

Q16. Are the standards / guidelines reviewed and modified to suit company, policy, practice etc. and if so in what manner are they reviewed?

....
....
....

Q17. To what extent do you consider part / subassembly commonality or standardisation between products, and is there any formal requirement for this?

....
....
....

Q18. Do you try to maximise use of carry over parts wherever possible, and why?

....
....
....

Q19. How important is product flexibility to your company?

please tick one

Not so important ☐
Relatively important ☐
Very Important ☐

Q20. How important is manufacturing flexibility to your company?

please tick one

Not so important ☐
Relatively important ☐
Very Important ☐

Q21. To what extent do you consider product flexibility for a new product? Do you ever consider future products when working on a current one?

....
....
....

Q22. To what extent are your products currently flexible, and how are they flexible?

....
....
....

Q23. Where do you think flexibility is most difficult to implement?

....
....
....
....

Modularity

Q1. How important is product configurabilty, through modularity or otherwise, to you and your customers?

please tick one

Not so important ☐
Relatively important ☐
Very important ☐

Any Comments :

....

Q2. Would a strategy / technique enabling this configurability to be achieved rationally be of interest to you?

please tick one

Yes ☐
No ☐
Maybe ☐

Any Comments :

....

Q3. Do you know what modular design, or a modular product is?

please tick one

Yes ☐
No ☐
Maybe ☐

Q4. If you answered yes or maybe to Q3, could you briefly explain in your own words what you understand by the term?

....

....

....

Q5. What do you perceive are the main benefits of the modular way of product design? Please rank them in order of priority (1 for the highest through to 15 for the lowest).

reduced repetition of work		increased customer satisfaction		reduced lead time to market	
simplified changes		bought in modules		ease of disassembly	
increased capability for product variation		easier project management		reduced stock holding	
ease of assembly		increased flexibility		consistent quality	
reduced part variety		simultaneous design of product and process		reduced manufacturing costs	

Q6. What do you perceive are the main disadvantages of the modular way of product design? Please rank them in order of priority (1 for the highest through to 6 for the lowest).

greater interface problems		increased perceived work load and cost		increased level of specification	
increased weight		increased part numbers		increased initial product development time	

Q7. Are there any apparent benefits or disadvantages that are not mentioned in the previous tables?

....

....

....

Q8. Do the benefits outweigh the disadvantages of a modular strategy?

please tick one

In general.

Yes ☐ Any Comments :
No ☐
Maybe ☐ ....

For your product.

Yes ☐ Any Comments :
No ☐
Maybe ☐ ....

Q9. If your company was embarking on a new modular design, in what way would you like guidance on the principles, way of working, and concept of the strategy? Please rank them in order of priority (1 for the highest through to 7 for the lowest).

regular team meetings		paper based, single line, guidelines		comprehensive paper based guidelines	
software presented guidelines		paper based checklist or workbook		software based checklist or workbook	
matrix based or other active methodology					

Q10. If your company was embarking on a new modular design, in what way would guidance of the principles, way of working, and concept of the strategy, be beneficial?

....

....

....

Thank you for taking the time to complete this questionnaire. Your answers will enable us to assess the need for a modular strategy and in what way guidance on its implementation / use would be helpful.

Now please post to:

Russell Marshall
Department of Manufacturing Engineering,
Loughborough University,
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Design Modularisation Survey

Russell Marshall. 16/04/96

Department of Manufacturing Engineering,
Loughborough University.

Corporate Questionnaire

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I will also provide a breakdown of the responses to all replies received.

Thanks,

Russell Marshall.

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email : R.Marshall@lboro.ac.uk

General Section

Q1. Please fill in the details below.

Your Name	Address for correspondence ....
Job Title	....
Organisation	....
Department	....
Telephone	....
Fax	Country .... Postcode.................
E-mail	Date completed ....

Q2. Please describe your job content and responsibilities.

....

....

Q3. In what type of industry is your company involved?

....

Q4. What mode of production does your company employ?

please tick one

One offs	☐	Any Comments :
Small batch	☐	
Large batch	☐	....
Large volume	☐	

Q5. How would you describe your company?

please tick one

In-house design, subcontract manufacture and assembly.	☐	Any Comments :
In-house design and assembly, sub contract part manufacture.	☐	
Design and production in house	☐	....
Combination of in-house and external design	☐	
Other (please specify)	☐	....

Q6. How many staff are employed at your company, and how many of these are considered technical staff?

....

....

Q7. Is your design process integrated with manufacturing to enable the concurrent design of the manufacturing process?

....

....

Q8. Is the development of new products / designs by your company led by market or customer demands or by the availability of new technologies?

please tick one

Market led	☐	Any Comments :
Led by new technology developed within the company	☐	
Led by technologies developed externally	☐	....
A combination of the above	☐	

Q9. How many products do you have in development at any one time?

please tick one

1	☐	Any Comments :
2	☐	
3	☐	....
4	☐	
5 or more	☐	....

Q10. How many of your current products share the same or similar features but have probably been repackaged due to modifications?

please tick one

1	☐	Any Comments :
2	☐	
3	☐	....
4	☐	
5 or more	☐	....

Q11. What is the importance of the following aspects of your business strategy in order to retain competitiveness?

	Very Important	**Important**	**Desirable**	**Not Important**
Flexibility of product	☐	☐	☐	☐
Reduction in overall time to market	☐	☐	☐	☐
Increase in added value	☐	☐	☐	☐
Reduction in design changes during development	☐	☐	☐	☐
Reduction in product cost	☐	☐	☐	☐
Flexibility in product range production	☐	☐	☐	☐
Other (please specify)				
....	☐	☐	☐	☐
....	☐	☐	☐	☐

Q12. Of the aspects in Q11, which of the following apply?

	Previously achieved	**Currently trying to achieve**	**Intending to achieve in future**	**No intention of achieving**
Flexibility of product	☐	☐	☐	☐
Reduction in overall time to market	☐	☐	☐	☐
Increase in added value	☐	☐	☐	☐
Reduction in design changes during development	☐	☐	☐	☐
Reduction in product cost	☐	☐	☐	☐
Flexibility in product range production	☐	☐	☐	☐
Other (please specify)				
....	☐	☐	☐	☐
....	☐	☐	☐	☐

Q13. Please summarise the main constraints on your ability to meet the desired aspects in Q.11?

....

....

....

Q14. What standards / guidelines does your company follow whilst working on a new product?

....

....

....

Q15. In what way are these standards / guidelines communicated through the company, and is the method effective?

....

....

....

Q16. In what way are these standards / guidelines monitored to ensure that they are followed?

....

....

....

Q17. Are the standards / guidelines reviewed and modified to suit company, policy, practice etc. and if so in what manner are they reviewed?

....

....

....

Q18. To what extent is part / subassembly commonality or standardisation between products, part of company practice, and is there any formal requirement for this?

....

....

....

Q19. How important is product flexibility to your company?

please tick one

Not so important	☐
Relatively important	☐
Very Important	☐

Q20. How important is manufacturing flexibility to your company?

please tick one

Not so important	☐
Relatively important	☐
Very Important	☐

Q21. To what extent is product flexibility part of the company practice for a new product?

....

....

....

Q22. To what extent are your products currently flexible, and how are they flexible?

....

....

....

Q23. Where do you think flexibility is most difficult to implement?

....

....

....

....

Modularity

Q1. How important is product configurabilty, through modularity or otherwise, to you and your customers?

please tick one

Not so important	☐
Relatively important	☐
Very important	☐

Any Comments :

....

Q2. Would a strategy / technique enabling this configurability to be achieved rationally be of interest to you?

please tick one

Yes	☐
No	☐
Maybe	☐

Any Comments :

....

Q3. Do you know what modular design, or a modular product is?

please tick one

Yes ☐
No ☐
Maybe ☐

Q4. If you answered yes or maybe to Q3, could you briefly explain in your own words what you understand by the term?

....

....

....

Q5. What do you perceive are the main benefits of the modular way of product design? Please rank them in order of priority (1 for the highest through to 15 for the lowest).

reduced repetition of work		increased customer satisfaction		reduced lead time to market	
simplified changes		bought in modules		ease of disassembly	
increased capability for product variation		easier project management		reduced stock holding	
ease of assembly		increased flexibility		consistent quality	
reduced part variety		simultaneous design of product and process		reduced manufacturing costs	

Q6. What do you perceive are the main disadvantages of the modular way of product design? Please rank them in order of priority (1 for the highest through to 6 for the lowest).

greater interface problems		increased perceived work load and cost		increased level of specification	
increased weight		increased part numbers		increased initial product development time	

Q7. Are there any apparent benefits or disadvantages that are not mentioned in the previous tables?

....

....

....

Q8. Do the benefits outweigh the disadvantages of a modular strategy?

please tick one

In general.

Yes ☐
No ☐
Maybe ☐

Any Comments :

....

For your product.

Yes ☐
No ☐
Maybe ☐

Any Comments :

....

Q9. If your company was embarking on a new modular design, in what way would you like guidance on the principles, way of working, and concept of the strategy? Please rank them in order of priority (1 for the highest through to 7 for the lowest).

regular team meetings		paper based, single line, guidelines		paper based checklist or workbook	
matrix based or other active methodology		comprehensive paper based guidelines		software based checklist or workbook	
software presented guidelines					

Q10. If your company was embarking on a new modular design, in what way would guidance of the principles, way of working, and concept of the strategy, be beneficial?

....

....

....

Thank you for taking the time to complete this questionnaire. Your answers will enable us to assess the need for a modular strategy and in what way guidance on its implementation / use would be helpful.

Now please post to:

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Design Modularisation Survey Questionnaire - RESPONSES.

Corporate Questionnaire (denoted C)
Operational Questionnaire (denoted O)

General Section.

Q2.(O&C) Please describe your job content and responsibilities.

Range covers: Product introduction.
Design management.
Project management.
Engineering design
Project engineering
Manufacturing engineering

Q3. (O&C) In what type of industry is your company involved?

Range covers: Pre - press design of imaging systems
Oil service electronic design
Labelling technology
Shoe machinery

Q4. (O&C) What mode of production does your company employ?

All: Small batch

Q6. (C) How many staff are employed at your company, and how many of these are considered technical staff?

Range covers: 70 - 1000

Q7. (C) Is your design process integrated with manufacturing to enable the concurrent design of the manufacturing process

All: Yes.

Q8. (C) Is the development of new products / designs by your company led by market or customer demands or by the availability of new technologies?

All: Market led. Heavily dependent on state of the art technology.

Q5. (O) Q9. (C) How many products do you have in development at any one time?

All: 5 or more. Includes software products.

Q6. (O) Q10. (C) How many of your current products share the same or similar features but have probably been repackaged due to modifications?

Range covers: 3 - 5 or more.

Q7. (O) Q11. (C) What is the importance of the following aspects of your business strategy in order to retain competitiveness?

Averaged order: Reduction in time to market
Flexibility in production
Flexibility of product
Reduction in product cost
Reduction in design change
Increase in added value

Q12. (C) Of the aspects in Q11, which of the following apply?

Averaged order:
Flexibility of product (Previously achieved)
Reduction in overall time to market (Trying to achieve)
Increase in added value (Trying to achieve)
Reduction in design changes (Trying to achieve)
Reduction in product cost (Trying to achieve)
Flexibility in product range production (Previously achieved)

Q13. (C) Please summarise the main constraints on your ability to meet the desired aspects in Q11?

Averaged order: Product complexity
Inadequate or inappropriate design tools
Insufficient attention to up front design
Supplier capability.

Q8. (O) Do you work on a single project at a time, or are you responsible for a particular area over several projects?

Range covers: Single - 4 or 5.

Q9. (O) What experience / knowledge do you have of manufacturing or design issues?

Range covers: Generally 3 - 20 years experience
Some knowledge of DFM, DFA,
Broad range of design knowledge
Enough for the job requirements!!

Q10. (O) What do you think are the major drivers in terms of design improvements within your company? Please rank them in order of priority (1 for the highest through to 11 for the lowest

Averaged order: Improving reliability
Improving ease of manufacture
Improving performance
Reducing cost
Improving quality
Reducing the number of parts
Meeting customer requirements exactly
Improving the ease of use
Improving perceived value
Reducing weight
Aesthetics

Q12. (O) Please summarise the main constraints on your ability to meet the desired improvements in Q10?

Range covers: Resource and need to reduce development time.
Component specification
Backward compatability
Lack of clearly defined customer requirements.

Q13. (O) Do you practice any form of design for assembly? e.g. reduction of parts, ease of assembly.

All: Limited.

Q13. (O) Q14. (C) What standards / guidelines do you / your company, follow whilst working on a new product?

All: Internal procedures and quality standard ISO 9000

Q14. (O) Q15. (C) In what way are these standards / guidelines communicated to you / through the company, and is the method effective?

All: Part of culture, Training as appropriate, Management attention.

Q15. (O) Q16. (C) In what way are these standards / guidelines monitored to ensure that they are followed?

Range covers: Reviews
Informal communication

Q16. (O) Q17. (C) Are the standards / guidelines reviewed and modified to suit company, policy, practice etc. and if so in what manner are they reviewed?

Range covers: Task teams.
Informal and formal reviews.

Q17. (O) Q18. (C) To what extent do you consider part / subassembly commonality or standardisation between products, and is there any formal requirement for this?

All: Considered important
No formal requirement.
Some 'culture'

Q18. (O) Do you try to maximise use of carry over parts wherever possible, and why?

All: We try to resist proliferation of part variety, but with little data base.

Q19. (O&C) How important is product flexibility to your company?

Averaged order: Relatively important.

Q20. (O&C) How important is manufacturing flexibility to your company?

Averaged order: Relatively important.

Considerable discrepancy visible if a manufacturing or product engineer is asked.

Q21. (O) To what extent do you consider product flexibility for a new product? Do you ever consider future products when working on a current one?

All: Product flexibility is considered, usually in depth but whether it appears as flexibility is limited.

Q21. (C) To what extent is product flexibility part of the company practice for a new product?

All: No formal requirement, only a desire.

Q22. (O&C) To what extent are your products currently flexible, and how are they flexible?

Range covers: More flexible with respect to software upgrade. Mech upgrade could be better.

Q23. (O&C) Where do you think flexibility is most difficult to implement?

Range covers: Mechanical and optical areas.
"If product and manufacturing process has not been originally designed to cope with need"

Modularity

Q1. (O&C) How important is product configurability, through modularity or otherwise, to you and your customers?

All: Split between very and relatively important.

Q2. (O&C) Would a strategy / technique enabling this configurability to be achieved rationally be of interest to you?

All: Yes.

Q3. (O&C) Do you know what modular design, or a modular product is?

All: Yes

Q4. (O&C) If you answered yes or maybe to Q3, could you briefly explain on your own words what you understand by the term?

Range covers: The ability to design, assemble and test a sub-system as a single item. Ability to replace a sub-system in the field as a single item.

to

Commonality of parts and processes

Q5. (O&C) What do you perceive are the main benefits of the modular way of product design? Please rank them in order of priority (1 for the highest through to 15 for the lowest).

Averaged order:
Reduced lead time to market
Reduced repetition of work
Reduced manufacturing costs
Consistent quality
Reduced stock holding
Reduced part variety
Easier project management
Ease of assembly
Increased flexibility
Simultaneous design of product and process
Increased capability for product variation
Increased customer satisfaction
Ease of disassambly
Simplified changes
Bought in modules

Q6. (O&C) What do you perceive are the main disadvantages of the modular way of product design? Please rank them in order of priority (1 for the highest through to 6 for the lowest)

Averaged order:
Greater interface problems
Increased perceived work load and cost
Increased part numbers
Increased initial product develop. time
Increased level of specification
Increased weight

Though two responses: I don't agree that the above (disadvantages) will always occur if a modular approach is taken. A modular approach enforces good design disciplines.

Q7. (O&C) Are there any apparent benefits or disadvantages that are not mentioned in the previous tables?

Range covers: Overall a more thorough design in so much that you have to do a more thorough product module specifications to start. Redundancy may be a problem.

Q8. (O&C) Do the benefits outweigh the disadvantages of a modular strategy?

All: In general - yes.
For your product - yes.

Q9. (O&C) If your company was embarking on a new modular design, in what way would you like guidance on the principles, way of working, and concept of the strategy? Please rank them in order or priority (1 for the highest through to 7 for the lowest).

Averaged order:
Regular team meetings
Software presented guidelines
Software based checklist or workbook
Paper based checklist or workbook
Matrix based or other active methodology
Comprehensive paper based guidelines
Paper based, single line, guidelines

Q10. (O&C) If your company was embarking on a new modular design, in what way would guidance of the principles, way of working, and concept of the strategy, be beneficial?

Range covers:
Guidance and experience from others
Conceptual level to integrate into existing processes.
Avoidance of pit-falls.

version 1.2 12/09/97

Loughborough University

Holonic Product

holon (**hohl**-õn) *n.* the autonomous and co-operative nodes in a hierarchy that behave partly as wholes or wholly as parts, according to the way they are looked upon.

Design (HPD)

holonic (**hohl**-õn-ik) *adj.* of or like a holon. □**holonic product design,** a method employed to make use of systems concepts and modular design.

A Workbook

product introduction

hpd - methodology.

modular design.

manufacturing strategy.

self analysis.

checklists.

guidelines.

This package provides a framework for companies who feel that modularity in their product architecture and manufacturing process would assist in providing:

1. flexible or agile manufacturing
2. a rationalised introduction of new technology
3. an efficient means of deploying customer requirements
4. a structured approach to dealing with complexity

Holonic product design (HPD) is a technique or process in which products are designed in a modular form, as oppose to an amorphous whole, the manufacturing system is also designed in accordance to these principles.

This is presented through a generic Product Introduction Process (PIP) in concordance with ISO 9000 and BS 7000 that embodies a process for modular design. Building upon this is a self assessment technique to tailor the process to individual situations. Finally leading to a series of checklists and guidelines to maintain control over the process and ensure that the process becomes an integral part of the company's PIP.

Full benefit will be gained by using this template on top of an existing PIP and integrating the techniques slowly and systematically. To provide a natural and successful process for providing the desired solution using the appropriate level of modularity.

HOLONIC PRODUCT DESIGN WORKBOOK - VERSION 1.2.

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E-mail: R.Marshall@lboro.ac.uk

CONTENTS

INTRODUCTION

This workbook provides a framework based upon systems engineering and systems thinking, for companies who feel that modularity can address a number of business issues. Through a modular product architecture and an associated modular manufacturing practice, attaining a flexible or agile manufacturing system will be facilitated. In addition this alternative perspective on product design and manufacture will provide an opportunity to strengthen market position through a rational introduction of new technology and customer requirements to the product family.

Section 1. The workbook begins by introducing a product introduction process (PIP) based on two British standards: BS EN ISO 9000 (formerly BS 5750) and BS 7000. This provides a basis of a popular standard to which many companies are accredited that provides a quality management system directly aimed to meeting customer requirements (ISO 9000), and a standard which provides direct guidance on the topic of manufactured goods (BS 7000, Part 2.). A generic systems engineering process is also outlined to highlight the links between the systems framework, the holonic product design (HPD) methodology and the modular design process.

Section 2. Additions to the generic PIP are highlighted and explained in greater depth.

Section 3. Having introduced the PIP the workbook goes on to provide detail on the process of designing for modular products, and how this process fits into the generic PIP. The detail of designing for modular products provides guidance on the process and some of the new issues that must be dealt with for a successful modular design.

Section 4. Complements the previous section by providing detail on the manufacturing strategy for modular products.

Section 5. The next section presents a self assessment to allow the HPD methodology to be integrated into current practice within the company. The self assessment aims to:

- ☑ clarify the reasons for the change to modular product architectures
- ☑ clarify the business strategy and corporate objectives
- ☑ define the required company organisation and working practices
- ☑ provide a platform on which to base the framework of the new HPD methodology
- ☑ examine existing and future products and their features for suitability to modularity
- ☑ provide guidance on the level of modularity suited to the product and the company.

The result from this section should be a clear understanding of what is required in terms of company goals and a modular product. In addition, there should also be a list of benchmarks, priorities and relevant guidelines to the specific needs of the user.

Sections 6 & 7. Provide a series of checklists and related guidelines. The aim of these is to ensure that the HPD methodology is followed and to provide guidance to the employees embarking on a new process and dealing with product architecture in an un-familiar manner. The guidance ensures that the best practice of HPD is instilled within the employees yet avoids imposing inflexible 'rules' which are not always practical.

Sections 8 & 9. The final sections provide guidance on maintaining the processes learnt and references to other material that may help address certain needs or clarify specific issues.

It is not the intention of this workbook to provide the solution to a whole product introduction process and the requirements for modularity. There are many good PIP's in existence and to try to mould companies to any single one over an existing and equally good PIP would be self defeating. The aim to bear in mind is that the PIP and systems process introduced are generic and are used to provide structure to the modularity detail. This then provides a framework into which the company is free to place its existing preferred systems and practices and also allow the method to grow.

AIM >> The aim of this section is: To present the generic PIP and systems engineering process, and to show how the HPD methodology and detail of modular design relate. To allow the users to relate their own PIP to the generic model. And to provide a basis from which to integrate the HPD methodology into the generic model and thus the individual custom PIP's.

The key to HPD is that it is a fresh approach to the development of products. In order to provide the necessary degree of relevancy, material and ideas are presented that can be related to individual situations. It begins by presenting a generic PIP from which the process can be built. The building will then serve to tailor the process to individual user requirements and to provide a greater understanding by actually performing the tailoring process.

A Generic PIP Based Upon ISO 9000 And BS 7000.

This section presents a product introduction process based on the standards below. The documents provide familiarity through the popularity of BS EN ISO 9000 accreditation, combined with the embodiment of current best practice in the form of the new BS 7000 Part 2.

- ISO 9001 (1994) Model for QA in design, development, production, installation & service.
- BS 5750 Part 4 (1990) Guide to the use of BS 5750 Parts 1, 2, & 3.
- BS 7000 (1989) Guide to managing product design.
- BS 7000 Part 2 (1997) Design management systems: Guide to managing the design of manufactured products.

The process of product introduction has to reflect on two aspects; the customer's needs and expectations, and the supplier's needs and interests. An organisation providing a product has to meet the customer needs and expectations fully but in the most economical way (meeting the suppliers needs) (BS 5750 Part 4 - 4.2.1, 1990). BS 5750 Part 4 presents the design function as the ability to take the customer requirements and translate these in a systematic and controlled way into a specification which defines a product or service. This specification should be such that the product is producable, verifiable and controllable under the proposed production, installation, commissioning or operational conditions. A number of points are highlighted:

- There must be an organised structure, with responsibilities clearly defined.
- Project plans should include:
    1. Identification of responsibilities for each design and development activity
    2. Qualified personnel with adequate resources
    3. Effective communication
    4. Monitoring and control of activities
    5. Timing and review
    6. Verification of design to requirements
- The design specification should comply with the customer requirements and contain all the necessary information from which the design can be created.
- During the process of design of the product, the acceptance criteria with respect to its required performance should be continually evaluated and means for verification should be provided.
- It is likely that changes will occur before the design is complete. These changes must be recorded, and a number of questions should be answered:
    1. Does the product still meet the specification?
    2. Is the fitness for purpose affected?
    3. Are changes to the spec possible in order to accommodate the change?
    4. Are associated parts of the product or system affected by the change?
    5. Is there need for further interface design?
    6. Does the change create problems in manufacture, installation or use?
    7. Does the product still remain verifiable?
- Design verification should be an ongoing process with regular and formal design reviews.

The Product Life Cycle.

Figure .1.
Idealised Product Evolution.

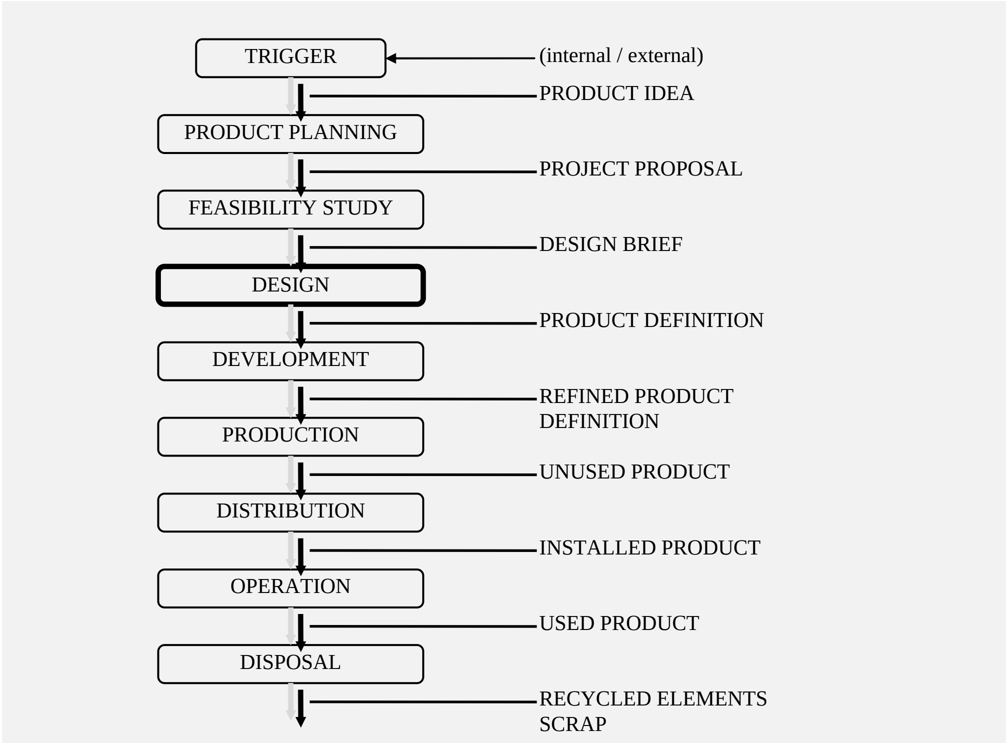


Figure 1. presents a generic product life cycle (BS 7000 1989) and embodies within it a product introduction process. This process covers from the trigger to the product launch (unused product point) and is presented in the following table in more detail (BS 7000 Part 2. 1997):

Phase of project	Process	Output
	Trigger for the design project	Perceived opportunities
	Analysis of opportunities	Alternative business concepts
Concept phase	Analysis of business concepts and product identification	Identification and selection of preferred business concept and product characteristics
	Formulation of the project, objectives and strategies	Preliminary definition and project proposal
	Preliminary evaluation and approval of the project by the corporate body	Permission to proceed
	Planning, research and feasibility studies leading to the formulation of a project proposal	Criteria of acceptability to organisation
Feasibility phase	Refine characteristics. Development of a functional specification	Product design brief
	Development of project configuration and work programme	Project plan. Resource plan
	Evaluation and sanctioning of project by corporate body and commitment of resources	Project approval
	Bringing together of a multi-disciplinary team of specialists to realise the project	Roles and responsibility matrix
	Design concept development. Rehearsing the customer-product experience	Preferred option
Implementation phase	Outline design (embodiment design or general arrangement design)	Product resolution
	Detail design	Specifications for product
	Construction and testing of pre-production prototypes	Confirmation of performance and reliability
	Finalisation of the completed design ready for manufacture. Design support for manufacture.	Product package
	Provisions for manufacture and delivery	
	Product launch	Product availability

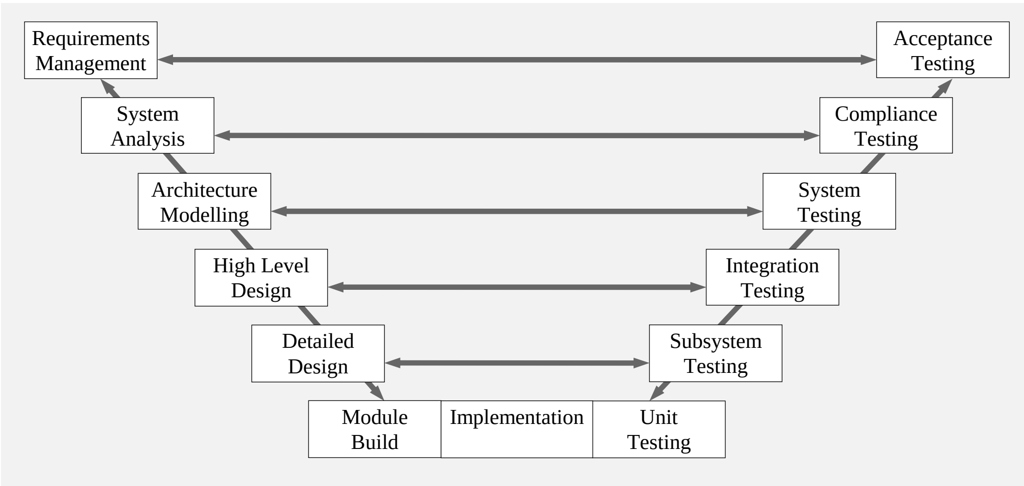
A detailed description of each process will be omitted as further information can be found in the relevant standards but a number of important features are present in this PIP.

- Stages should be undertaken in parallel as often as is possible.
- Concurrency of the work will emphasise good communication throughout the organisation.
- Project teams must be multi-disciplinary - this is extremely important to project success.
- Feedback plays an important part at all stages of the process.
- The process should be front weighted with effort. Effort must be expended in ensuring that things are right first time and that project decisions are sound.
- The awareness of manufacturing requirements must begin at the concept design phase and continue through to the actual manufacturing of the product.
- Customer requirements must be clearly, concisely, completely & correctly captured up front.
- Make use of techniques such as: Pugh concept selection matrices, QFD, dimensional management, DFA, value analysis, etc. where beneficial.
- Potential lies in the previous techniques through accepting and practising the principles and integrating them into an existing PIP.
- The process must take a total view and consider the whole life cycle, as areas outside of the PIP such as support and disposal are factors that are heavily influenced by design decisions.

In order to consider a total view, a systems engineering model is presented in Figure 2. This systems engineering V addresses key stages of modularity such as requirements management and system element interaction and integration in greater depth than the generic PIP. The presentation of this model also allows cross references between modularity, the generic PIP, and the systems engineering V. This highlights the integration of these processes and perspectives. Furthering the aim to integrate into company processes rather than replace them.

Figure .2.
The Systems Engineering V.

(adapted from Walker 1997).



THE HOLONIC PRODUCT DESIGN (HPD) METHODOLOGY *Section 2*

AIM >> This section is aimed to clearly highlight the relationship between the generic PIP, the systems engineering model, the HPD methodology and the modular design process. The relevant changes to the generic PIP that form the HPD process are also presented.

The Concept Phase.

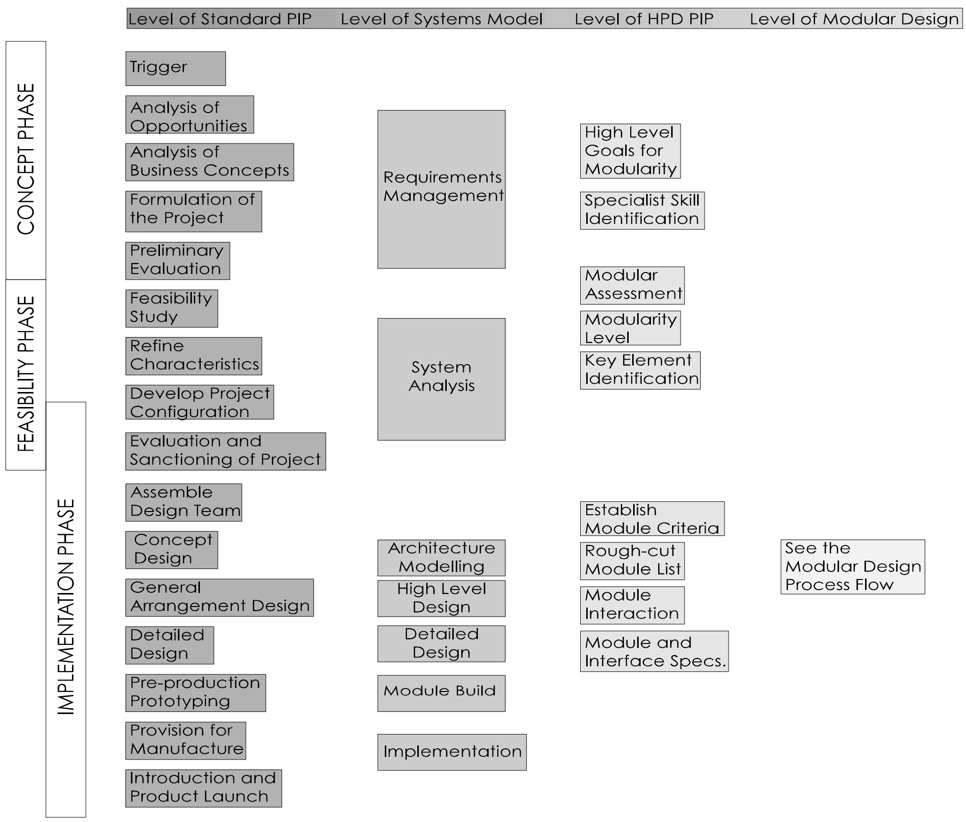
The first stage of the HPD is the concept phase and relates to the generic PIP and systems engineering model through the following processes. During the **analysis of opportunities** and **analysis of business concepts** additional consideration must be given to compatibility with corporate objectives and strategies. It is important that the corporate objectives should provide the foundation and main thrust of all activities, including design. Corporate strategies should be drawn up as prescriptions of approaches to be taken and how resources will be harnessed to achieve the corporate objectives set. These are fundamental company ideals and as such it is recommended that the appropriate corporate objectives and strategies be modified to include the company's wishes for modularity. Projects at this stage must then conform to these criteria.

The use of the corporate objectives and strategy in this way provides a universal platform for the integration of disciplines and the utilisation of resource in achieving business goals in an effective and efficient manner.

Modularity provides an excellent mechanism for enhanced product design, manufacture, testing and service. Used purely as a development methodology it can provide numerous benefits. One aspect of the modularity process is it's inherent capability of dealing with variety. The project should be considered in relation to existing and future products with the view to the development of a family of products to maximise the potential for the modules. Though future products may not yet be defined the capability to add models that use common modules must be considered, if only to be ruled out.

During the **formulation of the project** a project team should be assembled. A project team will involve a multi-disciplinary approach including, for example; design, manufacturing, test, and service personnel, but also have senior management buy-in and be prepared to include specialist personnel whenever required to lend a particular perspective. This team will then oversee the development of the project and make the key decisions along the project life-cycle, whilst maintaining a clear focus on product requirements. Depending on the size and available resource of the company, this team may also be the module team detailed later, but could also be high level body co-ordinating a number of module teams. During this phase specialist skills should be identified that can take a systems view of the design. Any bottlenecks to the change should also be identified, such as poor communication channels and employees unused to the team environment.

Figure .3. The HPD Methodology and Relations.



The Feasibility Phase.

The second stage is the feasibility phase. During the **feasibility study** a product must be assessed as to whether it is suited to a modular architecture. If the project requires a highly integrated and refined design, where criteria such as weight, size, and functional interfaces are an issue, a modular design may not be suitable aim.

At this stage an idea of the level of modularity must also be agreed by the project team. (*Section 3*, LOM and Section 5, A3 provide further detail on agreeing a level.) Levels of modularity alter the properties of the product and it's flexibility. Levels are defined by three factors: *Complexity*, *Resolution*, and *Composition*, which relate to the degree of functionality, the number, and the standardisation of modules. It is important that a benchmark be set for the project in order for all modules to aim for this agreed level. Key elements of existing and planned products must also be identified to allow targeting of modules during the concept design phase. Key elements may include; specific electronics packages, power supplies, user interfaces, consumable items, and ease of access.

Though there are many benefits of defining certain characteristics toward modularity as early as possible, some companies may not be committed to having modular products that share modules to any large degree, it is therefore recommended that the previous stages be left to the concept design stage, where a modular architecture may form one of a number of options.

The **refine characteristics** stage is where the product design brief is developed. Included in the brief should be the information already gathered such as the level of modularity. It may also be useful, if possible, to assign key elements that that are important, to a module. This is especially true as regards legislated requirements or items related to product reliability.

During the **development of the project configuration** project reviews should be assigned for each step of the design phase. This is especially important due to the added complexity that a modular product and modular way or working may introduce.

The Implementation Phase.

The final stage of the HPD is the implementation phase. This phase represents the main area of activity in developing modular products. In accordance with the PIP introduced we shall present a modular design process that will superimpose itself upon the PIP, specifically those sections labelled as: **assembly of design team, concept design**, **general arrangement design** and **detail design.**

DESIGNING FOR MODULAR PRODUCTS *Section 3*

AIM >> This section aims to clearly define the process of designing a modular product and highlight the necessary steps to be taken to ensure a successful design.

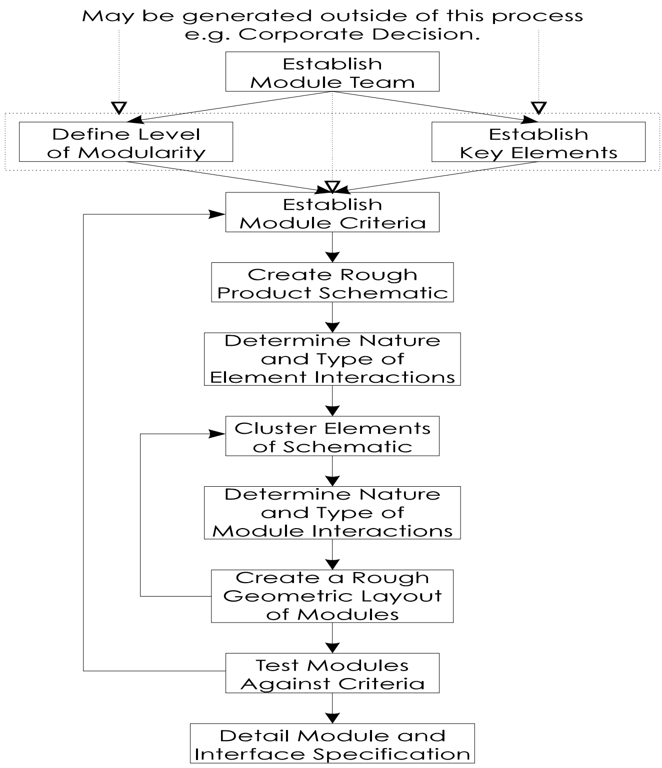
The Modular Design Process.

The process (Figure 4) was developed to be a logical flow based around the formation of a module team and occurs during concept and general arrangement design, early on in the PIP (Figure 3). As an initial activity the team would accept or determine a number of key requirements for the module for which they are responsible. The process of designing a modular product would then exhibit the following key points:

1. Establish team.
2. Define the level of modularity. *
3. Document key elements. *
4. Establish the module criteria. *
5. Create a rough product schematic.
6. Determine nature and type of element interactions.
7. Cluster elements of the schematic.
8. Determine nature and type of module interactions.
9. Create a rough geometric layout of modules.
10. Test modules against criteria.
11. Module and interface specification.

* These are requirements upon the system for modular design. It is important that each requirement is determined very carefully as they will have significant impact upon the outcome of the modular design process. It is possible that the source of the requirements will come from many areas, such as; customers, the company's corporate strategy, company departments, and the team itself, all requirements must be collected and considered for the module criteria. The result is a list of module criteria that function as a design specification.

Figure .4.
The Modular Design Process Flow.



Establish Team.

The initial priority is to establish a multi-disciplinary module team to develop the product. Team members must be familiar with product function as seen by the customer and should be aware that modularity is not just decomposition of a product but that the key is to maintain a total view whilst dealing with specific modules. The team must be co-located, properly resourced, allowed to communicate freely and have responsibility for their strategic direction.

The module team may be based around a core project team, but for a complex product likely to contain many modules, individual teams may be assigned to individual or small groups of related modules. This facilitates concentration of team members and also allows for parallel working. Each team has a representative that forms part of the main project team. Time must be set aside for regular full project group meetings.

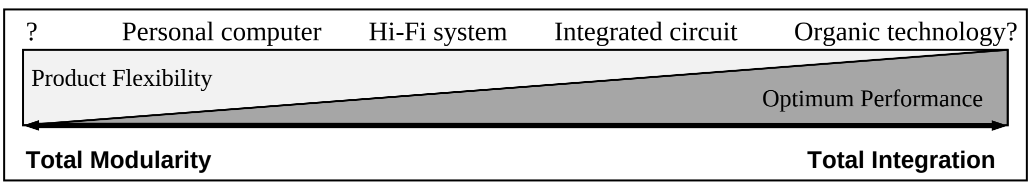
Define the Level of Modularity (LOM).

The level of modularity (LOM) must be defined in order to provide a fundamental direction to the process of defining modules. The level of modularity is defined by three factors:

1. *Complexity* - this is the functional level of modularity for each module. A module can contain anything from a single function to a combination of functions.
2. *Resolution* - this is the number of modules in the product. The number of modules relate to the complexity, where high numbers of modules will likely have low individual functionality
3. *Composition* - this is the degree to which complexity varies within a single product, and whether the product is a hybrid of an integrated common modules and variant modules.

Figure .5.
The Modularity Scale.

See *Section 5*, A3 for a detailed analysis of LOM.



Where products with a high LOM exhibit benefits in terms of flexibility, those with a low LOM act as an integrated whole and tend to be products where optimum performance is critical. There are many critical factors in the decision of the level of modularity.

1. The LOM gives a basis for development of modular products, to maximise the ability to utilise common modules. Products of greatly differing LOM are unlikely to be compatible.
2. The LOM will affect the flexibility and the performance of the product. Though highly flexible modular solutions can perform extremely well, they are unlikely to exhibit the optimal architecture and performance. However this only relates to examples of exacting performance, as non-integrated systems can also be designed to function to very high levels.
3. The LOM will affect the manufacturablity of the modules, and subsequently the product. The more common modules that can be used the more efficient the manufacture. The more complex the individual modules the more complex the manufacture.
4. The LOM will also affect, complexity, robustness (both in quality and flexibility), and cost.

Document Key Elements.

The documenting of key elements is a process whereby any feature that is important to the product is noted. Key elements may include a particular power supply that is required or desired for some reason, a specific software operating system, a particular product branding to be exhibited, a specific standard or legislated requirement to be met. Though these key elements may appear later in the design brief, the product specification or in the concept designs, this early stage in the actual modularisation phase allows these elements to be considered in the modular scheme. A considerable number of key elements may arise from analysis of existing products (see, *Section 5*, A6), such as common elements, implementations or modules to become generic throughout the range.

Establish the Module Criteria.

Module criteria takes the LOM, the key elements, and adds to them specific module requirements. Module criteria are features and functions that are deemed necessary, or essential by the modularity team. Module criteria act as a focus, a reminder and as a benchmark for the design of the modules. Module criteria will be analogous to system and design requirements e.g. Can be tested, Self-contained, Clear access, Totally interchangeable. Traceability and weighting (e.g. mandatory, important, and desirable) should be indicated against requirements. This allows actions to be traced to requirements and also trade-offs to be made if required.

Create a Rough Product Schematic.

Having determined the requirements these are then translated into an initial form for the product. This is done through a diagrammatic representation which represents the agreed understanding of the constituent elements of the product. A schematic is developed using a familiar technique such as FAST diagrams (functional analysis). The elements in the schematic may refer to physical concepts such as a ‘gearbox’, to critical components such as a ‘charge coupled device’ (ccd), or to a functional element that may not yet be described such as ‘deliver power’, or ‘rotate wheel’ (note the verb+noun format, this allows a high degree of freedom for the design process). The schematic should reflect the teams best understanding of the state of the product but does not have to include every imaginable detail. Schematics should avoid over complexity and may be related to the LOM if helpful. If the product is extremely complex the elements should be spit into differing hierarchical levels, each with their own schematic.

The schematic generated is already beginning the process of defining the product architecture, it is therefore recommended that a number of schematics are drawn up to facilitate the consideration of several product feature and architecture types. The best suited to the teams needs should be chosen for further examination.

Determine Nature and Type of Element Interactions.

Interactions between elements are determined to understand the implications of manipulating the elements. The interactions are defined using the product element interaction chart.

Figure .6.
The Product Element Interaction Chart.

		1.	2.	3.	4.	5.	6.
CCD	1.		S	-	E	S	EI
Carriage	2.			-	E	S	EI
Focus image	3.				E	-	EI
Provide power	4.					E	E
Position carriage	5.						E
Control process	6.						

Where the defined elements are plotted against one another in a matrix format. The area where the elements coincide defines the interaction and the interface type is denoted by a simple key based upon Crosfield Electronics and Pimmler & Eppinger's work (1994), where:

M = Material Interaction. E = Energy Interaction. I = Information Interaction.
S = Spatial Interaction. ◯ = Fundamental or critical interaction.

It may be beneficial in certain cases to define degrees of the various interactions, such as fluid, or gaseous material interactions.

Cluster Elements of the Schematic.

Once the agreed schematic elements and interactions are finalised, the elements should be assigned to a module. This process is one that must be done purely intuitively by the team but there are a number of points that can be used for guidance.

- The level of modularity that was defined earlier provides a guide to the number of modules that will be acceptable.
- The easiest process is to start with a schematic of one element per module and then group elements where advantageous.

There are also a number of factors in deciding if grouping is advantageous:

- ***Interactions:*** Some interactions will be more critical than others, and some may be easier to perform over a distance. Any interactions between elements that is critical may benefit from the elements being grouped as may interactions utilising mechanical movement which is not sympathetic to being made to function over long distances. The benefit is also seen in manufacturing as the process will be simplified if complex interactions are not split over module interfaces. Interactions that utilise digital signals can be easily separated and may allow for benefit from being in separate modules, as in multiplexed systems.
- ***Geometric location:*** Integrating elements that require geometric alignment between them will benefit from being in the same module, as control of the alignment is done in a localised area or by a single component. This will influence the ease of manufacture especially in low tolerance areas, and will thus effect quality and repeatability, or reusability of the modules.
- ***Function deployment:*** When a single element can implement a number of functional elements of the product the elements can be grouped. This simplifies manufacture i.e. design for assembly (DFA) but may inhibit flexibility as integrated elements will be restricted for use in other products. However there is the possibility of redundancy if advantageous.
- ***Supplier capability:*** A regular supplier to the company may have specific expertise, elements in this area may be grouped to utilise the capability of a supplier to the maximum.
- ***Natural Modules:*** Groups of elements that naturally complement each other and benefit little from being separate are termed natural modules, such as power supply units and electronic packages. They ease the design process and provide additional advantages to manufacturing. They also benefit quality by preventing the split of closely related functions.
- ***Core Business:*** The grouping of elements into modules that contain features, functions and expertise that fall outside of the core business allows them to be provided by a supplier.
- ***Localisation of change:*** If change is anticipated in certain elements through, wear, use, obsolescence or fashion, these elements should have their own modules, such that they may be altered, replaced or serviced without effecting the whole, as in printer toner cartridges.
- ***Configurability:*** Elements should be grouped such that the company may combine modules in differing ways to provide variety if desired.
- ***Standardisation:*** Elements that maybe useful in a range of products should be grouped so that modules can be standard to the product range. These standard modules may form a generic platform or architecture. A generic architecture provides a standard proportion for each product in a family, and introduces benefits for product design and manufacturing through flexibility. In this regard it is recommendation that design of a product should not only include ideas from previously designed products but also bear in mind future products and how they may be integrated with current designs, components, processes, modules, facilities, and tooling etc.

- ***Manufacture:*** Elements that can be combined into a single module by a different manufacturing process such as injection moulding or casting can be grouped, as can elements that require the same manufacturing technique. This can be further extended to the grouping of elements composed of similar materials, not only for ease of manufacture but also for recycling purposes. Elements that can be grouped to provide modules that encapsulate the key features of the product (i.e. not the generic modules) will aid manufacturing if the design allows for these to be introduced to the assembly process late on. This will also speed delivery time as generic architectures can be made up independent of orders and only customised into the ordered products at the last possible moment.
- ***Failure modes and effect analyses:*** If FMEA studies are carried out early on, or previous data is available, the results may be used to group elements with a view to minimising the failures and their consequence.

Determine Nature and Type of Module Interactions.

Once a satisfactory grouping of elements into modules has been performed the nature and type of interactions between modules must be identified. It cannot be taken that the interactions will purely be combinations of those between elements determined previously. The interactions that we are considering here are those at a higher level than the element interactions and will arise due to the physical implementation of the functional elements or due to the geometric arrangement of the modules. These interactions will probably not appear on the schematic and must be identified to ensure that any detrimental effects may be removed.

These interactions will occur at interfaces between modules and these interfaces should be kept to one discrete location for each module to module connection wherever possible. Interfaces should transmit all necessary function between modules and should be designed such that they can readily be assembled and disassembled. Their ease of connection will aid in assembly of the product initially but also at a later date for upgrade or service.

It is strongly suggested that a set of standard interface types and standard interface locations are determined that will be used wherever possible through the product range, and in future products. Thus carry-over modules will have a set of defined interactions associated with them. Standard interfaces ensure that new and existing product modules are compatible, if only in physical connection. It also provides economies of scale, reduced stock holding, and ease of manufacture and assembly. Standard interface locations can aid in the flexibility of the product by allowing changes to the product through upgrade to be simply introduced. There is a further effect that provides a degree of manufacturing flexibility in that tooling for different products can be common if assembly operations occur at the same points.

Figure .7.
The Product Module Interaction Chart.

		1.	2.	3.	4.	5.	6.
Top skin	1.		S	S	S	S (circled)	-
Bottom skin	2.			SE	SE	S	S
System board	3.				SI	-	-
Power supply unit	4.					E	-
Fans	5.						E
Drive & Platform	6.						

The interactions are defined using the product module interaction chart. Where the defined modules are plotted against one another in a matrix format. The area where the modules coincide defines the interaction and the interface type is denoted by the key as before.

Create a Rough Geometric Layout of Modules.

Once the elements of the schematic are grouped into modules and the interactions determined, a geometric layout should be created using drawings, CAD, or foam mock-ups. This model forces the team to consider if the groupings can be realised geometrically, and to optimise the manipulation of the modules with respect to the interactions, and to many of the criteria highlighted in the grouping of elements. As with the schematic a number of layouts should be made in order to try out differing solutions. Depending on the results of these layout trials, the process of grouping the elements may have to be revised.

Test Modules Against Criteria.

Having determined the rough module list, modules are tested against the criteria defined earlier. This acts as a check to ensure all desirable criteria are included or considered in the module design. This is especially important in complex products where addressing the details may make the team loose sight of the overall desires. Those modules not meeting the criteria must be looped back and the process performed again. Any particularly advantageous grouping that is in conflict with criteria may also require the criteria to be addressed. If modules contradict a non-essential criteria there may be compromise in the interest of the overall product.

Module and Interface Specification.

When the grouping of elements has formed modules, the modules have been checked against the criteria and the interactions between modules defined, detail specifications must be drawn up for both the modules and the interfaces. These specifications will form part of the standard product design specification but will document the detail regarding a modular architecture.

Interactions documented in the specifications are very important and may be used to structure and manage the remaining development activities. Modules that have many interactions should be developed by a single or few groups that are closely tied. Modules that have few or no interactions can be developed by an independent team or by an outside supplier. If a module is to be developed in isolation there must be strict specification of interfaces with other modules.
A number of general good practice points should also be considered.

- Modules should be as simple as possible whilst adhering to the specification.
- Modules must use as many standard parts and subassemblies as possible.
- Modules must be testable independently.
- Separate specifications should be drawn up for each module.
- Use should be made of bought in modules when a module falls outside of the core business.
- Modules should always bear in mind ease of manufacture and assembly.
- Modules should be capable of assembly without adjustment.
- Modules should make use of standard locating features.
- Modules should make use of existing standards, wherever they are appropriate.

Software Considerations.

Software is increasingly a highly functional element of product design. Many products derive a fundamental degree of functionality through their software. Reflecting this, there are a number of points that need to be considered when developing products that have a software element.

Software development should be addressed vary carefully. It is often a feature that is considered to be effectively free, infinitely adjustable, changeable at the last minute and an ideal way to compensate for shortfalls in the basic design. In reality software complexity increases rapidly with the complexity of the problem and, due to temporal dependencies in real time systems, can have extremely complex failure mechanisms. This requires a very rigorous design and test philosophy based around software modularity and it is very important that software requirements are treated with as least as much care as mechanical or electronic systems.

During the **document key elements** phase ensure any software considerations are included, this will then become part of the **module criteria**. The criteria for a software element may in turn have its own criteria. When **determining the nature and type of element interactions** it may be beneficial to highlight those interactions that are made or controlled by the software element. This will allow the domain of the software's influence to be clearly identified. This boundary can then be used during software development to indicate the interactions with the product modules and the personnel responsible.

When the process of **clustering elements of the schematic** is being carried out a subset of the ***Interaction*** factor may be the desirable feature of grouping elements that are controlled by software to do complimentary functions or to perform simultaneously. There is an advantage to be gained from linking the product architecture to the software architecture, such that changes to software functionality may be mirrored through localised changes to the product modules.

When product modules are determined any software requirements should be included as a module themselves. So that it may be developed in parallel, analysed for interaction with physical modules, and finally integrated with greater efficiency.

Though the software elements are very important they are generally beyond the scope of this process to address significantly here. For further information there are a number of standards related to this area, a good example of which is: BS 5750 Part 13. 1991. Guide to the application of BS 5750 Part 1: to the development, supply and maintenance of software.

The Legacy Factor.

It is unlikely that a company considering the use of a modular strategy for one of their products is embarking on their first product design project. The implications of this are that the company will have it's own experiences and their own existing products, preferred components, systems and suppliers. This section will provide some guidance on dealing with the legacy of previous products and how to manage this legacy for future products.

From the outset this workbook was developed to be integrated into an existing product development process through the generic PIP. The reasons for this are to combine the familiar and useful elements already in place with the improved Holonic Product Design process. This methodology is also taken to the product level where existing elements that are useful or desired are identified for the modular design. *Section 5*, A6 & A7 provide some analysis of the existing product and manufacturing features.

Typically the product and manufacturing legacy presents two attributes that are both constraints and yet possibilities. Existing products that have to be supported constrain the development of new products to maintain compatability between old and new systems. Constraints may also be due to the level of resources invested in specific engineering and manufacturing capability ensuring that a new product greatly different from the 'known' status of previous products is not viable. The possibility is that of self imposing a form of backward compatibility in terms of a generic or common approach to the product.

Backward Compatibility.

Backward compatibility provides a severe constraint upon product development, yet provides a clear possibility for success if the user does not have to replace their existing system on the basis of a new incompatible product. A modular design provides an ideal platform from which to deal with this constraint and maximise its potential. A number of guidelines can be followed to allow maximum freedom for design whilst maintaining the important backward compatibility.

During the **document key elements** phase ensure all compatibility issues are documented fully. If there are elements in the older products that may form a module, develop modules that may in future be used to retro-fit older products and allow a step-change to update them. For example; use new PCB's that have the same footprint as older generations so that they may be used to repair or upgrade old models with the new components, features or interfacing elements. Identify any **module criteria** that will provide flexibility in the product range. Try to provide backward and forward compatibility, this will turn the constraint of backward compatibility into a possibility for a common element for the new and future products.

When **creating a product schematic** clearly identify those elements that will interface to older products. Also maintain this when **determining the interactions**, so that when the **clustering of elements** is performed, those that provide compatibility may be formed into a module. This realises the possibility to supply products that do not need the compatibility, simplify changes to compatibility dependent areas, and ensure that interaction is localised thus easier to ensure full compatibility. Also **cluster elements** to group components, processes and features that are traditionally used so future products may easily replace them if economic circumstances allow.
Try to break the dependency. By using the above suggestions or others that may be specific to your case, move away from being dependent on support of previous products. This will allow greater flexibility in development, reduced problems when there are issues with procurement difficulty, etc. and allow the 'possibly redundant but necessary for compatibility' elements to be phased out at a later date.

Generic Features.

Generic or common elements to products provide a constraint on product development, but with care turn the constraint into a possibility for savings in development time, work, space, and cost. The key to using this feature to advantage is getting it right early on, and also providing flexibility for the unpredictable situations that can, and do present themselves.

Generic elements build upon common features to provide a generic module, platform or architecture that is a physical building block for all products within a range. It embodies the concepts of commonisation and rationalisation. It provides economies of scale such that development, manufacturing, and procurement costs are spread over many products. It eases and speeds development, manufacture, procurement, test, and maintenance, by reducing the number of procedures and features that staff have to be comfortable with. It presents a philosophy that can meet the customers needs for variety, yet through the generic element make the proposition economically viable for the developer.

When developing a product to take advantage of a generic element start by **defining the level of modularity** that suits the product and takes account of a generic platform. Ensure that the concept for a generic element is part of the **key elements** and state if an existing or new module is to be used. **Module criteria** must also give consideration to forward compatibility so that the generic element will have as long a life as possible before modification.

When **creating the schematic** the generic element must be included and carefully considered for the **determination of interactions**. If the nature of the generic element is known (i.e. being used from another product) the process will continue as though two products are being developed that must closely interact and only give the overall required function when combined. When **creating a geometric layout**, try to ensure that a range of module geometries can be combined with the generic element.

Balancing It Out.

It is possible that such a radical change from a conventional integrated architecture product to a modular one may have some disadvantages. There may also be situations when modularity is not always justified for a product or for a specific part of a product. *Section 5* provides a number of analyses on determining suitability and lessening the impact of disadvantages In general the main disadvantages of a modular strategy can be summarised as follows:

- Increase in number and complexity of interfaces.
- Possible increase in part numbers due to redundancy requirements, and extra interfaces.
- Possible increase in assembly operations. (A 6 part product requires 7 handling operations if assembled serially, two modules of 3 parts require 8 handling operations plus more fixtures.)
- An increased ‘perceived’ work load and cost through greater resource requirement up front.
- The management of change to the modular strategy.
- Possible increases in weight and size.

The majority of modularity disadvantages can be lessened or removed by careful consideration and implementation of the surrounding framework and support. For example, modularity may cause an increase in part numbers, though is likely to be quite low and could easily be negated by use of DFA techniques. Size and weight also fall into this category, overall reduction in part numbers, and closer product tailoring to user requirements potentially realise a product of equivalent or reduced size and weight. Also, due to the front loaded effort required for modularity, initial project costings and time commitments may look discouraging. However this increased ‘perceived’ work load is easily outweighed by the downstream benefits of such an approach.

Regardless of the specific details of the process to be implemented it is likely to have significant impact upon the company. Of course implementation is likely to be an extremely specific task relative to the organisation in question. The management of change is always difficult no matter the change involved. A management perspective must see the potential and be prepared to overcome teething troubles and re-education of staff in order to achieve long term benefits.

The increase in interfaces should be seen as a key opportunity rather than purely a disadvantage. By modularising and thus decomposing the system, module interfaces will become a priority. This priority will force consideration of the function of the system as a whole. Novel interface solutions and standardisation will aid the assembly and configurability of the modular product.

There will be situations when the application of modularity comes into question. However it can be argued that no matter the constraint it is likely that modularity will not adversely effect the product or its development, as a modularity process is inherently a combination of best practices. This leads to the conclusion that the application of modularity is not a black and white decision. Instead modularity will provide benefit to almost any application no matter the constraints, the issue that must be addressed is the level to which the product is modularised.

MANUFACTURING STRATEGY FOR MODULAR PRODUCTS *Section 4*

AIM >> The aim of this section is to provide guidance on the manufacturing strategy for modular products. The methodology is maintained to promote integration of specific points into an existing manufacturing strategy to compliment the new design process for modular products.

The Manufacturing Advantage.

Manufacturing is fundamental in providing a competitive advantage to the company. The influence of manufacturing is wide spread and often directly affects the customer. These influences include: high quality production, rapid order fulfilment, keeping delivery promises, timely introduction of innovative new products, providing a range of products to satisfy customer requirements, flexible production volumes and delivery dates to customer demands, and the company's ability to offer products at the right price. The implications of this are that the manufacturing function is central to providing competitiveness, and that through a modular strategy, each one of the influences of manufacturing may be facilitated in meeting the five performance objectives of: quality, speed, dependability, flexibility and cost (Slack 1991).

Quality.

This is the objective of not making mistakes. Products must be produced that meet all of the known requirements and are free from errors. There are many initiatives and techniques that aim to provide this capability such as Kaizen, 'right first time' and 'zero defects'. By doing this manufacturing provides a *Quality Advantage* to the company. The influence of a modular product, the manufacturing strategy, and manufacturing's input into the design can help to achieve a high level of quality through modular simplification and parts reduction, ease of assembly, the buying in of non-core modules, simplified and reduced verification and test, and the structured approach to the design and manufacture of the product.

Speed.

This is the ability to minimise the elapsed time between the onset of manufacturing and the customer receiving the product ordered. This provides a *Speed Advantage* to the company. The influence of a modular approach facilitates the *Speed Advantage* through ease of assembly, reduced tooling, parts inventory, part count, and a reduction in process operations. The ability to produce a product that is simpler and has been designed for manufacture and assembly reduces quality problems and increases efficiency and speed of the overall process. Modularity also improves the production time by allowing parallel production and test of modules.

Dependability.

Not only should manufacturing be fast, but also be able to keep delivery promises. Thus, manufacturing should be able to meet customer or self imposed delivery dates with consistency. In doing this manufacturing gives the company a *Dependability Advantage*. A modular approach has a number of characteristics that provide this consistency:

- Simplified assembly of modules implies that the process will have a consistent throughput.
- Modules can be produced in parallel and configured to an individual order in final assembly.
- Modules cab be tested prior to final assembly, moving the impact of test upstream.
- Products are all analogous, thus production times are similar and new products will be relatively easy to plan as they will typically be a new modules on a common framework.

Flexibility.

Manufacturing should be flexible in order to vary and adapt the operation to meet changing customer needs, changes in the production process or supplier changes. Not only must manufacturing be able to change, but it is important that the change is far enough and fast enough. The ability to do this gives the company a *Flexibility Advantage*.

Flexibility is a key feature in a modular approach. The use of modules facilitates manufacturing flexibility through the flexibility of the product. A modular design provides manufacturing with the ability to easily meet design changes for customer requirements by meeting specific customer requirements through a limited number of modules. Thus changes are limited to the manufacturing processes that deal with these modules leaving the rest of the process unaffected. In addition, planned redundancy in modules or interfaces allows for changes with no modification to manufacturing. Finally, a modular approach deals with the issue of flexibility up front in the life cycle of a product so changes are anticipated and allowed for.

Cost.

This means achieving a price that is lower than a competitor can manage. Meaning that resources must be obtained cheaper and they must be converted more efficiently than the competition. In doing this manufacturing provides a *Cost Advantage* to the company. A modular approach can influence the cost of a product by allowing suppliers to produce non-core modules. Thus removing needless capability, the burden of investment in technological expertise, time and effort in production and test, and by providing suppliers with responsibility. Though responsibility may mean some increase in part cost it will ultimately lead to company-supplier loyalty and a greater likelihood of reduced overall costs. Secondly, modular production allows the company to meet the previous four performance objectives and through improved quality, faster production and greater flexibility cost can be maintained at a low level.

These objectives are the building blocks of a competitive advantage from manufacturing. A company should be able to rank the importance of these objectives and how they perform against each of them. Achieving a high level of performance in each of the objectives should be a major priority of any manufacturing strategy.

A Generic Manufacturing Strategy Structure.

Below is a generic structure for a manufacturing strategy (Greenhalgh 1991), and its key elements. The nature of the manufacturing strategy should essentially be dynamic, updated regularly to meet the changing needs of the company, and the markets it serves. The strategy must also be given a time period over which the statements and assumptions are made.

1. Background
   a. Function definition
   b. Current situation
2. Basis for competitive advantage
   a. The key factors for success in the markets in which the organisation competes
   b. On the basis of the business key factors manufacturing will contribute to the success of the organisation through the following.
3. Key issues
4. Strategic aims
   a. What must to be done to address the key issues.
5. Strategic initiatives
   a. How the strategic aims are to be met.

The manufacturing strategy will now be used as a basis on which to highlight the key points and considerations related to the manufacturing strategy for modular products.

Background.

The aim of this section is to provide a statement as to the precise role of manufacturing over the time period considered, and to provide a perspective for the strategic aims and objectives. The **function definition** and **current situation** sections should also include specific references to the implementation of modular products and modular assembly processes. In order to successfully incorporate a modular design into a manufacturing system, there must be a clear statement of the current situation and the functional aims of manufacturing.

Basis for Competitive Advantage.

When identifying the basis for competitive advantage a list of **key factors for success in each major market in which the company competes** should be developed. The layout of these factors should highlight the influence of a modular product. Highlighting the influencing region provides a focus for defining the **contribution of manufacturing** to the success of the modular product and the success of the company. In addition the influence of the modular product allows the company to avoid allocating resources to areas which have no real impact on success.

Key Issues.

This section covers events, trends, facts or realities which are likely to have, or have had a significant impact on the company and manufacturing in particular. They can be summarised as the issues that have to be dealt with to ensure the long term effectiveness of manufacturing. Identifying and defining the key issues is paramount and requires a thorough and multi-disciplinary analysis. A number of key issues should include the management of change to a modular approach and its implications to manufacturing and to the company. Furthermore key issues should be identified that are influenced by a modular approach in order that the appropriateness of the level of modularity and commitment to this approach may be optimum.

Strategic Aims.

The strategic aims provide direction as to *what* must be achieved within the time period considered and are in direct response to the key issues. The aims are not necessarily a one-to-one correlation with the key issues but it is important to a modular approach that there are a number of issues that must be dealt with. A number of strategic aims include:

- To ensure the maximum benefit from the possibility of parallel production of modules.
- To provide an infrastructure and climate which encourages the work force to contribute to the development of the modular concepts and their production.
- To ensure that module assembly is as simple, responsive and flexible as possible.
- To investigate the possibilities for outsourcing all non-core modules.
- To ensure manufacturing input into module development as early as possible.

Strategic Initiatives.

The strategic initiatives are the statements as to *how* the relevant strategic aims are to be met. These statements must be qualified with an explanation and example of what is to be done. Examples of the initiatives that may be relevant to a modular approach are:

- Elimination of non-value adding activities. This covers the need to address outsourcing of modules but also calls for a tightening and refining of operations in manufacturing.
- Training of shop floor employees. This must be done to educate the workforce as to the new products and manufacturing processes associated with them.

Manufacturing Organisation.

Cellular Manufacturing.

Cellular manufacturing (CM) is an organisational framework that allows a modular approach to system design (Alford 1994) and facilitates the introduction of programmes such as computer integrated manufacture (CIM), just-in time (JIT) and total quality management (TQM). CM expands upon the theory of group technology, grouping products with the processes and personnel required to produce them. These groups form the basic cells from which the whole production process is structured. A cell may be defined by the processes that go into it, and the particular products that require those processes, or by a recognisable product, such as a subassembly, encompassing some part of the production process. The distinction gives the cell its identity, where a process based cell can produce different products yet retain its identity. A product based cell would be linked to that particular product, modification to the processes would not effect the identity of the cell, yet removing the product would remove the cell.

CM has advantages in both of it’s forms but the product based organisation is one that would be complimentary to a modular product. A manufacturing system structured to a cellular form in which cells are linked to modules of the products it produces would maximise the benefit of parallel production, and aid in the planning of production and scheduling tasks. This manner of organisation also provides continuity throughout the enterprise where module design teams will relate to module production teams in the cells of the manufacturing system, and should provide greater links throughout the system and simplified organisation.

It is recommended that a cellular manufacturing organisation of product based cells be given serious consideration. The use of product based cells for individual modules or a strategic selection of similar modules could be integrated with cells that form hierarchies of cells depending on the level of modularity, the size of the manufacturing organisation and the available resources. A high level cell may represent a common platform of a product range which is composed of a number of individual modules and therefore cells. Cells would operate in parallel and feed into a final assembly line or cell. Final assembly would then be responsible for assembly of modules to modules to form the finished product. This system would be fast and responsive allowing generic products to be easily tailored with the specific modules to meet customers need through the introduction of variety late on in the manufacturing process. The late introduction of variety, the ability to buy in complete, pre tested modules, together with simple final assembly all lead to an efficient manufacturing process.

After Manufacturing.

To reflect a total view to product realisation it is important to consider the impact of the product after it has been manufactured. Servicing and maintenance of products and also take-back, recycling and reuse all require serious consideration during the development phase. A modular design allows for the maximum utility to be made of these aspects. Modules can be specified that localise service or maintenance, allowing easy removal and replacement in the field. For the end of the life cycle, recyclable and reusable elements can again be grouped in a module. In fact, modules extend the possible life of a product by allowing common modules to be reused and upgraded, and modules added that contain the new features or technology.

SELF ANALYSIS — *Section 5*

AIM >> This section aims to begin a process which allows the generic HPD process to be tailored to individual requirements through analysis of the current situation, the clarification of aims, and the derivation of some metrics, in the form of goals or benchmarks. The self analysis will look at both the business and the product in order to provide a clear basis for a HPD framework.

The following analysis should be carried out honestly. This process is an attempt to provide the maximum benefit to the user and accurate answers will aid in this process. It should ideally be carried out by a multifunctional team, or as a minimum by a senior staff member who has views of both general company, and specific product details.

A1. Qualification analysis - to ascertain if the product is suited to a modular architecture.
A2. Advantage analysis - to ascertain the key business issues to which modularity is to be used.
A3. Implementation analysis - to ascertain the LOM most suited to the product and company.
A3. Groundwork analysis - to ascertain if basic groundwork requirements have been met.
A4. Driver analysis - to provide tailored guidance based on the reasons or drivers for modularity.
A5. Product analysis - to ascertain the possibilities for modularity, and highlight key elements.
A6. Manufacturing analysis -to ascertain how current facilities and practices may effect modularity.

Qualification Analysis (A1):

Please ring as appropriate.

correlation is?	strong	moderate	neutral
1. Does the product to be modularised require an integrated architecture?	3	1	0
2. Is the product sensitive to functional interfaces?	3	1	0
3. Is the product uniform in substance or formed through continuous processing?	3	1	0

Qualification Review: Your responses to the **qualification analysis** are weighted in importance according to the three responses. The summation of the three responses provides a qualification metric. A qualification metric in the range 0-3 indicates that the proposed product will be acceptable as a modular product. A further aid to qualification is the use of the manufacturing grids shown in **Figure 8**. Complexity refers to the variety of products, components, processes, sources of supply etc. Uncertainty is about the volume and stability of demand and the degree to which the product design is static. The shaded area represents the suitability of modular products:

Figure .8. Modularity Manufacturing Grids (adapted from PA Consulting Group 1989).

Modularity Classification

Uncertainty \ Complexity	**High**	**Low**
High	Sophisticated capital equipment	Fashion
Low	Consumer durables	Commodities

Modularity Classification

Uncertainty \ Complexity	**High**	**Low**
High	Aerospace Defence Ship building	Cosmetics Jobbing builders Packaging
Low	Automotive Machine tools Consumer durables	Simple components Paper Commodity tools

Advantage Analysis (A2):

Please ring as appropriate.

correlation is?	strong	moderate	neutral
1. Is the efficient deployment of customer requirements an important issue for your company?	3	1	0
2. Is the rationalised introduction of new technology an important issue for your company?	3	1	0
3. Is a structured approach to dealing with complexity an important issue for your company?	3	1	0
4. Is flexible or agile manufacture an important issue for your company?	3	1	0

Advantage Review: Your responses to the **advantage analysis** are summed to provide the advantage metric. An advantage metric in the range 8-12 presents an excellent opportunity for advantage through modularity, 3-7 an opportunity, and 0-2 little opportunity.

Implementation Analysis (A3):

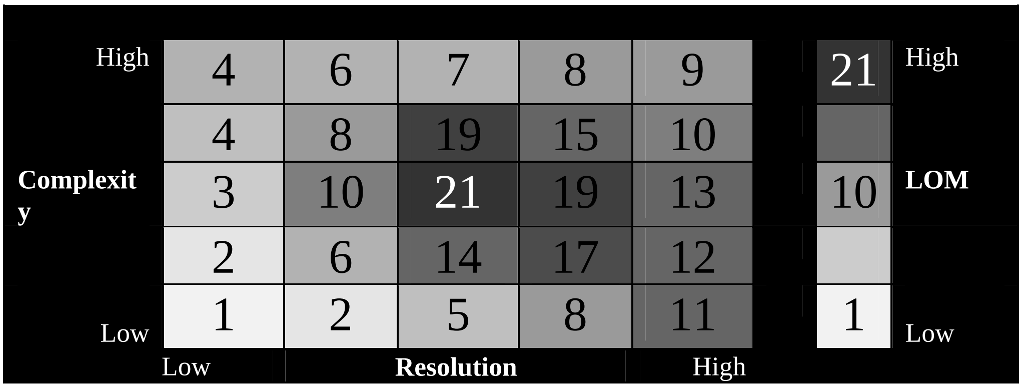
Please ring as appropriate.

correlation is?	strong	moderate	neutral
1. To what extent will the user desire / require configurability of the product?	3	1	0
2. What is the degree of possible commonality between the product and any other?	3	1	0
3. To what extent is the product likely to be modified / updated in the future?	3	1	0
4. How complex is the product and project undertaken?	3	1	0
5. To what extent is the product constrained by manufacturing strategy and processes?	3	1	0
6. To what extent will the product include elements requiring regular service or replacement?	3	1	0
7. What is the degree of possible recyclable / reuseable elements within the product?	3	1	0

Implementation Review: Your responses to the **implementation analysis** are a guide to determine the appropriate level of modularity for your product. The summation of the responses provides the level of modularity metric. A LOM metric in the range 17-21 corresponds to a very high level of modularity, 11-16 a high level, 5-10 a moderate level, and 0-4 a low level. The LOM metric can be related to a broad level of complexity, resolution, and composition, using Figure 9. as guidance.

1. *Complexity* - this is the functional level of modularity for each module. A module can contain anything from a single function to a combination of functions.
2. *Resolution* - this is the number of modules in the product. The number of modules relate to the complexity, where high numbers of modules will likely have low individual functionality
3. *Composition* - this is the degree to which complexity varies within a single product, and whether the product is a hybrid of an integrated common modules and variant modules.

Figure .9.
Level of Modularity Graph.



A further aid to the determination of the LOM is the **permutation chart**. The permutation chart is based on a morphological matrix and is a simple graphical method of exploring the possibilities for module levels and module standardisation. Possible solutions are marked in each column and the desired combination built up by linking solutions from row to row. However, this particular analysis is very subjective and should only form part of an important discussion on the level of modularity suited to the company's products.

Figure .10.
Permutation Chart.

Factors \ Solutions	1	2	3	4
Composition	No common element, all variant modules	Integrated common element	Modular common element	Only a common layout principle
Complexity	Low level of complexity in all modules	Medium level of complexity in all modules	High level of complexity in all modules	Mixed complexity levels in modules
Resolution	Only a small number (2-4) of variant modules	A medium number (5-10) of variant modules	A high number (10+) of variant modules	A variable number of modules to meet requirements

Groundwork Analysis (A4):

Please ring as appropriate.

correlation is?	strong	moderate	neutral
1. Does your company run an active concurrent engineering programme, using multi-functional teams?	3	1	0
2. Does your company have a defined product introduction process in place?	3	1	0
3. Does your company have a clear view of their corporate strategy and objectives?	3	1	0
4. Does your company have a clear product plan?	3	1	0
5. Does your company organisation allow for easy; use of multi-functional teams, communication, adoption of ideas?	3	1	0
6. Does your company know it's reason for developing a modular product?	3	1	0
7. Is your companies product suited to a modular architecture? (See analysis A1.)	3	1	0
8. Is your company committed to providing up front effort and accommodating the changes required for this process?	3	1	0
9. Have you an idea of the level of modularity suited to your product? (See analysis A3.)	3	1	0
10. Have you analysed your current situation in terms of products and future plans / corporate strategy and how they fit with a modular philosophy?	3	1	0

Groundwork Review: Your responses to the **groundwork analysis** are summed to provide the groundwork metric. A groundwork metric in the range 25-30 is acceptable and much of the structure and ground work has been provided to allow a modular design programme to be undertaken However, a perfect score of 30 is desired. These initial questions are to ascertain the readiness of the company for this work, the indication that there are some areas that are lacking requires further work to be done. All responses < 3 should be addressed before any further action is taken.

Driver Analysis (A5):.

Please place in order of preference.

Relating to the questions in A3, your desires for modularity are for:

1. Configurability	
2. Commonality	
3. Modification	
4. Complexity	
5. Manufacture	
6. Service	
7. Recyclability	

Driver Review: Your responses to the **driver analysis** will be used to provide a focus on the different benefits that may be derived from a product with a modular architecture. In addition, though all *Section 7* guidelines are important, specific implementation phase guidelines of interest are highlighted.

1. Configurability:

Module variety, simple assembly, flexible interfaces.
Consider:

- Ensuring modules are easy to assemble and disassemble.
- Placing user specific features in variant modules.
- Provide a generic architecture / module that is common to all products and combines the minimum basic features of the product.
- Ensuring modules are self contained.
- Providing flexible interfaces to allow modules to be combined without modification.
- Guideline numbers: 8-12, 15, 17-22, 25, 27, 32-33, are especially pertinent.

2. Commonality:

Common modules and interfaces, carry-over modules, generic architectures.
Consider:

- A generic ‘platform’ module or modules.
- An open design that allows the greatest flexibility for future product specifications.
- Redundancy to provide the degree of functionality to meet all requirements from a standard.
- Standardising from the bottom up; look at part standardisation, service standardisation, configuration and architecture standardisation.
- Guideline numbers: 8, 10-13, 15, 16, 19, 20, 24, are especially pertinent.

3. Modification:

Localised areas subject to change, common interfaces, upgrades.
Consider:

- Modularise areas that are liable to change through customer requirement or new technology.
- An ‘open’ interface design to provide flexibility for possible future designs.
- Allowing flexibility in the physical size and location of modules for future upgrades.
- Allocating customer specific features to single modules.
- Building in greater potential functionality than may be initially required.
- Guideline numbers: 10-12, 15, 18-22, 27, are especially pertinent.

4. Complexity:

Product complexity and project complexity management.
Consider:

- Utilising module teams to decompose the design project.
- Ensure the total view is maintained and consider systems engineering approaches.
- Linking product module development to manufacturing cell development.
- Decomposing complex systems into modules that combine for a common purpose.
- Use variety modules to minimise complexity, diverting it to configuration for the customer.
- Standardising wherever possible, from components to architectures.
- Guideline numbers: 2-4, 8-9, 12-13, 17, 19-20, 23-24, 28, are especially pertinent.

5. Manufacture: Reduced part numbers and part variety, self location, standardisation.
Consider:
- DFA techniques, look to reduce part numbers, part variety, make parts easy to locate, align and insert.
- Treating complete modules as parts in an assembly, look to make modules self locating, easy to align, and easy to insert.
- Ensure final assembly is all modules. Avoid introducing parts at this late stage.
- Linking modules to manufacturing cells to localise change.
- Introducing variety only during final assembly for maximum order flexibility.
- Guideline numbers: 10, 14, 17, 19-24, 28, 31-38, are especially pertinent.

6. Service: Self contained features that require maintenance or replacement.
Consider:
- Locating serviceable elements in accessible locations.
- Serviceable modules that are self locating for ease of disassembly and re-assembly.
- Grouping all serviceable elements into a single or limited number of modules.
- Guideline numbers: 10, 12, 15-16, 18-20, 22, 26, 35, are especially pertinent.

7. Recyclability: Recyclable or reuseable modules, ease of disassembly.
Consider:
- Modularise recyclable materials by material type.
- Modularise recyclable elements.
- Modularise reuseable or refurbishable elements.
- Ease of disassembly of recyclable modules as this will affect their reuse.
- Guidelines: 10, 16, 18, 27, are especially pertinent.

Though not directly part of the driver analysis the following guidance is presented relating to some popular drivers for modularity. Though they are actually derived from the seven drivers of A5 they are presented as additional guides for convenience.

A. Project management: Divisioning and deploying of responsibilities and work loads, parallel working.
Consider:
- Using separate multifunctional teams for separate modules.
- Decomposing the project into modules that exist around product modules.
- Ensuring modular design is a clear focus from the outset of a new product.
- Guideline numbers: 1-9, 12, 30, are especially pertinent.

B. Lead time to market: Parallel development and manufacture, reduction in reengineering.
Consider:
- Developing separate modules with separate teams in parallel.
- Manufacture modules off the main line, so that final assembly is just assembly of modules.
- Those points for Manufacture and Modification.
- Introduce variants late, so products are not dedicated to specific orders until late as possible.
- Guideline numbers: 3, 4, 7, 12, 15, 17, 31, 38, are especially pertinent.

C. Bought in modules: Bought in modules tested and ready for assembly.
Consider:
- Isolate any areas of non-core business and modularise them.
- Get modules to be fully tested by the supplier, to your specifications.
- Working to a JIT principle with the delivery of modules.
- Guideline numbers: 5, 10, 25, 30, are especially pertinent.

D. Consistent quality: The control of quality in manageable modules with defined traceability.
Consider:
- Keeping critical features of quality in single modules.
- Adopting principles of dimensional control where appropriate.
- Testing modules when complete, prior to final assembly.
- Guideline numbers: 4-6, 10, 14., 23-25, 29, are especially pertinent.

Product Analysis (A6):

Using your existing or precursor product, or prototype:

1. Begin by drawing a schematic or retrieving an original, and listing the functional blocks.
2. Relate the functional blocks to physical groups of components / sub-assy's in the existing product?
3. Identify the boundaries between the *physical* blocks of the product.*
4. If components do not satisfactorily fit into a block, create a new one and link it into the schematic.
5. If there are obvious secondary groupings of blocks in the product, identify these on the schematic.

Having related the product to it's schematic we now begin to identify modularity possibilities.

6. Identify the functional blocks that are necessary in the new product.
7. Identify the functional blocks that would be advantageous in the new product.
8. Identify the functional blocks that would be a possibility in the new product.
9. Ensure that those blocks that have not been identified above have no use in the new product.
10. Starting with necessary blocks, check to see if they can physically cohere as separate assemblies.
11. Further identify the secondary groupings of blocks that can cohere as assemblies.
12. Identify any blocks that may form a secondary grouping once freed from the existing product.

The modules, or basis for modules that can be carried over have now been identified.

13. Identify any blocks or secondary groupings that may form a generic element to a range of products.
14. Identify any blocks key to backward compatibility.

* All components in the product must belong to a block.

Product Review: Your findings in the **product analysis** can be used to provide valuable material for the new product development. The blocks or secondary groups can be used as modules in the new product with a varying degree of modification. The goal is to make use of as many modules as possible with as few a modifications as possible. The modules should be worked through in order, from necessary to possible, placing them directly into the new product schematic or placing them on the key elements list. Opportunities should be sought to standardise on the interfaces that will likely be poor on the identified blocks.

Manufacturing Analysis (A7):

1. Identify the structure of the manufacturing organisation and obtain the results from A 6.
2. Identify the links between the blocks from A 6. and the manufacturing processes that produce them.
3. Identify any corresponding grouping of processes to the blocks.
4. Aim to mirror the block structure (modules) by grouping processes that manufacture them (cells).
5. Ensure that the processes related to any generic element are grouped separately.
6. Group assembly operations into workstations for the modules.
7. Identify modules that are non-core business and aim to procure them as a total package.

Manufacturing Review: Your findings in the **manufacturing analysis** will allow the existing facilities and processes to be adapted to maximise the benefit from a modular product architecture. The degree to which this can be done is related to the size of manufacturing operation. Large organisations can aim to mirror the modules by manufacturing cells such that changes to the product are localised in manufacturing and will not effect other parts of the product. Smaller organisations must look toward identifying modules that can be procured totally from one vendor, and to rationalising vendor usage by grouping similar components and materials for procurement.

Assembly should be grouped about modules where possible. This provides efficient assembly by having workstations that run in parallel, leave the definition and thus variety of the product till late on, provide completed modules, allow modules to be tested individually, and provide interesting work and responsibility for the assembly workers. The modules then go to final assembly which can be used to define the final product.

AIM >> This section presents a number of checklists to be completed by those employees involved (programme team) with the HPD methodology. Their function is to aid the application of HPD principles by acting as a framework for the many activities of the programme, a focus for effort, and a visual reminder of the status of the programme. They should be completed and kept in a central location (database / server) to allow all employees involved access to their status.

It is important that these checklists are customised with user specific questions, and preferably linked with a number of further checklists that relate to product development stages not included in this workbook such as, marketing, distribution etc.

Holonic Product Design Checklist.

Checklist 0.

Due Date	On Schedule	Person Responsible		Number
			1. Programme fundamentals complete?	Checklist 1
Item 1 to be completed prior to 2-5.				
			2. Timeliness of overall project: on schedule?	Checklist 2
			3. Self analysis complete?	Checklist 3
			4. Modular design (by team) on target?	Checklist 4
			5. Manufacturing strategy on target?	Checklist 5

Programme Fundamentals Checklist.

Checklist 1.

Due Date	Date Complete	Person Responsible	
			1. Purpose and objectives for modularising product noted?
			2. Benchmarks set and being measured?
			3. Business strategy statement documented and agreed?
			4. Schedule for programme agreed and set?
			5. Total elapsed time required for module definition set?
			6. Adequate staffing to assure schedules?
			7. Vendor participation planned?
			8. End user / customer participation planned?
			9. Team members and leader identified?
			10. Management signoff on modularity vision, levels and spec?

HPD Schedule Timeliness Checklist.

Checklist 2.

Due Date	Date Complete	Person Responsible	
			1. Modularity / Design reviews held per plan? Percent to plan?
			2. Key elements identified?
			3. Module criteria identified?
			4. Internal documentation on schedule?
			5. Hardware module design on schedule?
			6. Software module design on schedule?
			7. Manufacturing tasks on schedule?

Self Analysis Checklist.

Checklist 3.

Due Date	Date Complete	Person Responsible	
			1. Qualification analysis performed and completed?
			2. Current modularity problems / bottlenecks analysed?
			3. Advantage analysis performed and completed?
			3. Implementation analysis performed and completed?
			4. Permutation chart complete?
			5. Groundwork review performed and completed?
			6. Driver review performed and completed satisfactorily?
			7. Product review performed and completed satisfactorily?
			8. Manufacturing review performed and completed?

Module Design Checklist.

Checklist 4.

Due Date	Date Complete	Person Responsible	
			1. Team members identified, and Chair?....................................
			2. Regular team meetings scheduled and attended by team? %..
			3. Team communication channels established?
			4. Level of modularity agreed and understood?
			5. Key elements collected and deployed?
			6. Module criteria documented with traceability?
			7. Rough product schematic drawn up and agreed?
			8. Element interaction analysis performed?
			9. Elements clustered into modules?
			10. Module interaction analysis performed/
			11. Rough geometric layout of modules performed?
			12. Modules tested against criteria?
			13. Module sign off when adherence to criteria satisfactory?
			14. Module specifications drawn up in full?
			15. Interface specifications drawn up in full?
			16. Standard modules identified?
			17. Standard interfaces defined?

Manufacturing Strategy Checklist.

Checklist 5.

Due Date	Date Complete	Person Responsible	
			1. DFMA conceptual analysis performed on modules?
			2. Tolerance studies performed to guarantee assembly fit?
			3. Close tolerances self locating?
			4. Modules designed with location tooling considered?
			5. Benchmark set for ease of module assembly (B-D) %...........
			6. Benchmark set for ease of upgrade?
			7. Benchmark set for ease of service?
			8. DFMA analysis performed on final assembly modules?

AIM >> These guidelines present a comprehensive explanation of many of the principles of the HPD methodology. They are related to the checklists and where relevant should be used to explain the checklist points in greater detail. In addition, the guidelines can serve as a stand alone document for reference of the desired requirements to lead to a successful modular product design and associated manufacturing process.

Concept Phase Guidelines.

1. **A definition of the purpose for modularising the product must be determined.**
   This definition will force a close examination of why modularity is deemed necessary in the new product development, and will act as a benchmark and focus for development

2. **The current situation must be documented to allow mapping to the new objectives.**
   The decision has been made to develop a modular product. What in the current system (product / design process) does and does not match the objectives for the new development system and new product? This identification of factors will aid in tailoring the change

3. **Working practices that may inhibit the change to modular design must be identified.**
   Any part of the product development process must be identified if it may not be suited to the new corporate objectives, and objectives for modular design. These areas can then be modified to allow modular design to take place

4. **A product must be committed to modularity from the beginning.**
   The decision to modularise the product must be made from the earliest possible moment and must then be a key element in the products development. Modularity fundamentally changes the traditional method of integrated design and cannot be done lightly.

5. **The commitment to modularity must include an acceptance of change.**
   For many companies modularity and its implications will be considerably different from their current processes. This transition may cause issues within the company to arise and thus the smooth and flexible handling of these will be essential for the technique to work.

Feasibility Phase Guidelines.

1. **A product must be assessed at to whether a modular architecture is beneficial.**
   A seemingly good product for modularisation may, in fact, be extremely difficult to define into modules and arrange suitable interfaces to other modules. The product in question may also be degraded by a modular architecture. Highly integrated systems where performance is the prime requisite are not suitable for modularity.

2. **A definition must be made as to the level of modularity required, and a limit placed on the degree of modularity, based upon the purpose for the modular product**
   The level of modularity ranges from one module per function; providing flexibility in function configuration but also high complexity and reliability issues. To, one module for a number of functions; providing less flexibility but also less complexity and greater robustness. In-between, standard products with modules for variants provide a balance of these properties. A decision must be made for suitability and then adhered to.

3. **The key elements of existing and planned products must be identified for assessment of module requirements.**
   The key elements of the product range can be targeted for modular design to allow new technology or innovation to effect the market edge of the products in a rationalised manner, without effecting the rest of the product adversely.

4. **Products that exhibit beneficial features must be identified.**
   Any product that has ‘good’ features can be built upon if modular or identified as an area to work around if integrated.

Implementation Phase Guidelines.

Project Management.

1. **The project must be assigned a multifunctional project team to provide expertise from all concerned departments.**
   In addition to the general good practice of using multifunctional teams there is the need for this approach due to the degree of parallel thinking required in complex modular problems.

2. **Modular design should be met by module teams being managed separately.**
   The project can be naturally broken down into smaller more manageable parts. These parts will relate to modules and thus personnel of appropriate fields may work on appropriate modules. Work may also be carried out simultaneously, thus interface problems that will always address more than one module can be worked on from both sides.

3. **The module teams must be multifunctional.**
   Module teams have responsibility for getting the module to meet all its criteria concerning the customer, design and manufacturing. The team must therefore include representatives from all relevant departments and suppliers so that all issues are dealt with at an early stage.

4. **Both project and module teams must have extremely good communication concerning interfaces.**
   Interfaces have special consideration within these guidelines and the process of design must reflect this. The interface definition and communication for interface decisions must be good. This may include a greater number of team meetings at an early stage.

5. **The purpose and definition derived at the concept phase must be deployed into objectives for the team.**
   The initial job of the team is to deploy the high level decisions into objectives for the development of the new product. This initial stage will provide focus for the team in specific design terms which relate to business goals.

6. **The results of the feasibility phase must be integrated into the team objectives.**
   Information from the feasibility phase must be used to provide the basis for the new development. Concerns with existing products can be integrated and built upon, and issues with the development process can be modified to meet the strategic objectives.

7. **Modules must be planned, designed and developed in parallel.**
   Modular design allows for parallel design and development of individual modules and also of the associated processes. Advantage must be taken of this ability to reduce lead times.

8. **Modules must be defined as early as possible within the development process.**
   The work on defining modules is done early on so that major decisions are made before any factors are agreed upon. Thus changes cannot interfere with work done previously. Also increased up front effort will reduce problems downstream.

Process.

9. **Each module must be assigned a number of functions based on the level of modularity.**
   The number of functions per module will be determined by the degree of modularity required, but this factor is very important when defining the modules as it will impinge on the complexity and structure of the modules and product.

10. **Modules must be self contained.**
    The required functionality of a module must be contained wholly within the module. There must be no components that do not belong to a module. A module must be able to be manufactured as a stand alone sub assembly.

11. **Avoid concentrating on a particular product when designing.**
    The team must be aware of variants or possible areas of commonality between other products, existing or future. This insight provides the broadest possible base for standardisation and flexibility throughout a product range or family.

12. **Generic architectures should be determined for all products, and new products should be based on this platform.**
A generic architecture will provide product and manufacturing flexibility. It will provide a framework for new products that will therefore be easier to design to be compatible, and be easier to manufacture with the maximum of reuse of components and equipment.

13. **Standard modules must be used as much as possible to standardise across products.**
HPD gives the advantage of a theoretically large product range with only a relatively small number of specific modules. The use of standard modules can be exploited fully to reduce stock holding, tooling, part variety, etc.

14. **Design to natural modules.**
Modular design does lend itself naturally to existing divisions, such as those between electrical, and mechanical areas. Designing to natural features will improve design quality.

15. **Develop modules for the areas likely to change in future products / revisions.**
If modules can be developed for areas of the product that are likely to change, a number of benefits are gained. A proportion of all products is standard. Instead of total redesign, upgrades and modifications may be made to a limited number of modules, so change to both the product and manufacturing system is limited. This is especially useful to parts the customer sees, or functional areas such as engines (same car, different engine). This is important for highly complex products or products constantly in a state of flux, such as those in high technology industries, where upgrades in products happen very frequently.

16. **Modules must be defined for any parts that are consumable, or that may be removed at a later stage.**
For consumables such as toner, bearings etc. and toxic or recyclable materials, should be contained in a module to allow easy service, removal and replacement, or disassembly.

17. **Modules must be designed such that variety can be introduced late on.**
The use of modules in a products design allows standard modules to be manufactured and then introduced to the final assembly. Thus individual variations are only assembled at the very end of the line, prior to shipping.

Interfaces.

18. **Modules must be designed with great care and attention to interfaces.**
Module use highlights the problem of interfacing the individual modules to one another. Normally these interfaces would not be so well defined, and would not be designed to come apart so readily, or indeed go together so readily thus the new interfaces must consider making all relevant connections between modules at purely one fixed set of interfaces.

19. **Standard interface locations should be determined wherever possible.**
The use of standard interfaces for modules will increase the flexibility of module usage by allowing easier interchange of variant or upgrade modules.

20. **Standard interface types should be determined wherever possible.**
Interface types, connector types and communication standards should all be consistent. This allows easier interchange or replacement of modules, negates incompatibility problems, eases assembly, reduces stock holding, and makes the designing of modules easier through only having to meet a limited number of interface criteria.

21. **Interfaces must provide transmission of all function required between modules.**
Interfaces must allow the required communication and transmission between modules at that discrete point / surface. Interfaces will be a key element in the functioning of the product. The interface cannot be made up from, or enhanced by, components not part of a module.

22. **Interfaces must allow easy connection / disconnection of modules.**
The interface design must allow modules to be assembled and disassembled with ease. The ease of these operations will benefit the functioning of the modular design in terms of upgrade, service, and recycling.

Good Practice.

23. **Modules should be as simple as possible whilst adhering to the number of functions defined earlier for each module.**
    The use of simple modules will avoid problems with reliability, manufacturing costs, servicing, and provide a greater chance for standardisation of modules between products. Even though it may be decided to have some highly integrated modules, these should still be developed with simplicity in mind.

24. **Modules must use as many standard parts and subassemblies as possible.**
    The use of standardised parts, reduces stock holding overheads, eases assembly and servicing, and reduces complexity.

25. **Modules must be testable independently.**
    Modules must be designed so that their function may be tested as a separate unit. The ability for modules to be pre tested gives a greater level of product quality by products being tested in individual areas and not just as whole products, thus allowing systems to be more robust and faults found easier.

26. **Modules must be designed to facilitate maintenance and servicing.**
    Modular products allow easier access to restricted locations and easier removal of individual units for service, reconditioning or replacement. There are also the advantages for simple operations such as lubrication, refilling, and the like, that may not come under service.

27. **Modules must be designed for ease of disassembly.**
    The modular product will provide natural decomposition into manageable units for requirements such as recycling or servicing.

28. **Both the product and the manufacturing process must be designed simultaneously.**
    Modules allow easier design of product and process simultaneously, by considering simplified individual units rather than a complex complete product. Thus when a module is being designed, the requirements for its manufacturing, assembly, and test facility and tooling can be drawn up. It is then a much simpler task to design the main assembly line where module combinations are assembled.

29. **Separate specifications must be drawn up for all modules.**
    The use of modules will not only require one overall product specification, but individual specifications for each module within the product. Across the range of specifications details will have to be standardised, and thus the actual management of such material will be increasingly difficult, due to individual groups responsible for individual modules. Specifications will also be more complex having to define interfaces and what will be required to ensure continuity.

Manufacturing and Assembly.

30. **Make use of bought in modules whenever a module falls outside core business.**
    Standard modules may be bought in directly from a supplier, pre-tested and ready for assembly. Thus benefits are gained through reduced assembly costs, material handling costs, and quality control.

31. **Modules must be designed with manufacturing issues in mind from the earliest point.**
    The use of multifunctional teams for product development will aid in the simultaneous engineering of the product, but manufacturing must be part of this process. Failure to address manufacturing concerns will prohibit much of the benefit from modularity.

32. **Modules must be designed for ease of assembly and manufacture.**
    Modularisation of a design can provide a platform for the use of other techniques such as DFA and thus promote reduction of parts and part variety within the product. Part reduction and DFA are integral parts of a modular strategy. If modules are designed to be easy to assemble with one another, much utility will be derived for the assembly process, the servicing of the product and the ease of customer upgrade.

33. **Modules must be assemblable without adjustment.**
Modules must be designed to assemble to one another without adjustment such that modules may provide easier assembly, easier replacement at a later date, and remove quality / reliability issues with adjustment.

34. **Modules should be designed with standard locating features.**
Standard locating features allows easier assembly and replacement of modules, and benefits the automated assembly of products. Thus transport systems can be used without modification for different modules.

35. **Modules must be self locating.**
Self location aids assembly and replacement of modules.

36. **Modules should be designed with the capability for automated assembly, if automation is commonly used or desired by the company.**
A modular strategy promotes the use of automation by simplifying assembly, using standard parts, and by grouping of similar types of operations within the same team work area.

37. **The plant layout should reflect the modules of the product.**
The grouping of module manufacturing into self-contained cells allows for easier planning of factory layout, and improves communication between key areas. A factory organised into these cells can operate with greater efficiency by running in parallel and thus do not suffer from a problem in an individual cell halting production.

38. **Modules should be assembled off the main line.**
By assembling modules independently of the main line, the main line is not tied to assembly of individual components, only modules to one another, and is thus more flexible. This set up also allows modules to be assembled in parallel.

REVIEWING THE PROCESS — *Section 8*

This section is to be added in a future version, through consultation with users and analysis of feedback. It will address any issues with the HPD methodology when it has been implemented and has been running for a short while. It is aimed to provide some guidance on any areas that may require modification or tuning.

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GLOSSARY

BS 5750 / ISO 9000	Quality systems standard that comes in a number of parts. The parts used in this document are: Part 1. ISO 9001 - Specification for design / development, production, installation and servicing, and Part 4. ISO 9004 - Guide to the use of BS 5750 : Parts 1, 2 & 3.
BS 7000	Design management systems in four parts. The parts used in this document are : Part 1 (1989). - Guide to managing product design, and Part 2 (1997). - Guide to managing the design of manufactured products.
Conceptual design	Preliminary research and design studies to establish design alternatives that merit further development.
Cellular manufacturing	The smallest natural grouping of manufacturing personnel and/or equipment producing a family of products typically defined by group technology, clustering or production flow analysis (John 1990)
Design brief	Statement that describes the purpose and required performance of a product or service. NOTE. The statement includes time and cost to complete the design. Product cost and investment targets are also included.
Design specification	A document that defines the requirements and restraints of the product design to those responsible for design. NOTE. A design specification differs from a design brief in that it contains only definitive design requirements whereas a design brief also contains project requirements, e.g. time scale, and is usually less prescriptive.
Design trigger	That which sets into motion a new product or design programme.
DFA - Design for assembly	A technique aimed at improving the design efficiency for assembly of a design. This is done by reducing the number of parts, part variety and providing guidance in the most efficient way of assembling components.
Detail design	The process in which the precise shape, dimension and tolerances are specified, the material selection is confirmed and method of manufacture confirmed for every individual part of the product.
Dimensional management	A system of accepting the existence of variation in assembly and learning to manage that variation. Often associated with a software solutions (such as VSA or Valisys) for manipulating assembly sequences to achieve the best stack up of tolerances or moving the variation to less critical areas.
Feasibility study	Examination of a possible design concept / proposal to determine whether it can realistically meet the specified requirements.
General arrangement design	The stage in the process where all the elements are brought together to establish physical relationships and practicality.
Holon(ic)	The word holon (Koestler 1967), is a combination of the Greek word *holos* meaning whole, with the suffix *on*, as in prot*on* indicating a part. The use of the word holon and holonic is an attempt to indicate something which is simultaneously a whole and a part of a whole. Thus a self contained module is a whole in such that it has a function and can operate on its own, but at the same time it combines to form a greater whole and thus can be seen as a part.
HPD - Holonic product design	A design framework aimed at employing systems concepts and modular design to providing efficient and effective product designs and manufacturing systems. The term HPD is used to provide an indication that the key to design is keeping the full complexities of interactions in view while dealing with specific sub-systems (Kidd 1994).
Interface	Boundary common to two or more systems, or other entities at which information flow takes place, or that have physical contact.
Just in time (JIT)	A manufacturing methodology whereby facilities are only presented the product on which to perform their operations when they are ready. This effectively negates stock holding as all components are called for or 'pulled' by the impending operation. The principle can be extended to JIT delivery of components from suppliers, and forms the backbone of a lean production process.
Modular products / design	Modules are independent units of function that are self contained. Combinations of these modules can be used to form products where different combinations alter the functions of the product. Modular design is the discipline of designing products in modules as oppose to an amorphous whole.
PIP Product introduction process	This is the total product development process from the product trigger to product availability. Embodied within this series of events is the design, development, and manufacture of the product.
Robust design	a) A design that is created with the intention or ability for future evolution. b) Design of a product that is insensitive to variations in its manufacturing or use.
Total quality management (TQM)	TQM has two main components; customer service and individual employee responsibility for quality. Customers are anyone to whom a service is supplied and includes internal departments. Each area strives to better understand their customer's needs and deliver a better service. The responsibility issues means that performance targets should be in place and if employees are expected to meet these targets they must be trained and consulted in developing the goals. Thus emphasis on team work, training, communication, and breaking down of barriers.

APPENDIX

Revision History.

Version 0. 21/05/96.
0. 19/06/96.
0.1 01/08/96.
0.11 10/09/96.

- Self analysis refined, tabular questions added and simple analysis presented.
- Guidelines arranged to format of HPD process.
- Format and presentation changes.
- HPD refined and details regarding modular design moved to the appropriate section.
- Designing for modular products refined and improved, more explanation, and focused on interactions.
- Glossary added.
- Manufacturing strategy for modular products conceived.

Version 0.2 13/11/96. **Major update.**

- Customising the HPD process dropped.
- Self analysis highly improved and focused.
- Checklists arranged to format of HPD process. Checklist items improved.

Version 0.3 22/11/96. **Major update.**

- Minor presentation and format improvements.
- Software considerations added.
- Manufacturing strategy for modular products added.
- References added.

Version 0.4 06/12/96. **Major update**

- Major presentation changes.
- Manufacturing strategy now includes cellular manufacturing.
- Self analysis improved and now includes a more detailed analysis of the LOM
- Glossary updated.
- Revision history added.

Version 0.5. 16/12/96. **Minor update**

- The legacy factor added.
- Balancing it out added (r).
- Self analysis modified, questions all in positive logic (r), LOM graph added.
- Manufacturing strategy now briefly includes after manufacturing.
- Implementation guidelines further subdivided for ease of use (r).

Version 1.0. 24/01/97. **Minor update**

- Product and Manufacturing reviews added.
- The legacy factor and Balancing it out completed.

Version 1.1. 16/06/97. **Minor update**

- Numerous small modifications (r)

Version 1.2. 12/09/97. **Minor update**

- Overhaul of self analysis section.
- Formatting changes.

(r) modifications denoted thus are due to feedback from industry.

Detailed Systems Engineering Phases. Adapted from Walker (1997).

Systems Engineering Phase	Process
Requirements Management	Identify and capture source documents
	Identify requirement categories
	Capture and categorise requirements
	Engineer and augment requirements
	Decompose and fuse requirements
	Trace requirements
	Generate compliancy matrices
	Perform initial risk assessment
System Analysis	Identify useage scenarios and mission profiles
	Identify system phases, activities and modes
	Identify alternate design cases and production possibilities
	Define the system environment
	Produce an environment model
	Perform functional analysis and decomposition
	Rationalise system functions
	Trace functions and scenario elements
	Generate compliancy matrices
	Refine risk assessment
	Complete a test strategy assessment
	Begin system failure modes assessment
Architecture Modelling	Produce platform component breakdown
	Identify system elements
	Determine system topology
	Identify possible manufacturing strategy and processes
	Allocate requirements to system elements
	Define performance constraints
	Allocate performance budgets
	Allocate manufacturing budgets
	Impose technology constraints
	Conduct performance assessment
	Continue risk assessment
	Refine system and integration test strategies
	Perform failure mode analyses
	Identify reversionary modes
	Investigate damage and failure modes
High Level Design	Characterise mandated & commercial off the shelf (COTS) equipments
	Assess suitability and / or shortfalls of equipments (process feedback)
	Allocate functions to equipments
	Integrate equipments into architecture
	Identify manufacturing processes for equipments
	Identify and integrate equipments suppliers
	Specify internal system / subsystem interfaces
	Fully specify environmental interfaces
	Impose technology constraints
	Conduct performance assessment
	Continue risk assessment
	Refine subsystem test strategy
	Trace design elements
	Refine failure mode assessment
Detailed Design	Refine component breakdown to assembly
	Perform DFMA analyses on assemblies
	Plan manufacturing and assembly processes and tooling requirements
	Specify all internal interfaces
	Allocate functions to hardware / software
	Allocate requirements to system elements
	Define performance constraints
	Allocate performance budgets
	Impose technology constraints
	Conduct simulation / execution assessments of product and process
	Complete risk assessment
	Define unit and subsystem tests
	Define process quality plan procedure and tests
	Prove reversionary modes
	Prove damage and failure modes
Module build	Code software modules and static analyse
	Produce hardware schematics
	Build and test pre-production prototypes
	Manufacturing and assembly facility layouts
	Produce PCB layouts
	Design mechanics/hydraulics/pneumatics
	Conduct engineering analyses
	Complete bill of materials
	Completion of manufacturing and assembly processes
	Trace all elements into system definition
	Produce compliancy matrices
Implementation	Purchase and installation of manufacturing facilities and tooling
	Arrangement of leasing and service provision
	Identification of premises
	Recruitment and training of personnel
	Provision of packaging and distribution network
	Product launch

5 THE PARABLE OF THE TWO WATCHMAKERS

Central to the concept of holonic manufacturing is the Holon. This term is derived from two observations by Koestler (1989). The first is from Simon (1962 & 1990) and is based on the parable of the two watchmakers:

> There were once two Swiss watchmakers named Bios and Mekhos, who made very fine and expensive watches. Although their watches were in equal demand, Bios prospered, while Mekhos just struggled along; in the end he had to close his shop and take a job as a mechanic with Bios. The people in the town argued for a long time over the reasons for this development and each had a different theory to offer, until the true explanation leaked out and proved to be both simple and surprising.
>
> The watches they made consisted of about one thousand parts each, but the two rivals used different methods to put them together. Mekhos had assembled his watches bit by bit - rather like making a mosaic floor out of small coloured stones. Thus each time he was disturbed in his work and had to put down a partly assembled watch, it fell to pieces and he had to start again from scratch.
>
> Bios on the other hand, had designed a method of making watches by constructing, for a start, sub-assemblies of about ten components, each of which held together as an independent unit. Ten of these sub-assemblies could then be fitted together into a sub-system of a higher order; and ten of these sub-systems constituted the whole watch. This method proved to have two immense advantages.
>
> In the first place, each time there was an interruption or a disturbance, and Bios had to put down, or even drop, the watch he was working on, it did not decompose into its elementary bits; instead of starting all over again, he merely had to reassemble that particular sub-assembly on which he was working at the time; so at worst he had to repeat nine assembling operations, and at best none at all. Now it is easy to show mathematically that if a watch consists of a thousand bits, and if some disturbance occurs at an average of once in every hundred assembling operations - then Mekhos will take four thousand times longer to assemble a watch than Bios. Instead of a single day, it will take him eleven years. Simon concludes: "Complex systems will evolve from simple systems much more rapidly if there are stable intermediate forms than if there are not."
>
> The second advantage of Bios' method is of course that the finished product will be incomparably more resistant to damage, and much easier to maintain, regulate and repair, than Mekhos' unstable mosaic of atomic bits.
>
> This leads to the fact that wherever there is life, it must be hierarchically organised.

The second is the relativity of hierarchies.

> The first universal characteristic of hierarchies is the relativity, and indeed the ambiguity, of the terms 'part' and 'whole' when applied to any of the sub-assemblies. Again it is the very obviousness of this feature which makes us overlook its implications. A 'part', as we generally use the word, means something fragmentary and incomplete, which by itself would have no legitimate existence. On the other hand, a 'whole' is considered something complete in itself which needs no further explanation. But *'wholes' and 'parts' in this absolute sense just do not exist anywhere.* What we find are intermediary structures on a series of levels in an ascending order of complexity: sub-wholes which display, according to the way you look at them, some of the characteristics commonly attributed to wholes and some of the characteristics commonly attributed to parts. The members of the hierarchy, like the Roman god Janus, all have two faces looking in opposite directions: the face turned toward the subordinate levels is that of a self contained whole; the face turned upward toward the apex, that of a dependent part. This '*Janus effect'* is a fundamental characteristic of sub-wholes in all types of hierarchies.

6 MFD EVALUATION CHART

Guide			
General Number of parts in average product (Np). A relevant objective for a new concept is 70%. (New Np = 0.7*Old Np). Estimate the average assy. time relation between part assy.op. Common average part assy. op. is 10 seconds (Tnorm = 10). 10 sec. op. time is an easy interface and 50 sec. a fairly difficult one (Tnorm ≤ Tint ≥ Tnorm). T_{int} = Average assembly time for interfaces T_{norm} = average assembly time for one part (10 sec).	N_p = ... assembly time relation T_{int} / T_{norm} = ...		
Lead time in assembly	**Ideal, Optimum or Goal**	**Actual**	**Yield**
$L = (N_p T_{norm} / N_m) + (N_m - 1)T_{int}$ Where: N_m = Number of modules in one product	$20 \sqrt{N_p} - 10$ = ... Ideal when assembly time relation = 1		%
System cost Share of purchased modules following the rules.	Goal = ...		
Product cost $C = \sqrt{N_m N_{mtot}} (\sum T_{int} / 3?)$ Where: N_{mtot} = Total number of modules.	$1.5 \sqrt{N_p}$ = ...		
Quality Estimate the expected average defects in figure "Expected....". (PPM).	Ideal value (all seperately tested) from figure, upper curve, 100% = ...		
Lead time in development Int. Compl. = $\sum T_{BDIi} / 3$ Where $\sum$ is between i = 1 and T_m -1, and T_{BDIi} = Assembly time for interface, i. (DFA-analysis)	$((N_m - 1)10) / 3$ = ... Observe Nm = the actual value for the concept evaluated.		
Development cost Estimate the share of "carry overs" following the rules.	Goal = ...		
Development capacity Share of purchased modules as above.	Goal = ...		
Sales / after sales Product variants as: $E_{var} = N_{var} / N_{mtot}$ Where: N_{var} = Number of variants that can be built N_{mtot} = Total numbers of modules needed.	"Maximise"	....	....
Service / Upgrading, check the MFD for functional "purity".	No functional connections between modules.	....	....
Recycling, see seperate Pareto chart.	The 80/20 rule	....	....

7 THE PROS AND CONS OF MODULARITY

Product design pros

1. **Improved product development.**
Consideration of a modular product promotes teamwork, and thus, development of the product by all departments simultaneously. Modules offer the ability to be developed in parallel, thus reduced lead time, and the use of carry-overs. Product changes may be introduced more smoothly as they can be focused on individual modules.
2. **Simpler Products.**
With the use of a modular strategy linked with DFA and the use of standard parts wherever possible, the product is inherently less complex. This subsequently affects manufacture, assembly, and various other factors such as reliability in a positive manner.
3. **Reduced product variations.**
A modular design gives the advantage of a theoretically large product range with only a relatively small number of specific modules. The use of standard modules can be exploited fully to reduce stock holding, tooling, part variety.
4. **Simplified changes to product or manufacturing system.**
Changes to the product or the manufacturing system are eased by the modular nature of both. Changes will generally only effect one area and thus total redesign does not occur. This is extremely important for highly complex products or products constantly in a state of flux, such as those in high technology industries, where upgrades in products happen very frequently.
5. **Eases product design and supervision of design.**
The product design process is simplified due to less complex products (modules) being considered rather than complex full products themselves. Modules ensure all areas are being covered and design changes do not hinder whole design process as they may relate to only one module.
6. **Natural method of design.**
Designing from a modular viewpoint does lend itself naturally to existing divisions, such as those between electrical, mechanical, optical etc. Designing in a natural manner will improve design quality.
7. **Simplified product planning.**
Product planning is simplified by using standard modules, thus reducing the number of design changes for product variations. Standardisation allows grouping of manufacturing operations, and grouping of module manufacturing within dedicated areas of the shop floor.

Product design cons

1. **Greater interface problems.**
The use of modules will obviously bring up the problem of interfacing the individual modules to one another. Normally these interfaces would not be so well defined, and would not be designed to come apart so readily, or indeed go together so readily thus the new interfaces must consider making all relevant connections between modules at purely one fixed set of interfaces.
2. **Definition problems.**
The actual definition of modules and interfaces may be problematic. A seemingly good product for modularisation may, in fact, be extremely difficult to define into modules and arrange a suitable interface to other modules. Products with many interconnections would perceivably prove difficult in this respect.
3. **No formal method of implementation.**
At present a formal method of implementing modularisation does not exist. This may cause problems for would-be users of this technique as they may be deterred by the vague concept-only theory, and may unsure how to proceed, possibly missing important factors or finding pit-falls.
4. **Increased weight.**
The use of modules and the strategy of providing discrete self-contained units may increase the overall weight of the product by providing connectors that may not have been there previously, and by extra or repeated components to allow the product to be physically broken down.
5. **Increased level of specification.**
The use of modules will not only require one overall product specification, but individual specifications for each module within the product. Across the range of specifications details will have to be standardised, and thus the actual management of such material will be increasingly difficult, due to individual groups responsible for individual modules. Specifications will also be more complex having to define interfaces and what will be required to ensure continuity.
6. **Uncommon way of working.**
Though we have stated that this is a natural method of design, by splitting the product into its obvious component parts, this way of working is not natural to many workers and thus may require considerable adjustment to settle into the new technique.

Manufacturing pros

1. **Simultaneous design of product and process.**
Modules allow easier design of product and process simultaneously, by considering simplified individual units rather than a complex complete product. Thus when a module is being designed, the requirements for its manufacturing, assembly, and test facility and tooling can be drawn up. It is then a much simpler task to design the main assembly line where module combinations are assembled.
2. **Simpler Products.**
With the use of a modular strategy linked with DFA and the use of standard parts wherever possible, the product is inherently less complex. This subsequently affects manufacture, assembly, and various other factors such as reliability in a positive manner.
3. **Increased capacity for variation.**
Though product variations are reduced, the number of add-on modules to create product variations is theoretically limitless and therefore a large product range is possible.
4. **Increased flexibility of product.**
The use of product modules allow a large number of different products to be manufactured from standard modules. But also modules could be replaced by others to allow an easily configurable product that can change with the customers needs.
5. **Reduced product variations.**
A modular design gives the advantage of a theoretically large product range with only a relatively small number of specific modules. The use of standard modules can be exploited fully to reduce stock holding, tooling, part variety.
6. **Increased quality.**
The ability for modules to be pre tested gives a greater level of product quality by products being tested in individual areas and not just as whole products, thus allowing for anomalies due to combinations of systems.
7. **Facilitates assembly.**
Modules, as self contained units lend themselves to ease of assembly by being of manageable size, of identical nature. That is to say that any one module is identical in its type from the point of view of no adjustment required. Modules must pay great attention to interfaces, therefore it is natural to assume that interfaces created will be as simple as possible and thus ease assembly
8. **Variability can be introduced at last moment.**
The use of modules in a products design allows standard modules to be manufactured and then introduced to the final assembly. Thus individual variations are only assembled at the very end of the line, prior to shipping.

9. **Simplified changes to product or manufacturing system.**
Changes to the product or the manufacturing system are eased by the modular nature of both. Changes will generally only effect one area and thus total redesign does not occur. This is extremely important for highly complex products or products constantly in a state of flux, such as those in high technology industries, where upgrades in products happen very frequently.
10. **Can reduce part numbers.**
Modularisation of a design can provide a platform for the use of other techniques such as DFA and thus promote reduction of parts within the product. Part reduction and DFA are integral parts of a modular strategy.
11. **Can reduce part variety.**
Standardisation and thus a reduction in part variety is another integral part of a modular strategy, not only having standard parts but standard modules wherever possible.
12. **Reduced manufacturing costs.**
Manufacturing costs can be reduced by; parallel manufacture of modules, resulting in faster manufacture and less tied up capital (wip), increased flexibility of the system, resulting in fewer changes for new products, greater efficiency, greater reliability and thus reduced rework or increased production numbers, and by the buying-in of self-contained modules.
13. **Reduced manufacturing uncertainty.**
All modules are manufactured identical within their type, thus any module should possess the capability to be assembled without adjustment.
14. **Reduced tooling required.**
Due to reduction in variety of products less tooling is required. Tooling is specific to individual modules and thus part of the self-contained nature.
15. **Can be JIT friendly.**
The use of a modular design can allow the use of bought-in, self contained, modules that will allow the use of a JIT strategy. Supplier willing.
16. **Promotes lean production.**
Goods in process are reduced. Modules can be manufactured and assembled in parallel. The use of standard modules with specialised add-on's for customer requirements, does not require large finished article stocks to be held for demand of variants. The nature of a modular product allows rapid assembly, and self contained and tested modules can have predicted reliability thus eliminating the need for over production to cover quality control failures.
17. **Test overheads reduced.**
Due to easier, faster, and more reliable testing, overheads are naturally reduced.
18. **Rapid feedback of quality data.**
As testing is carried out at each module station, quality information can be quickly collected and monitored so that any problems can be identified and dealt with greater speed and efficiency. Information coming from individual modules also reduces the problem of locating the problem.
19. **Increases manufacturing flexibility.**
The flexibility of the manufacturing system is greatly enhanced by having parallel manufacture of modules, but also a main manufacturing and assembly line that can take whatever modules that may be required from feed-in lines thus allowing one line to manufacture numerous different products simultaneously, based around a selection of modules.
20. **Bought in modules.**
Standard modules may be bought in directly from a supplier, pre-tested and ready for assembly. Thus benefits are gained through reduced assembly costs, material handling costs, and quality control.
21. **Consistent quality.**
The ability to test modules individually gives a higher level of reliability and allows faults to be located with greater ease and efficiency. Modules assembled and tested become self-contained requiring no further action than final assembly.
22. **Increases manufacturing efficiency.**
The efficiency of the manufacturing system is increased by making use of one continually used line for a range of products. Thus the utilisation of the line is maximised. Testing of modules is done off the main line and thus final assembly is as rapid and as efficient as possible. The use of standard modules also increases efficiency by reducing the need to manufacture similar products separately.
23. **Reduced rework.**
By tailoring products by add-on modules, products should be of ideal configuration first time. With pre tested modules the reliability of products should also be increased.
24. **Facilitation of maintenance and servicing.**
The modular product will allow easier access to restricted locations and also allow easier removal of individual units for service, reconditioning or replacement. There are also the advantages for simple operations such as lubrication, refilling, and the like, that may not come under service.
25. **Reduced material costs.**
Increased modularity has the same effect on material cost as traditional part standardisation. Modularity is a sort of standardisation at subassembly and assortment level. A broad range of variants can be built up with a controlled number of parts.
26. **Allows easier project management.**
The project can be naturally broken down into smaller more manageable parts. These parts will relate to modules and thus personnel of appropriate fields may work on appropriate modules. Work may also be carried out simultaneously, thus interface problems that will always address more than one module can be worked on from both sides.
27. **Reduced stock holding.**
The use of standard modules will cut the variety of components held in stock, and should reduce the overall level of stock holding.
28. **Increases capability for automation.**
A modular strategy promotes the use of automation by simplifying assembly, using standard parts, and by grouping of similar types of operations within the same team work area.
29. **Improved factory organisation.**
The grouping of module manufacturing into self-contained cells allows for easier planning of factory layout, and improves communication between key areas. A factory organised into these cells can operate with greater efficiency by running in parallel and thus do not suffer from a problem in an individual cell halting production.
30. **Facilitation of disassembly.**
The modular product will provide natural decomposition into manageable units for requirements such as recycling or servicing.

Manufacturing cons

1. **Can increase part numbers.**
Due to effectively splitting a product up into modules the need for extra or duplicate parts may be required to allow the modules to obtain their self contained nature. Problems will probably occur about the interfaces where the need for connectors that are not normally required may be apparent.
2. **Greater interface problems.**
The use of modules will obviously bring up the problem of interfacing the individual modules to one another. Normally these interfaces would not be so well defined, and would not be designed to come apart so readily, or indeed go together so readily thus the new interfaces must consider making all relevant connections between modules at purely one fixed set of interfaces.
3. **Increased perceived work load and cost.**
Due to the modularisation process being early on, the perceived level of work required will increase and also a perceived cost increase. Though this early on effort will ultimately result in lower cost and reduced rework etc. the modular idea might meet with strong opposition from project managers until proven as a technique.
4. **Definition problems.**

The actual definition of modules and interfaces may be problematic. A seemingly good product for modularisation may, in fact, be extremely difficult to define into modules and arrange a suitable interface to other modules. Products with many interconnections would perceivably prove difficult in this respect.

5. **No formal method of implementation.**
   At present a formal method of implementing modularisation does not exist. This may cause problems for would-be users of this technique as they may be deterred by the vague concept-only theory, and may unsure how to proceed, possibly missing important factors or finding pit-falls.
6. **Uncommon way of working.**
   Though we have stated that this is a natural method of design, by splitting the product into its obvious component parts, this way of working is not natural to many workers and thus may require considerable adjustment to settle into the new technique.

Management pros

1. **Improved product.**
   A combination of many factors mentioned will lead to an improved product overall.
2. **Increased customer satisfaction.**
   The customer benefits from higher quality products, configurable to their needs, and products that can develop with their needs. They will see lower costs from the reduced manufacturing costs, stock holding costs, and reduced lead times of the manufacturers. They will also benefit from ease of servicing or replacement of parts.
3. **Groups variety into a manageable level of complexity.**
   The use of a modular design allows product variations to be grouped into smaller, more manageable, modules. Thus individual complex products tailored to specific jobs may be avoided in favour of standard products with specialised add-on's.
4. **Early-on process.**
   The work on defining modules and the manufacturing system is done early on so that major decisions are made before any factors are agreed upon. Thus changes cannot interfere with work done previously. Also increased up front effort will reduce problems downstream.
5. **Simultaneous design of product and process.**
   Modules allow easier design of product and process simultaneously, by considering simplified individual units rather than a complex complete product. Thus when a module is being designed, the requirements for its manufacturing, assembly, and test facility and tooling can be drawn up. It is then a much simpler task to design the main assembly line where module combinations are assembled.
6. **Reduced lead time to market.**
   The product lead time is reduced through a reduction in overall product development time, manufacturing and assembly times, and test and service times.
7. **Increased capacity for variation.**
   Though product variations are reduced, the number of add-on modules to create product variations is theoretically limitless and therefore a large product range is possible.
8. **Increased flexibility of product.**
   The use of product modules allow a large number of different products to be manufactured from standard modules. But also modules could be replaced by others to allow an easily configurable product that can change with the customers needs.
9. **Reduced product variations.**
   A modular design gives the advantage of a theoretically large product range with only a relatively small number of specific modules. The use of standard modules can be exploited fully to reduce stock holding, tooling, part variety.
10. **Can be JIT friendly.**
    The use of a modular design can allow the use of bought-in, self contained, modules that will allow the use of a JIT strategy. Supplier willing.
11. **Eases product design and supervision of design.**
    The product design process is simplified due to less complex products (modules) being considered rather than complex full products themselves. Modules ensure all areas are being covered and design changes do not hinder whole design process as they may relate to only one module.
12. **Is virtually business and product independent.**
    Modularity lends itself to virtually any product and any business. Though some products may be very simple or otherwise unable to be modularised the majority of designs to some degree will allow modules to be developed. This also relates to businesses, those purely in a service role for example, will benefit just as much as a supply company from increased product flexibility, easier upgrades etc.
13. **Promotes lean production.**
    Goods in process are reduced. Modules can be manufactured and assembled in parallel. The use of standard modules with specialised add-on's for customer requirements, does not require large finished article stocks to be held for demand of variants. The nature of a modular product allows rapid assembly, and self contained and tested modules can have predicted reliability thus eliminating the need for over production to cover quality control failures.
14. **Bought in modules.**
    Standard modules may be bought in directly from a supplier, pre-tested and ready for assembly. Thus benefits are gained through reduced assembly costs, material handling costs, and quality control.
15. **Simplified product planning.**
    Product planning is simplified by using standard modules, thus reducing the number of design changes for product variations. Standardisation allows grouping of manufacturing operations, and grouping of module manufacturing within dedicated areas of the shop floor.
16. **Simplified planning.**
    There is a possibility to simplify planning by just planning the main flow. The different modules are made according to the needs of a kanban system.
17. **Allows easier project management.**
    The project can be naturally broken down into smaller more manageable parts. These parts will relate to modules and thus personnel of appropriate fields may work on appropriate modules. Work may also be carried out simultaneously, thus interface problems that always address more than one module can be worked on from both sides.
18. **Reduced stock holding.**
    The use of standard modules will cut the variety of components held in stock, and should reduce the overall level of stock holding.
19. **Reduced requirement of factory space.**
    Factory space requirement is reduced through having a more organised product manufacturing system, the use of such as parallel manufacture of modules and the grouping of testing with individual module assembly will greatly reduce the need for factory space. The use of such a technique as JIT reduces the requirement for store space and bought in modules further reduce the need for storage or assembly space.
20. **Increased utilisation of factory space.**
    Factory space required, is utilised to a greater degree by the use of module cells, that manufacture, assemble, and test the individual modules. Manufacture in this way reduces the need for transport of parts and subassemblies about the factory for various operations, and provides a more compact and easier to manage manufacturing facility.
21. **Improved factory organisation.**
    The grouping of module manufacturing into self-contained cells allows for easier planning of factory layout, and improves communication between key areas. A factory organised into these cells can operate with greater efficiency by running in parallel and thus do not suffer from a problem in an individual cell halting production.
22. **Increased work satisfaction.**
    Shop floor work can be organised in different ways in the different module areas. Work content, responsibility,

authority, and technical level etc. can all be varied, thus giving a development possibility for shop floor employees. The small module areas also promote a team work organisation around a module.

23. **Reduced stock numbering problems.**
    Problems with having to code all products with a separate number for even very minor alterations can lead to great quantities of part and product numbers. Thus the use of modules reduces these problems, which are especially troublesome in the military fields.

Management cons

1. **Increased perceived work load and cost.**
   Due to the modularisation process being early on, the perceived level of work required will increase and also a perceived cost increase. Though this early on effort will ultimately result in lower cost and reduced rework etc. the modular idea might meet with strong opposition from project managers until proven as a technique.
2. **The management of change.**
   For many companies the new method and its implications will be considerably different from their current way of working. It is the transition from old to new that may cause many issues within the company to arise and thus the smooth and flexible handling of these will be essential for the technique to work.
3. **No formal method of implementation.**
   At present a formal method of implementing modularisation does not exist. This may cause problems for would-be users of this technique as they may be deterred by the vague concept-only theory, and may unsure how to proceed, possibly missing important factors or finding pit-falls.
4. **Increased level of quality control required.**
   Due to the use of modules, there will be a need to test each module thoroughly, and especially test the interfaces, which will undoubtedly be a sensitive area. Thus the increased level of testing and the increased depth of testing will increase overall QC overheads.
5. **Increased level of specification.**
   The use of modules will not only require one overall product specification, but individual specifications for each module within the product. Across the range of specifications details will have to be standardised, and thus the actual management of such material will be increasingly difficult, due to individual groups responsible for individual modules. Specifications will also be more complex having to define interfaces and what will be required to ensure continuity.
6. **Increased initial product development time.**
   Though the development of modules in parallel will reduce the product development time, the new way of working, the requirement for increased specifications and the development of the module interfaces may initially increase overall product development times.
7. **Uncommon way of working.**
   Though we have stated that this is a natural method of design, by splitting the product into its obvious component parts, this way of working is not natural to many workers and thus may require considerable adjustment to settle into the new technique.

As a pre-cursor to the Phoenix performance model, a generic model was developed to represent the performance differences between a sequential assembly process of an 'n' part product and the extreme modular assembly process of an 'n' part product assembled in modules of two parts.

To represent the two assembly situations two models were developed within Ithink. Figure A8.1 shows the Ithink model for the sequential assembly process. The model broadly consists of the flow of components (*a handling*) into a fixture (*a fixture*). When the two components are in the fixture they can be fixed (the *a fixer* loop) until the *number of parts* within the assembly is reached, whereupon the completed assembly is unloaded (*a unloading*) into a bin of completed assemblies (*a completed assemblies*). The two further elements of the *a ops null* flow, and the *a fix trigger* flow are constructs purely for model function and do not affect the assembly concept.

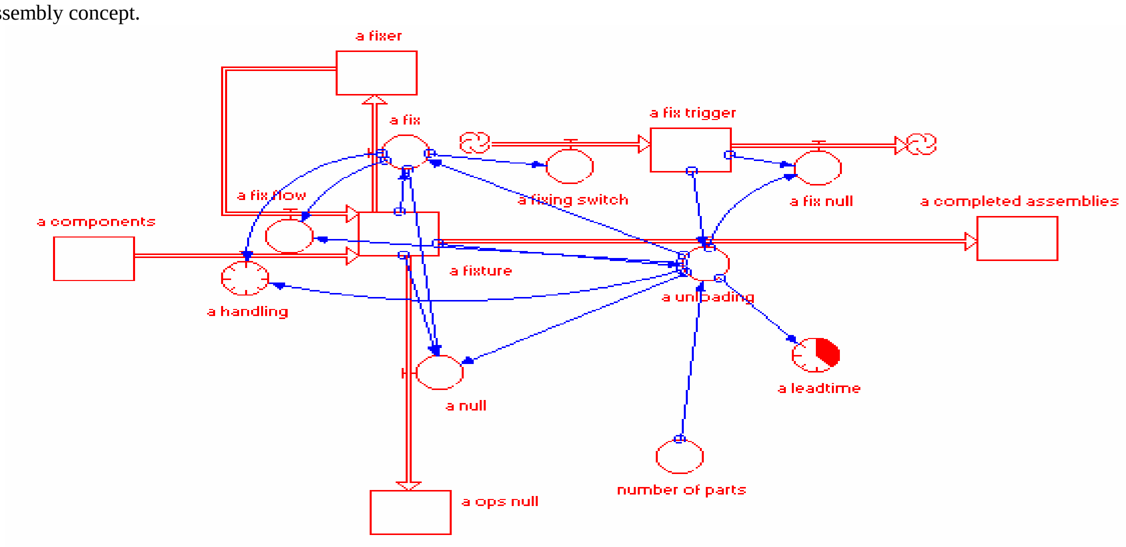

Figure A8.1. Sequential Assembly Process Model.

The second model is that of the modular assembly sequence of component pairs. Figure A8.2 shows the Ithink model for modular assembly process. To maintain consistency the model was constructed similarly to the sequential model but has a different internal operation. As before components are inserted (*b handling*) into a fixture (*b fixture*). When two components are in the fixture they are fixed and then removed (*b sub assy* store) to allow a further two components to be loaded and fixed. When the *number of parts* is reached *a handling* stops and the pairs of components or subassemblies process around the *b sub assy store* loop until the assembly is complete. The assembly is then unloaded (*b unloading*) into a bin of completed assemblies (*b completed assemblies*). As before the *b ops null* and *b fix trigger* flows are purely for model function.

From these models various parameters can be monitored and graphed to analyse the performance of the model. In order to analyse the assemblability metric the performance of the two models were graphed. Figure A8.3 shows the parameters of *a completed assemblies, a fixture, a unloading, a fix flow,* and *a fix trigger* for the sequential assembly of eight components graphed over a period of 100 cycles or operations. From the graph a number of points can be identified:

- The time to produce one completed assembly is 16 cycles, the equivalent of 16 operations.
- Of those 16 operations, 7 are fixing and 9 are handling.
- Only one fixture is required.

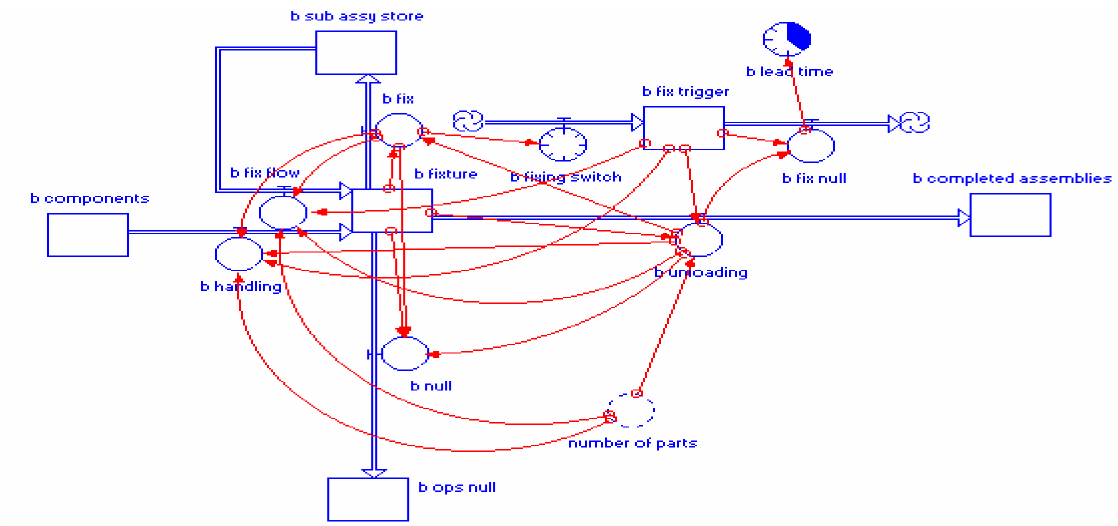

Figure A8.2 Modular Assembly Process Model.

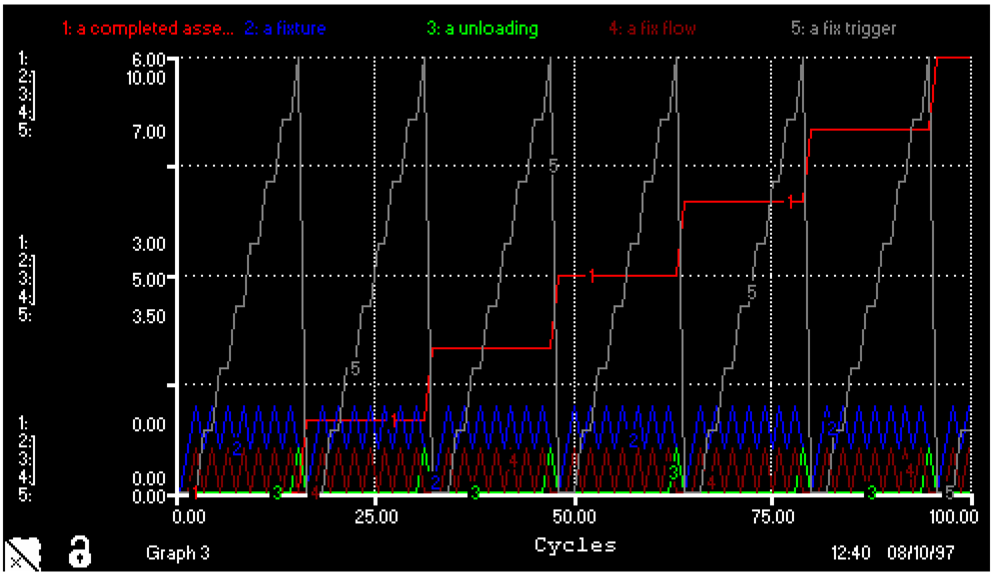

Figure A8.3 Sequential Assembly Process Graph.

Figure A8.4 shows the parameters of *b completed assemblies, b fixture, b unloading, b sub assy store,* and *b fix trigger* for the modular assembly of eight components graphed over a period of 100 cycles or operations. From the graph a number of points can be identified:

- The time to produce one completed assembly is 22 cycles, the equivalent of 22 operations.
- Of those 22 operations, 7 are fixing and 15 are handling.
- Four fixtures are required.

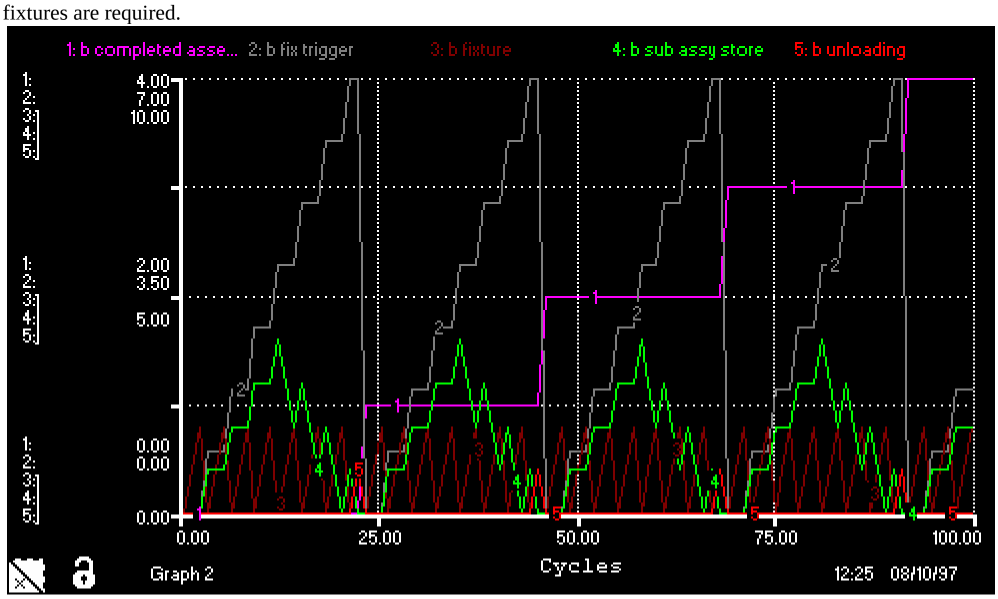

Figure A8.4. Modular Assembly Process Graph.

The models operate under a number of assumptions and constraints. All components require fixing operations. A single fixture is sufficient to support all components within the sequential assembly or subassembly of the modular assembly. All assemblies consist of even numbers of parts, as the modular assembly process has two component modules and is not sufficiently flexible to deal with the odd single component. Finally it is assumed that all operations take an equal amount of time. Under these conditions comparing the results for assemblies consisting of a range of component numbers there are some general rules that apply to assembly:

- The number of fixing operations required is always equal to the number of parts minus one.
- The total number of operations for sequential assembly is always equal to double the number of parts. This breaks down as 1 operation for handling each part, the number of parts minus 1 fixing operations and 1 handling operation for unloading.
- The total number of operations for modular assembly is always equal to triple the number of parts minus 2. This breaks down as 1 operation for handling each part initially, the number of parts minus 2 for subsequent rehandling of the subassemblies, the number of parts minus 1 fixing operations and 1 handling operation for unloading.
- Number of fixtures required is always 1 for sequential assembly and equal to half the number of components (i.e. number of modules) for modular assemblies.

In terms of the assemblability metric these results show that modularity has a negative impact upon assembly operations and number of fixtures required. For a modular product consisting of two component modules the number of operations is always increased by a number of additional handling operations equal to the number of parts minus two. The number of fixtures required is also increased to equal the number of modules.

With respect to the manufacturing attributes however the results are not so clear cut. In terms of the speed attribute the increased number of assembly operations for a modular product will have a negative impact on assembly time. However these results assume a serial arrangement even for the modular assembly. If modules were assembled in parallel the actual time for assembly of an 8 component assembly would be the equivalent of 10 operations, actually less than the sequential assembly process. However the number of fixtures is still increased to the number of modules. In addition, the sequential assembly is dedicated to its order. Thus it can only be assembled on receipt of that order. If assembled to order the full assembly time is included as part of the order to delivery lead time. A modular assembly however can be assembled to a point that only includes the generic components of the assembly and thus only the operations required to assemble the dedicated components are included as part of the order to delivery lead time. Of course the sequential assembly can also be partially assembled but it is unlikely that the generic components will be sequential in the assembly sequence. Thus modularity facilitates the late introduction of variety and thus has a further positive impact upon the speed attribute.

The late introduction of variety and parallel production also affects the flexibility attribute by allowing flexibility within the scheduling of production and the meeting of urgent orders. It also affects dependability through easier and more consistent order fulfilment, and improves quality through ease of testing, and improved robustness.

9 CRADLE SYSTEMS MODEL

The Cradle systems model contains a complex set of requirements, cross-references and system diagrams. This section presents a section of the most relevant information.

SOURCE DOCUMENTS

CRADLE Model
Brand Positioning Profiler
Personal Use Vehicles

Program: *Brand 4*

Market: *United Kingdom*

Bodystyle: *Options*

Date: *July 1, 1998*

Brand Positioning

Target Customers • *Families, practical thinking, but young in outlook* • *Want a highly functional design yet with style and individualism* • *A car is a practical necessity but should also provide a statement about the owner*	Brand Personality • *Practical* • *Stylish / Individual* • *Flexible*
Product Benefits • *Superb around town* • *Individual style* • *Safe and secure*	Price Considerations • *Net transaction price: £7.000* • *Priced at parity with Brand X* • *Price strategy: Best small car value*
Positioning Statement *Brand 4 is a practical and highly functional town car, built without compromise to safety, and quality. It couples its practicality with an choice of expressive and individual styling at a price which is parity with Brand X*	Competition *Brand X: The car for the family. Practicality at a low price.* *Brand 4 Advantages:* • *Practicality: larger available room inside for same exterior size, flexible space utilisation* • *Safer: ABS, airbags, alarm* • *Stylish: No sacrifice in 'trendiness' with 'new edge' modular design*

SOURCE DOCUMENT REQUIREMENTS

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Modularity Model Requirements Document No.1  First draft 26/01/98.

These requirements represent the market analysis performed upon the
general public in ascertaining the customer needs for a new car aimed at the family
market.

CUSTOMER REQUIREMENTS.
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1.      The car should be able to hold up to four adults in comfort.
2.      The car should have a good level of safety in design and features.
3.      The car should be economical.
4.      The car should have sufficient power to be able to overtake in      safety.
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5. The car should have good sized boot, or hatchback space.
6. The car should have good security features.
7. The car should be compact.
8. The car should look stylish and individual, preferably with a choice.
9. The car should have a good warranty.
10. The car should have good reliability.
11. The car should have a good after-sales support.
12. The car should come in a range of interesting colours and options.
13. The car should allow third party radio/music systems to be fitted.
14. The car should be easy to manoeuvre.
15. The car should be comfortable.
16. The car should have good visibility.
17. The car should have clear and easily accessible controls.
18. The car should have a competitive price.
19. The car should have good noise insulation.
20. The car should be available as manual or automatic.
21. The car should have plenty of adjustment including seats, steering wheel etc.
22. The car should have clear and easily visible dials and indicators.
23. The car should have a short order-to-delivery time.
24. The car should facilitate simple maintenance.
25. The car should be of a high quality.
26. The car should have smart but functional interior finish.

ATTRIBUTES

Modularity Model Attributes Document No 1. First Draft 26/01/98.

This list represents the important product attributes related to any car produced by Brand Y. They will be used to develop and measure the performance of the new car aimed at the family market.

PRODUCT ATTRIBUTES.
----

1. Safety
2. Security
3. Package / Ergonomics
4. Thermal / Aerodynamic
5. Vehicle dynamics
6. Emissions
7. Performance / Fuel economy
8. NVH
9. Electrical / Electronic
10. Interior climate environment
11. Weight
12. Product / Process design compatability
13. Customer life cycle
14. Styling / Appearance
15. Cost

MANUFACTURING ATTRIBUTES
----

1. Quality
2. Flexibility
3. Speed
4. Dependability
5. Cost

PRODUCTION ATTRIBUTES
----

1. Work groups
2. Capacity
3. Zero waste
4. Zero defects
5. Performance
6. Throughput

REQUIREMENTS AFTER ENGINEERING

1. TEXT

1. The car should be able to hold up to four adults in comfort.
5. The car should have good sized boot, or hatchback space.
7. The car should be compact.
8. The car should look stylish and individual, preferably with a choice.

Engineered to:

The vehicle must provide a flexible system of body units that provide a choice of user space, storage space and body style. This flexibility must exist within the following parameters:

min user space: L=1.8M W=1.5M D=1.2M
min storage space: L=0.5M W=1.2M D=0.4M
max dimensions: L=2.7M W=2M D=1.7M

2. TEXT

2. The car should have a good level of safety design and features.
6. The car should have good security features.

3. TEXT

3. The car should be economical.

4. TEXT

4. The car should have sufficient power to be able to overtake in safety.

PRODUCT ATTRIBUTES AFTER ENGINEEERING

A1. TEXT	1.	Safety
A2. TEXT	2.	Security
A3. TEXT	3.	Package / Ergonomics
A4. TEXT	4.	Thermal / Aerodynamic
A5. TEXT	5.	Vehicle dynamics
A6. TEXT	10.	Interior climate comfort environment
A7. TEXT	14.	Styling / Appearance

MANUFACTURING ATTRIBUTES AFTER ENGINEERING

AM1. TEXT	2.	Flexibility
AM2. TEXT	3.	Speed

SYSTEM MODEL DIAGRAMS

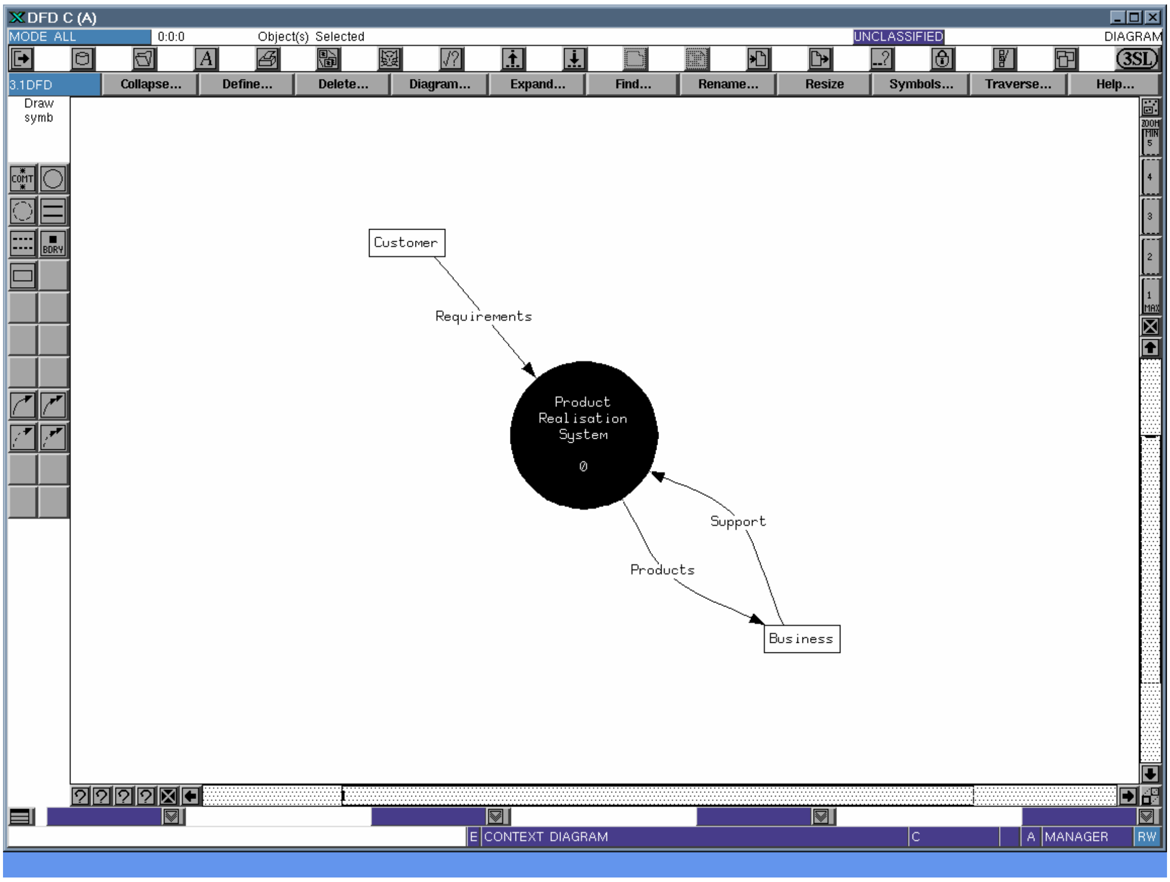

Figure A9.1. Context Diagram

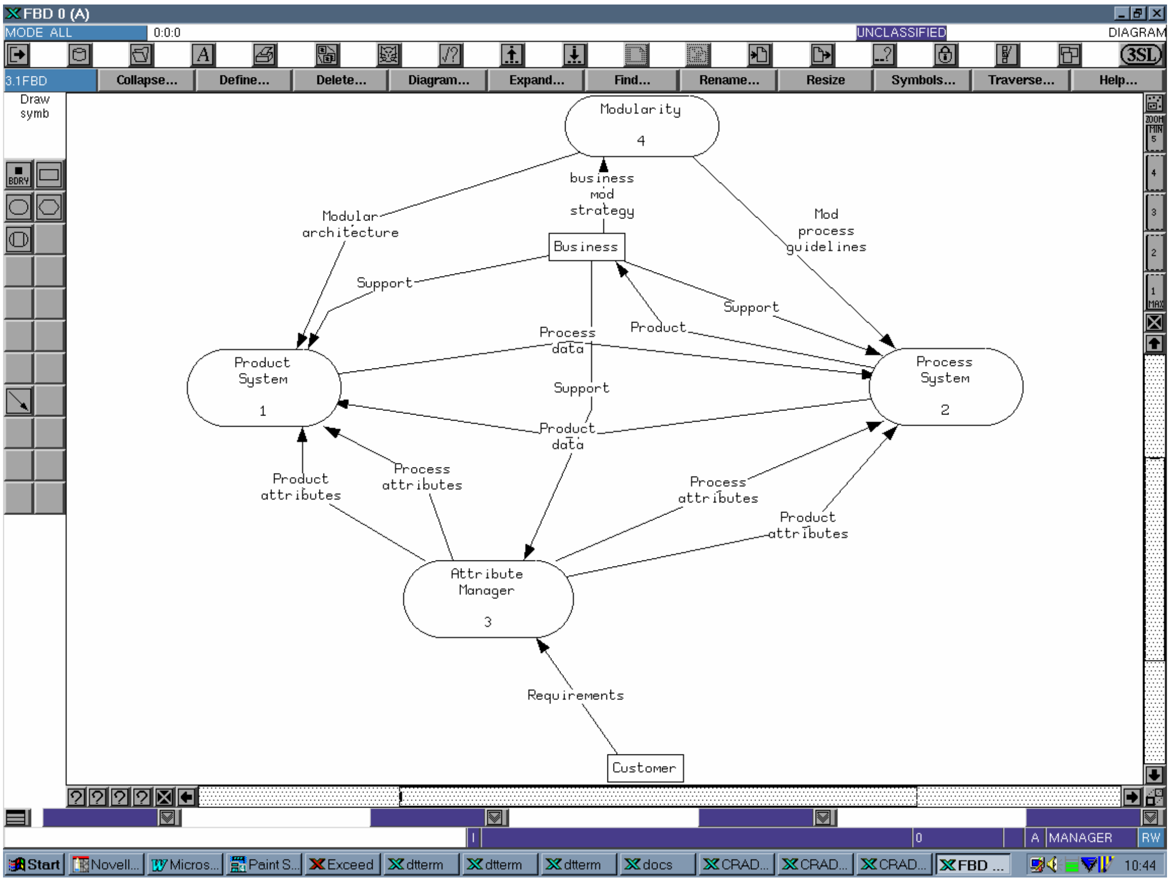

Figure A9.2. Realisation Diagram Level 0.

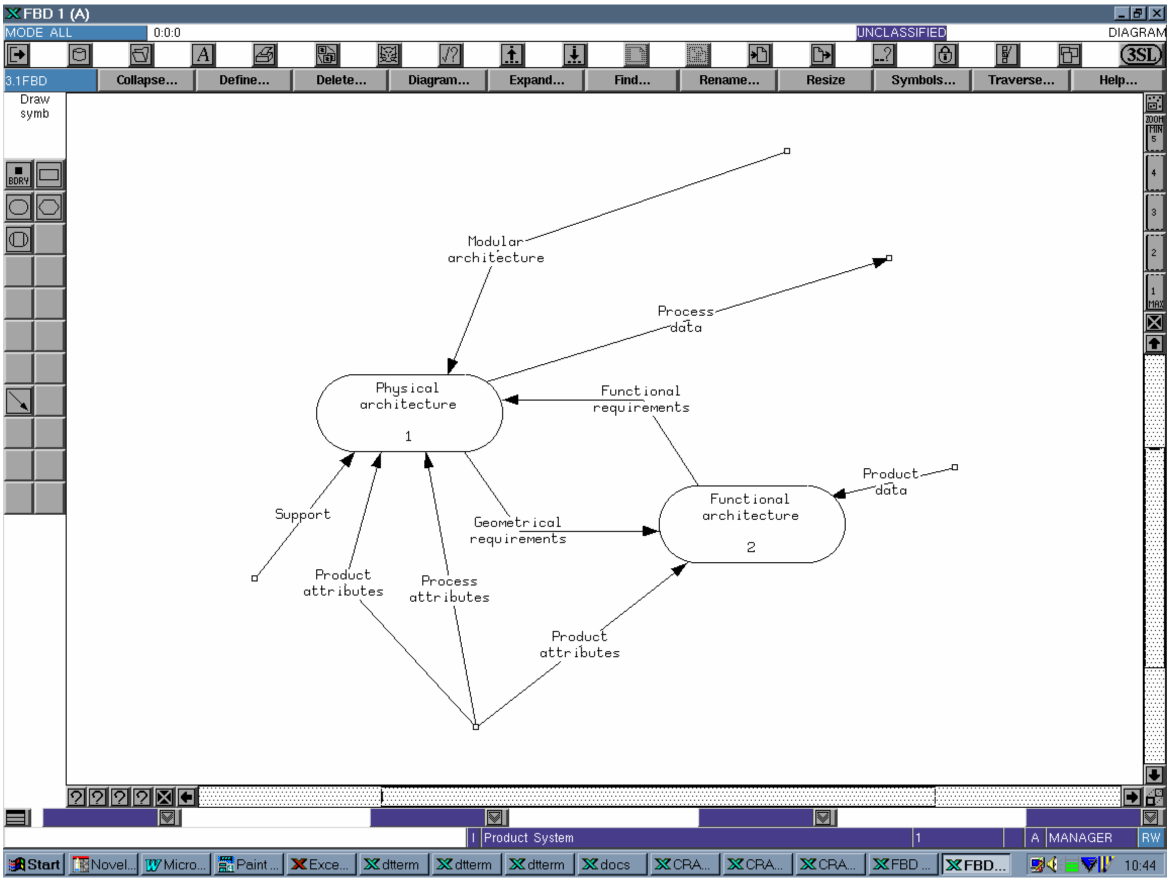

Figure A9.3. Product System Level 1

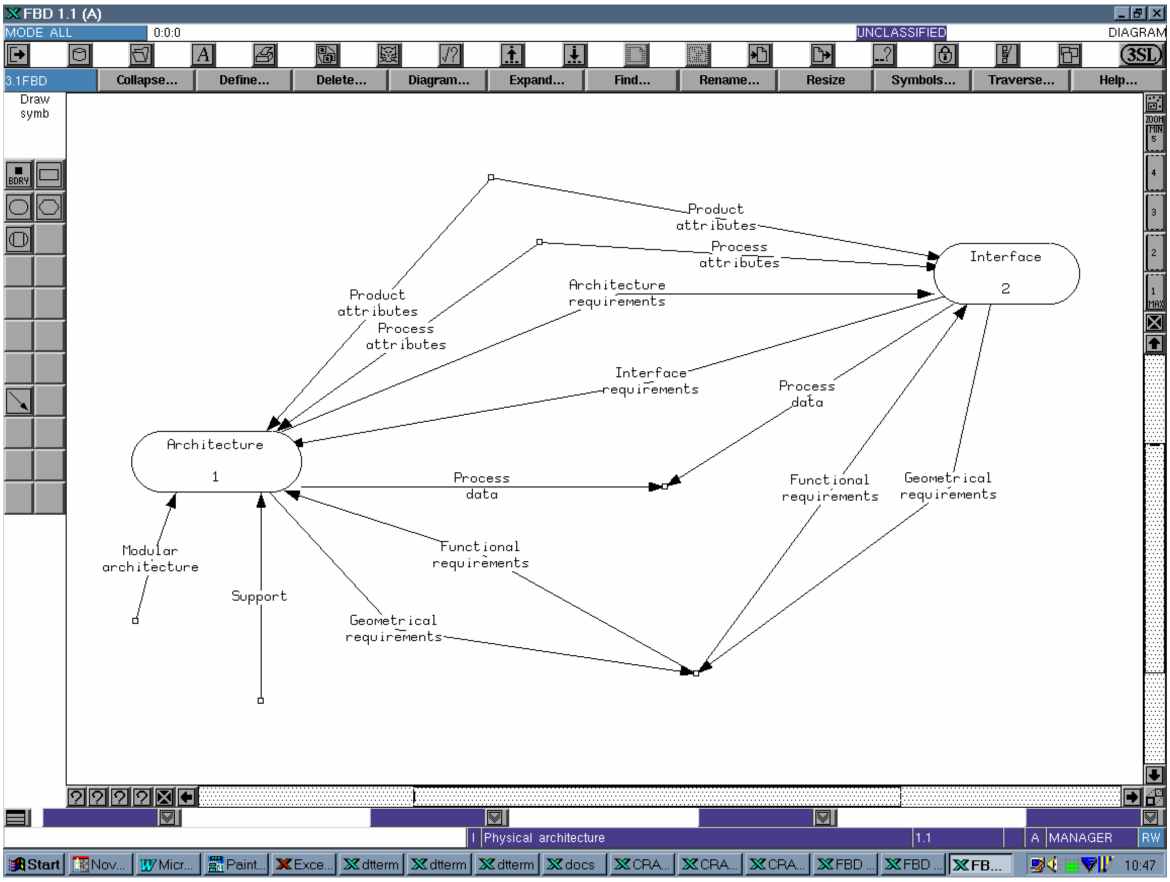

Figure A9.4. Physical Level 1.1

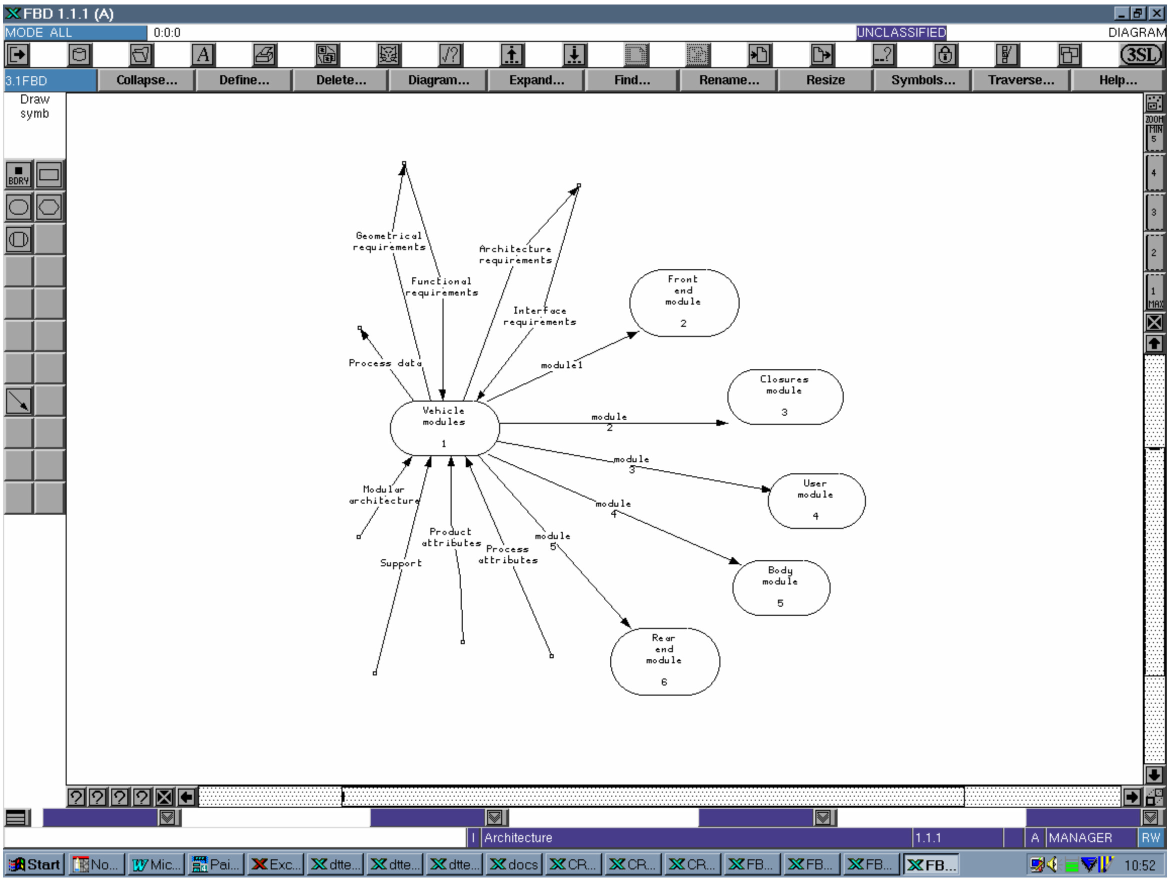

Figure A9.5. Architecture Level 1.1.1

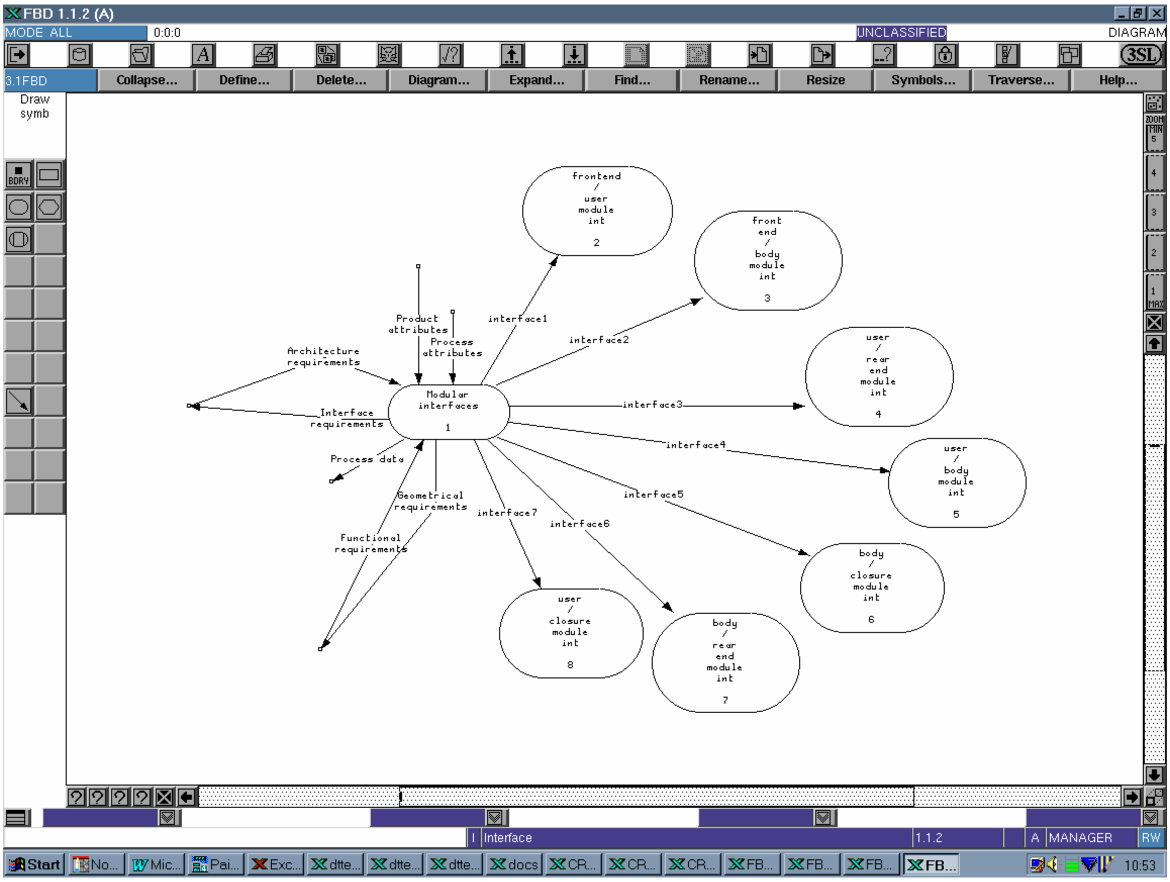

Figure A9.6. Interface Level 1.1.2

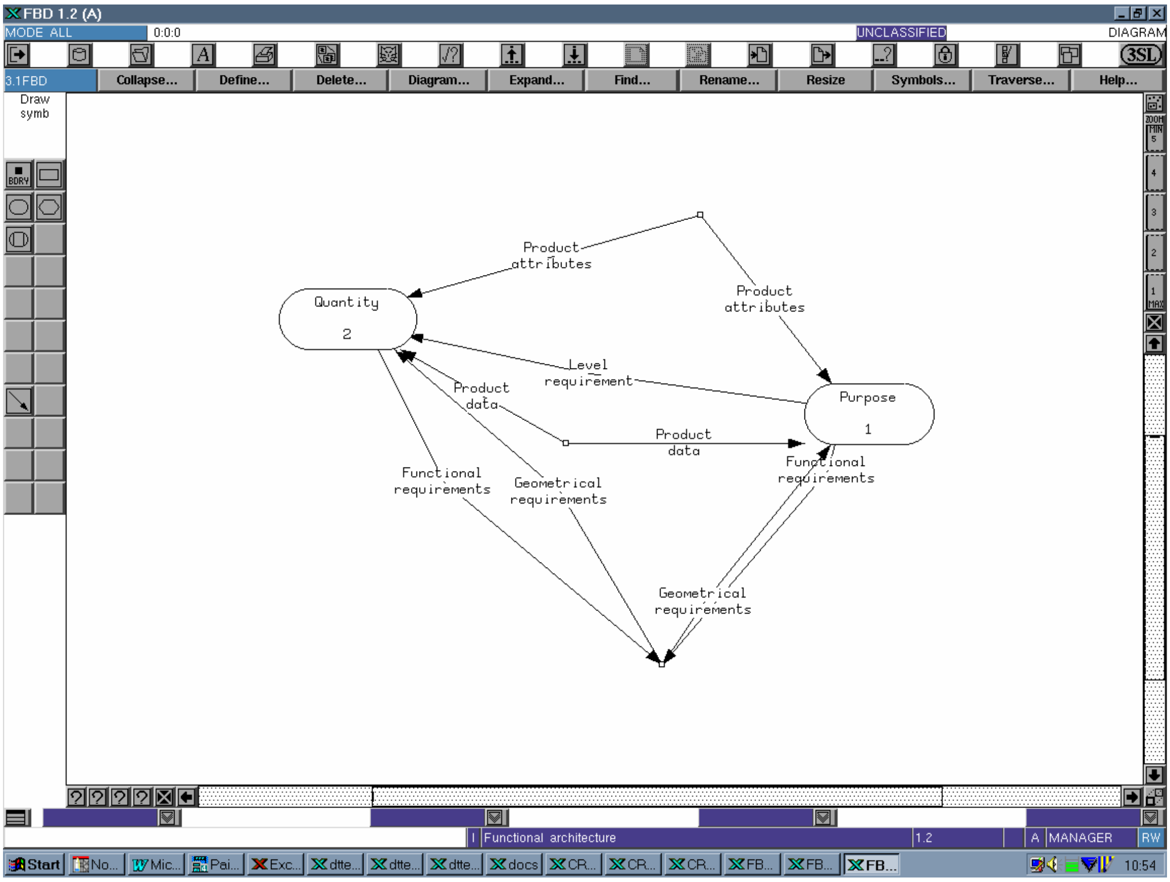

Figure A9.7. Functional Level 1.2

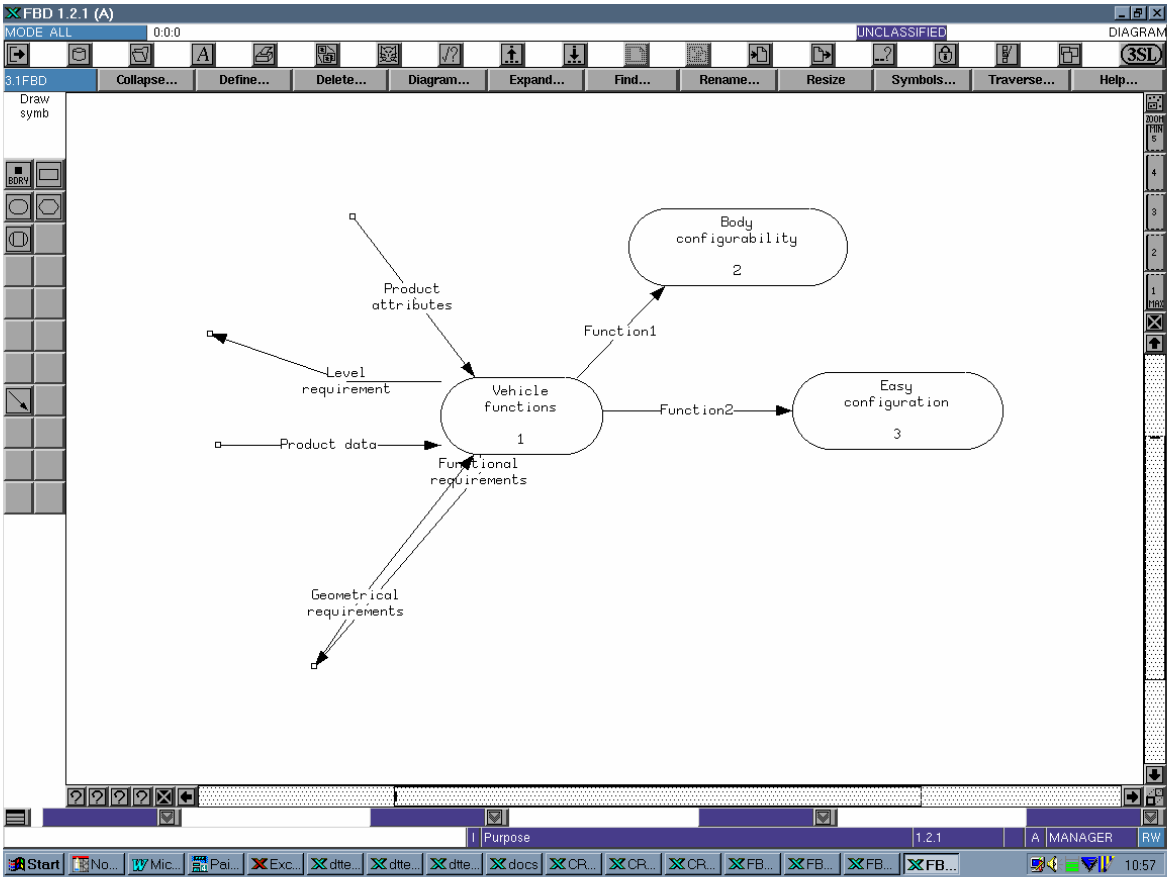

Figure A9.8. Purpose Level 1.2.1

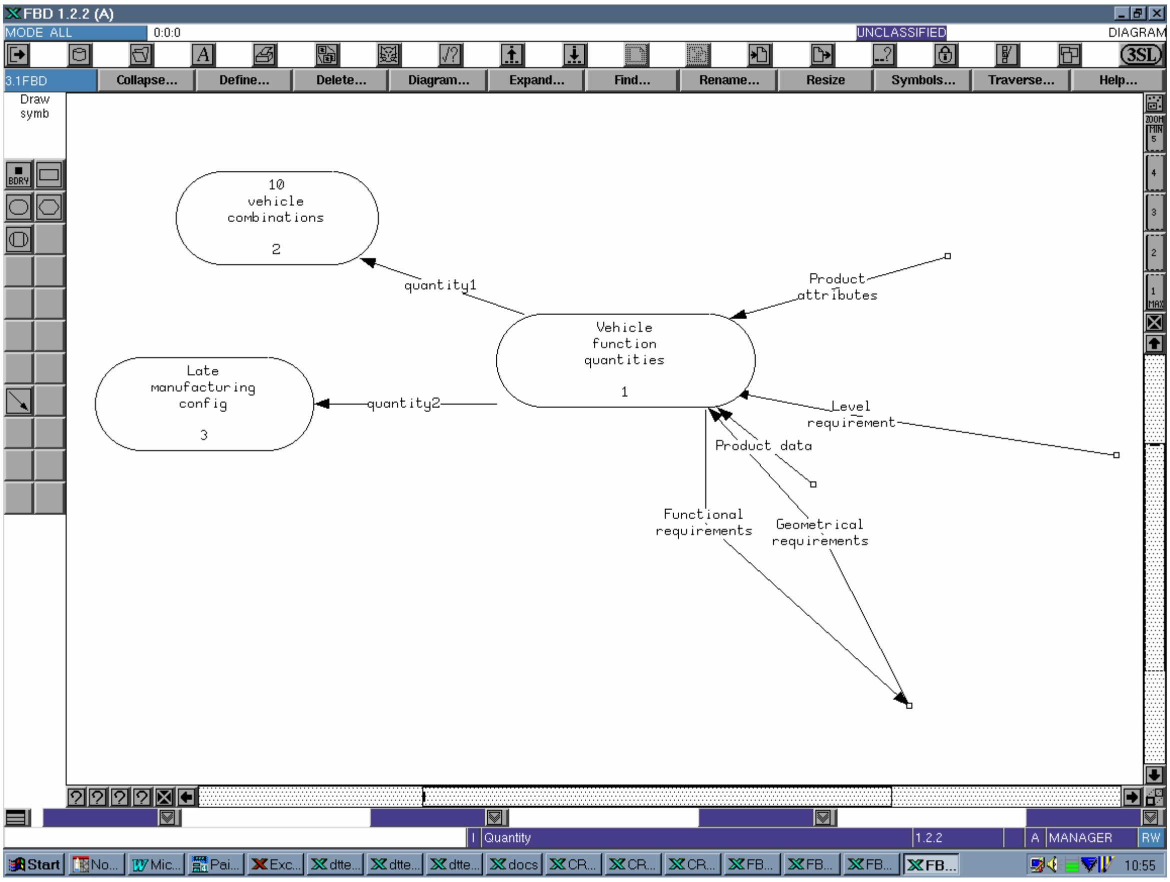

Figure A9.9. Quantity Level 1.2.2

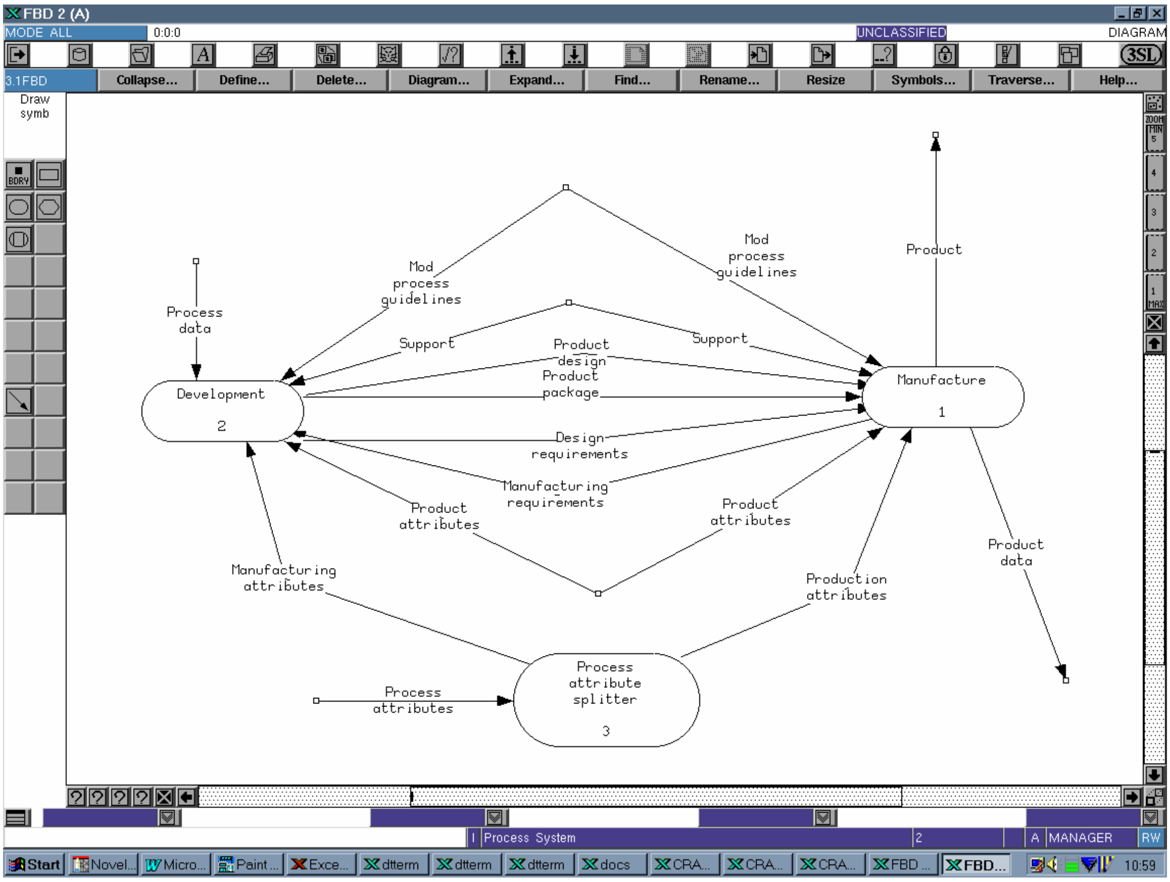

Figure A9.10. Process System Level 2

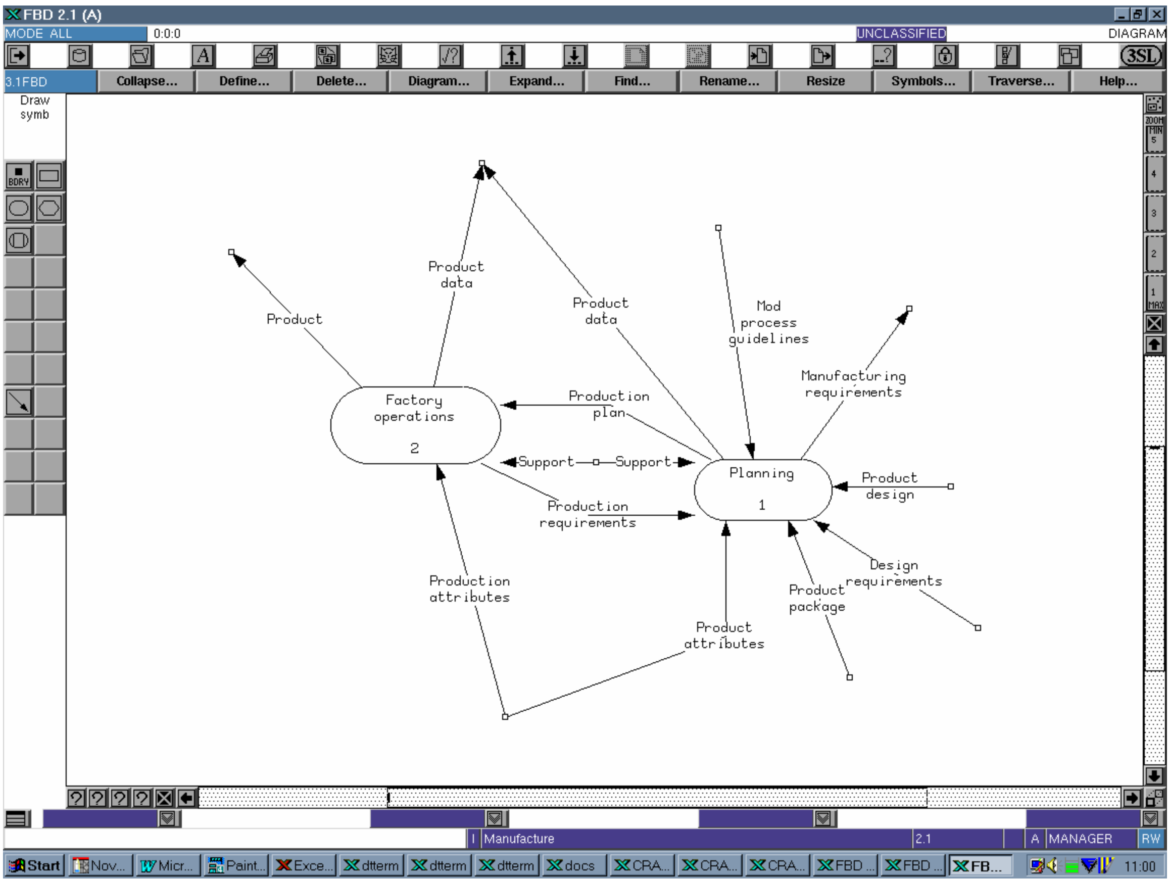

Figure A9.11. Manufacture Level 2.1

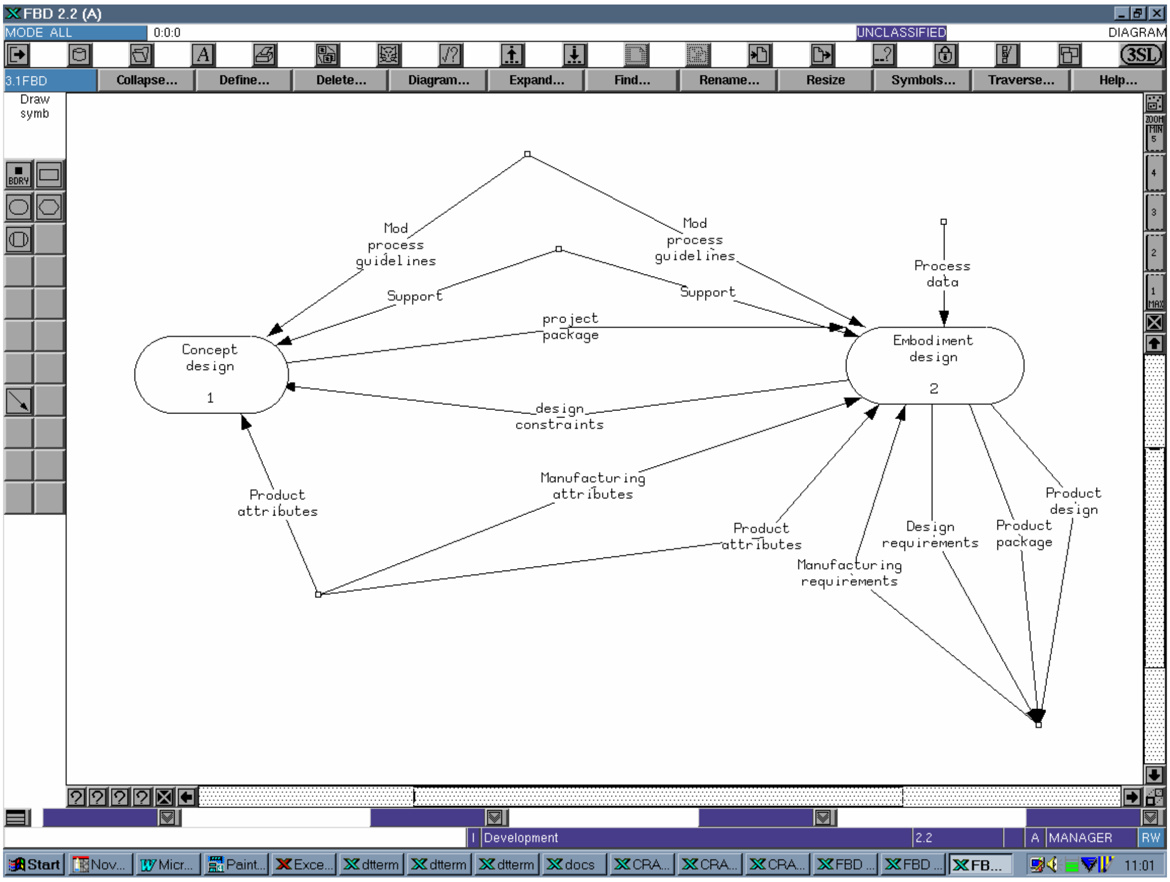

Figure A9.12. Development Level 2.2

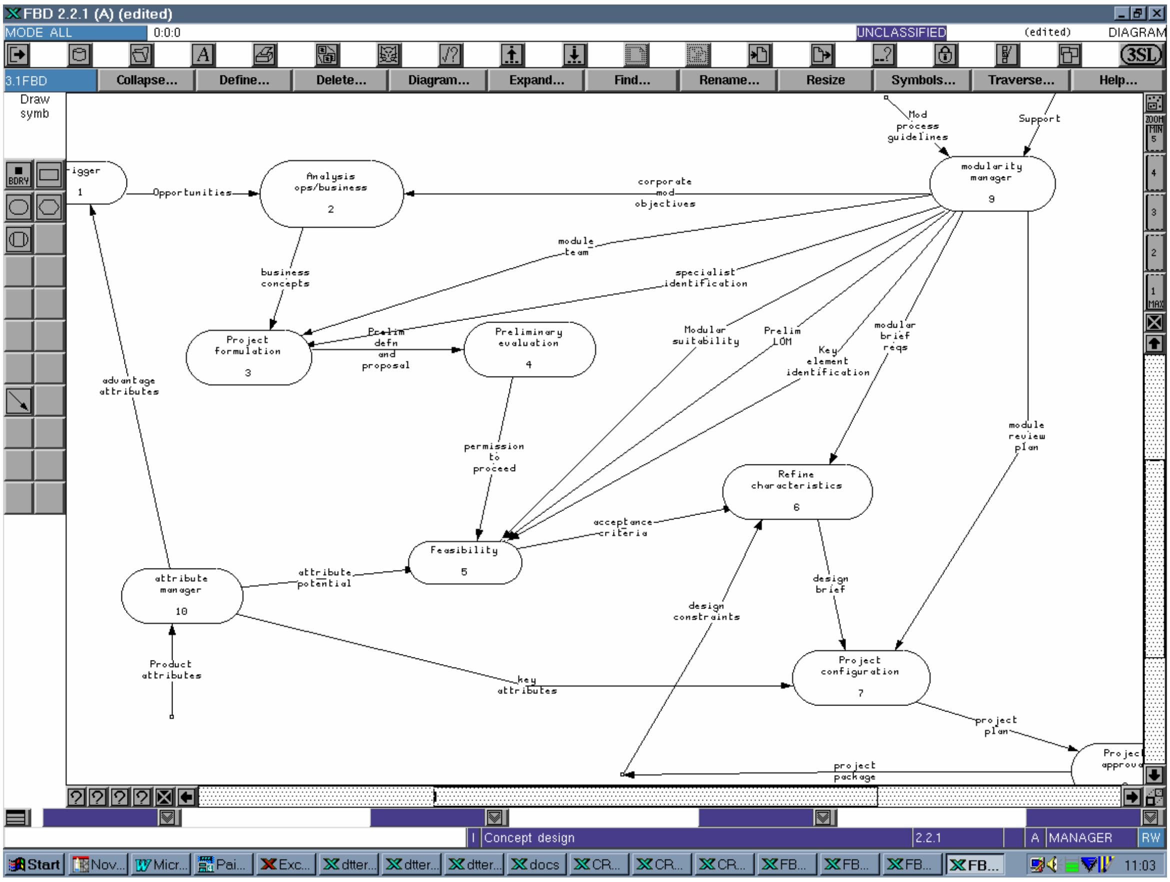

Figure A9.13. Concept Design Level 2.2.1

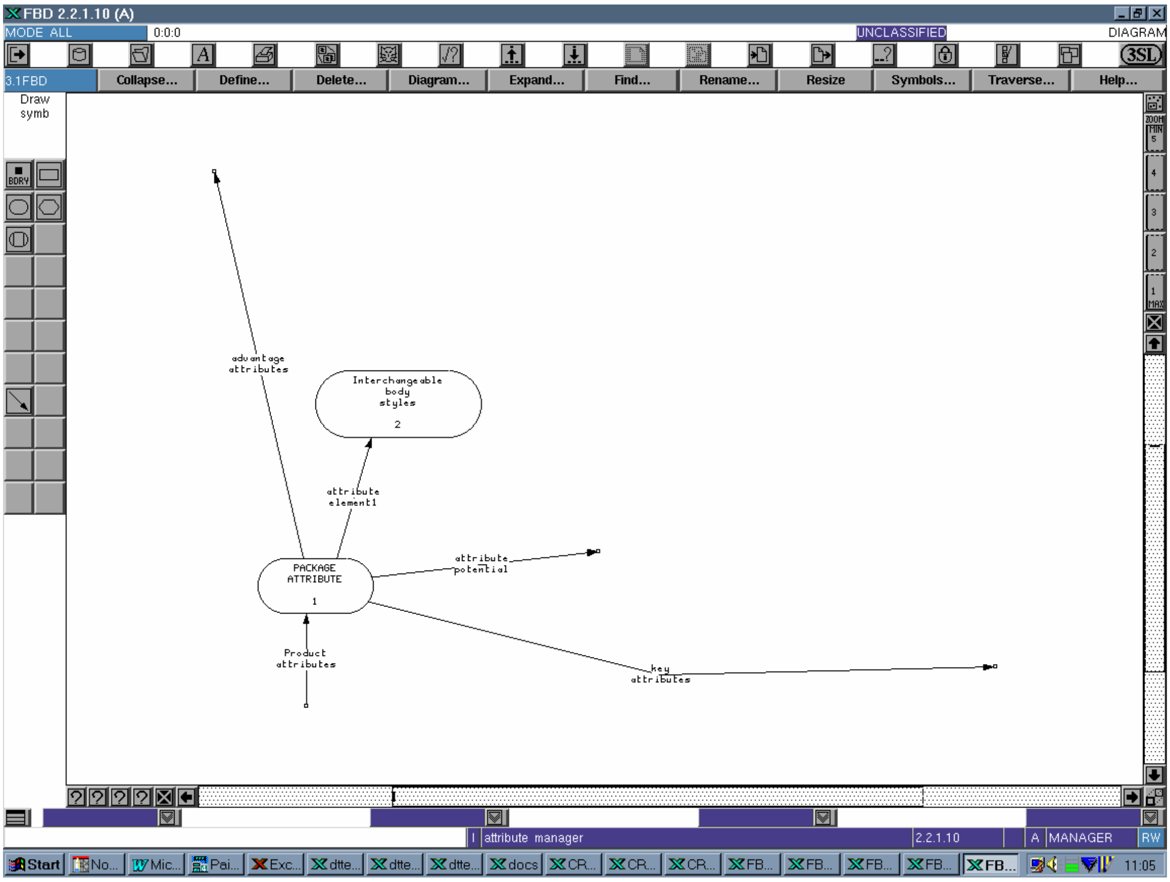

Figure A9.14. Attribute Manager Level 2.2.1.10

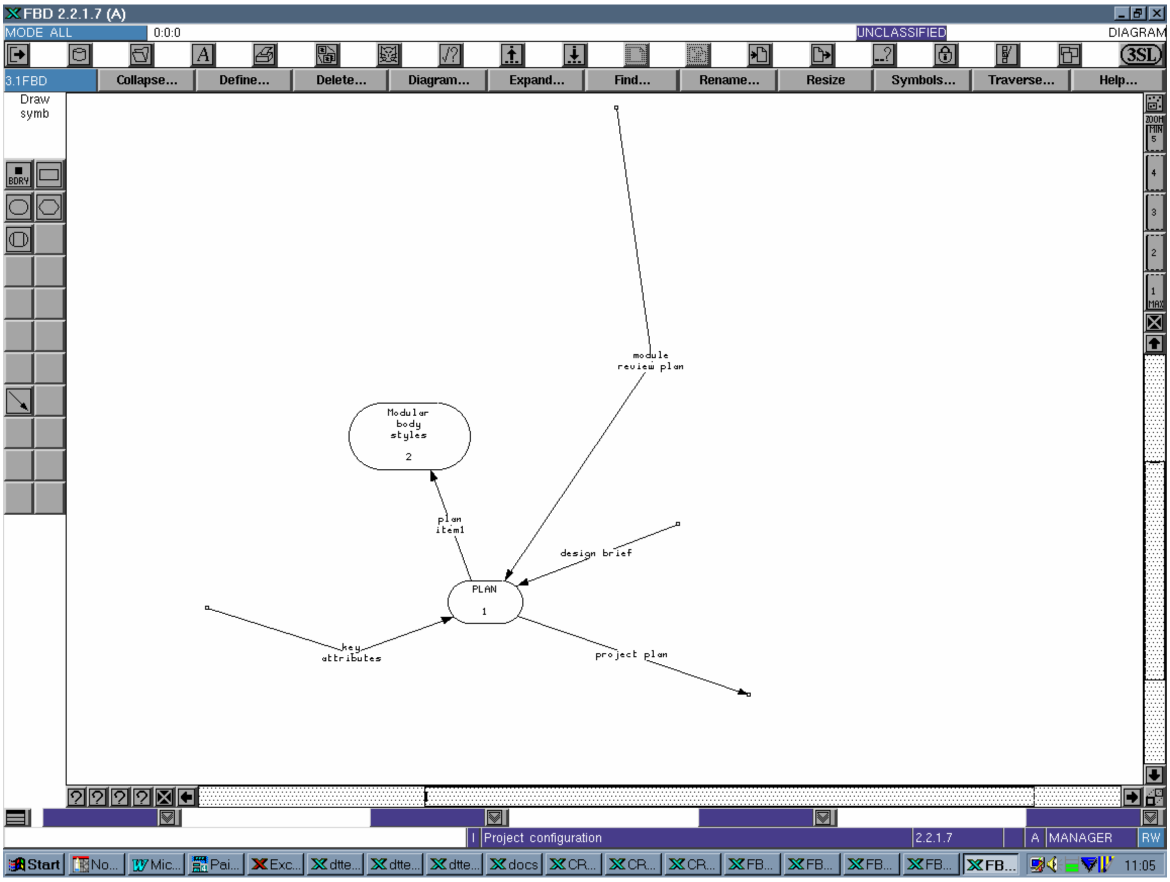

Figure A9.15. Project Configuration Level 2.2.1.7

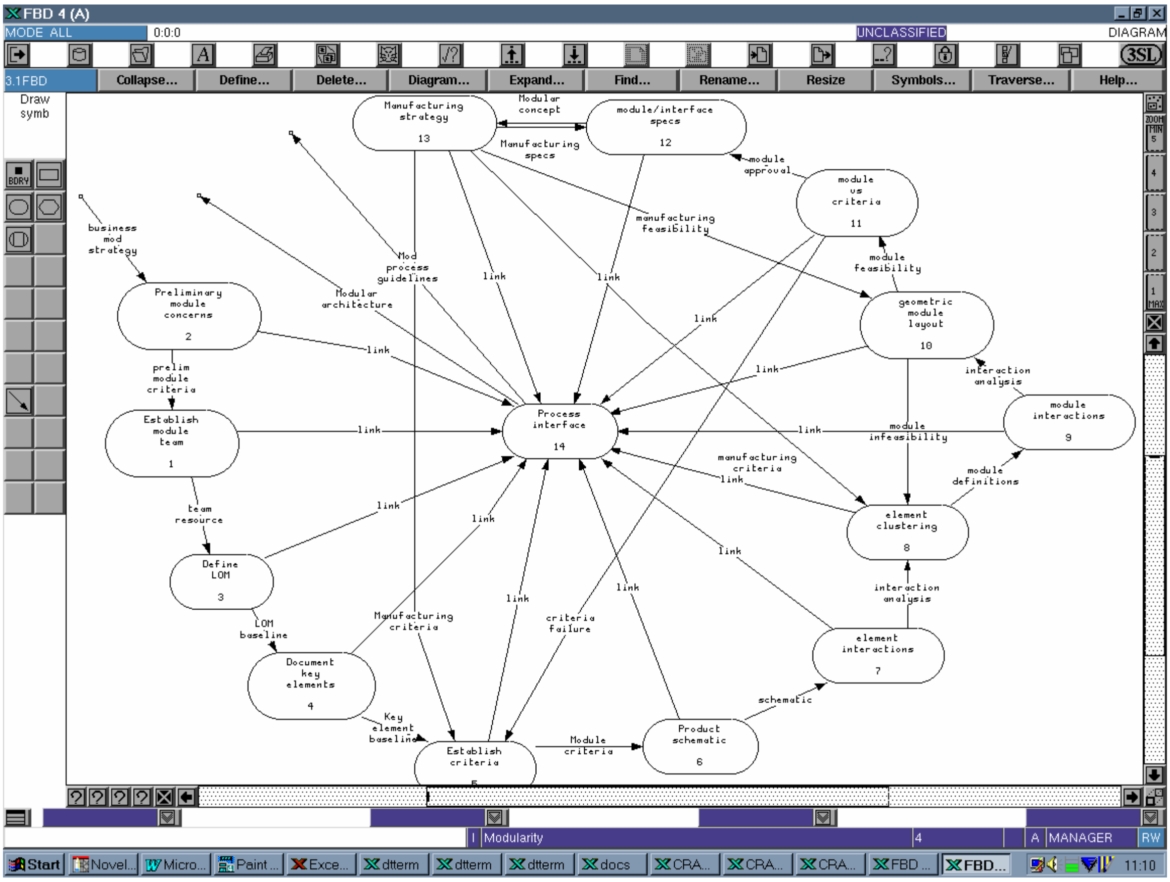

Figure A9.16. Modularity Level 4

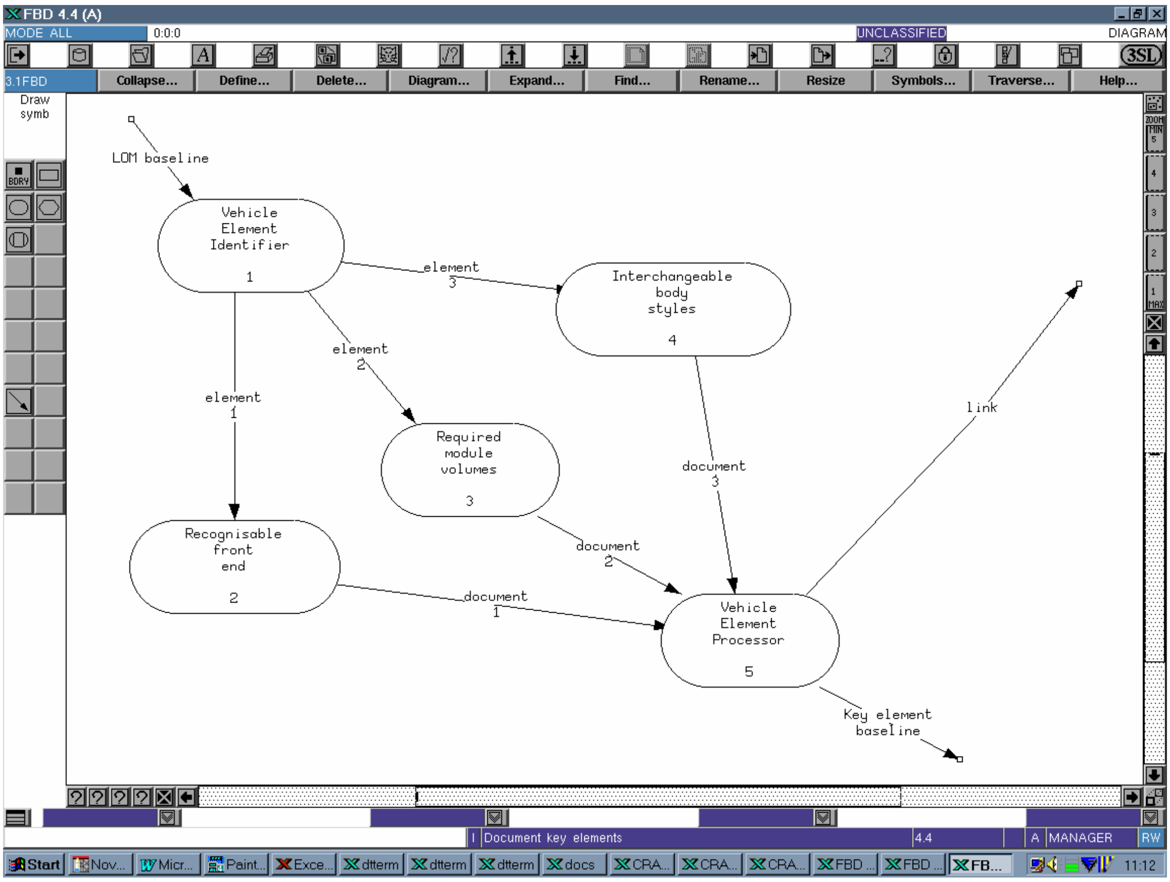

Figure A9.17. Document Key Elements Level 4.4

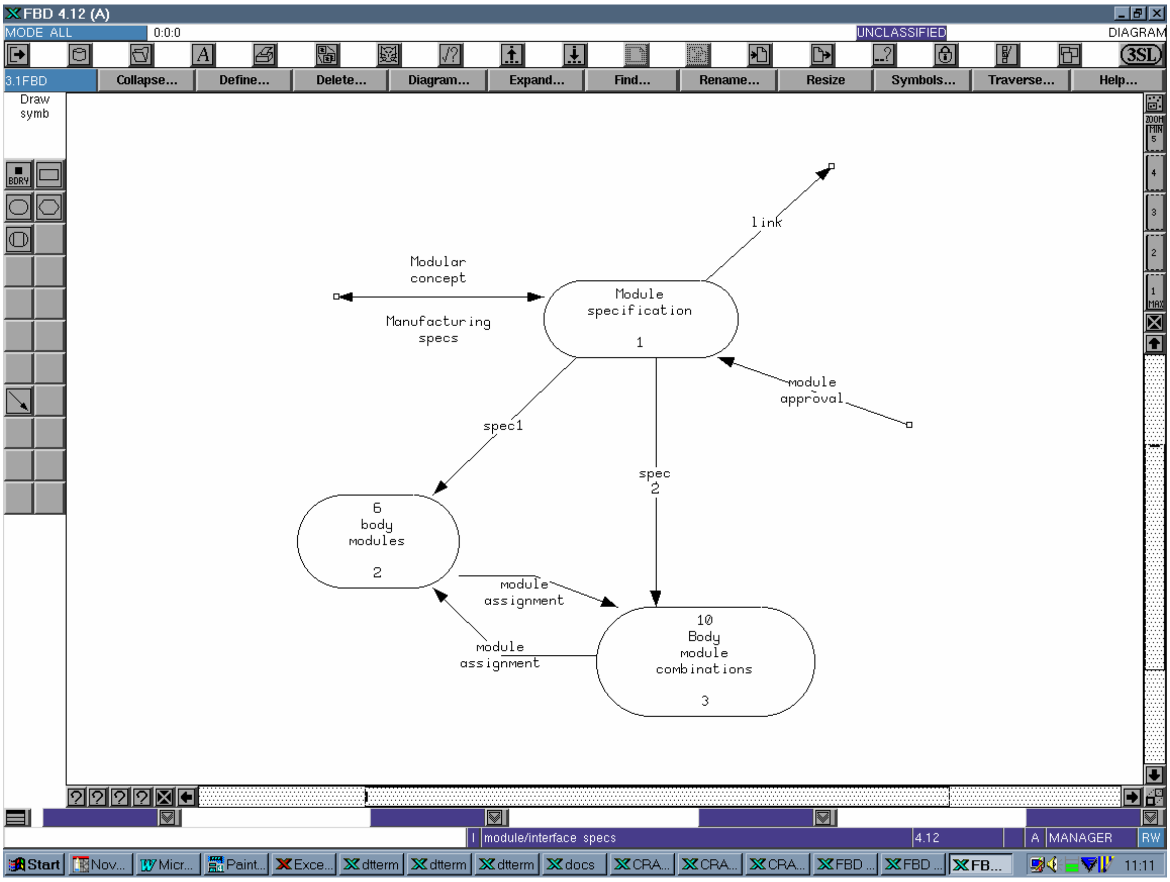

Figure A9.18. Module / Interface Specs. Level 4.12

10 OTHER PUBLICATIONS BY THE AUTHOR

MODULARISATION AS A MEANS OF PRODUCT AND PROCESS INTEGRATION.

Marshall, R. & P.G. Leaney, 1995. Modularisation as a Means of Product and Process Integration. *Advances in Manufacturing Technology IX. Proceedings of the 11th National Conference on Manufacturing Research.* London: Taylor & Francis, 1995, pp. 129-133.

Investigative work carried out to determine a strategy to address modularity as a facilitator for integration of design with manufacture. Modularisation is considered in conjunction with a large car manufacturer, a company that produce geophysical measuring systems for down hole drilling, and a company that produce electronic scanners for the pre press printing industry. Generic factors are being determined. These factors touch upon the benefits to product and process integration and also areas in which modularisation enables effective product customisation in meeting market needs. The aim, is to pool and document experience that can then be analysed and presented in a more accessible form by providing guidelines / checklists, evaluation tools and a product strategy based on derivatives.

Introduction

A visible trend in today's marketplace is toward products targeted at specific areas of the market, Shirley(1992), so called 'niche' products, with their associated low production volumes and high variety. To cater for this specific demand many companies have found themselves having to adapt existing products, or undertaking the development of new products, often in an incremental or evolutionary manner. During the normally short timescales involved, this leads to re-engineering of their products and finding ad-hoc solutions for customisation. Thus companies are left with a large array of product variations showing much in common in function but little in design.

The aim of this paper is to address the issue of product variation and the requirements for product customisation through the use of modularity as a structured design technique. The approach taken is to analyse the advantages and disadvantages of such a strategy, to determine a range of suitable case studies in which to apply the technique and monitor its implications, and to extract the generic elements in a form that would be more broadly applicable.

Modularity

In general, product variation has given rise to conflicting aims for a product's development. There is a need to adapt to the customer requirements and provide versatility, yet variation is detrimental to manufacturing concerns. One solution to this conflict is the introduction of variation as late as possible, to maintain a high degree of product variation, with the minimum of impact on manufacturing. There are however other considerations. Manufacturing flexibility can be seen as a means to integrate product variation. Manufacturing flexibility however, only addresses the problem in the short term, usually associated with high monetary and complexity costs. Alternatively by achieving product flexibility, the use of existing products and technologies will be maximised, the manufacturing system will be inherently more flexible, and flexible systems will then aid in the overall design to manufacture process. It must be recognised that the problem of flexibility is a combination of product and process, and the integration of the two will directly address many of the problems currently encountered.

The method of product and process integration considered in this paper is that of modularity. Here we consider a product composed of self contained units or modules that are manufactured as sub-assemblies and assembled together. Modularisation, to create a product composed of modules, provides product flexibility by means of combining developed modules together in various ways to extend the product range, Erixon and Östgren (1993). By implementing a modular strategy, product and process will naturally become more interlinked by providing a stable and common platform to design and manufacture. Modularity should thus increase the robustness and flexibility of a product and its associated manufacturing system.

An extension to the theory of modularity for product design relates the module concept to processes and also to businesses. The benefits gained by a modular product design can also be mirrored in the concept of holonic manufacturing systems and also holonic enterprises. Holonic manufacture is part of the Intelligent Manufacturing System (IMS) programme, Valckenaers and Van Brussel (1994), that addresses the so called 'fragility' of today's manufacturing systems. In general, the manufacturing systems of today suffer from inflexibility and generally perform poorly when they must operate outside their normal / expected conditions. By replacing rigid and inflexible hierarchical manufacturing systems with those that are much more adaptable to change, holons act to fulfil the role of hierarchical intermediaries. Thus, holons are autonomous, discrete and co-operative units, that are capable of dealing with disturbances and yet provide the functionality to support the greater whole, and thus increase the robustness of the system. Holons may be seen as the building blocks of a manufacturing system. The holonic concept can also be taken one step further by examining the holonic enterprise. This builds on the theory of Business Process Reengineering, by defining a holonic network as a group of businesses that, cooperate in an integrated and organic manner, forming a system able to configure itself to manage each business opportunity that a customer presents, McHugh, Merli and Wheeler (1995). Holonic enterprises, holonic manufacture and modular design share many similar concepts and objectives. The development of such concepts as the holon will further aid in the integration of product and process by providing an increased awareness of manufacturing concerns, and a means of implementing them at an early stage, in addition to a system that will be able to integrate changes much more easily and rapidly throughout a products life-cycle.

Investigation and Case Studies

The investigative work done into modularity has focused on three products that are different in function, design, and scale of production. The products considered consist of; a future small car from a major automobile manufacturer, an optical scanner for the pre-press printing industry manufactured by Crosfield Electronics, and a geophysical measuring system that is used for down-hole drilling, from Geo Measurement Systems. These products also presented a range of enabling technologies; both mechanical, electronic and optical.

The investigation, complementary to existing initiatives within the companies, initially realised a number of pro's and con's that modularity would provide to a product and its associated process. In addition to the rational introduction of variation in a structured and systematic manner, modularisation provides further utility in design, manufacture and also, to the customer.

1. To product development, modularisation means reduced lead times due to the possibility for parallel design and manufacture of modules, and the use of bought-in modules that require no further attention.
2. Manufacture will benefit from a JIT friendly system, leaner production from reduced WIP and finished article stocks, and improved and more consistent quality-with associated reduction in test overheads.
3. Assembly benefits from a product inherently designed for assembly with modules being; of manageable size, and identical within each type (e.g. no adjustment required for fit). Modularity can also facilitate assembly by a reduction in part numbers and part variety, and also the possibility for disassembly, if desired for service (DFS).
4. Management considerations are simplified, by allowing a project to be naturally broken down into smaller

components, and increased product planning accuracy, Erlandsson and Yxkull (1993). In addition, the necessity to consider modules early on, as a design and manufacturing concern, will reduce the downstream activity overhead.
5. Environmental aspects may be addressed (DFE), through the ability to group similar materials for recycling, or the ability to reclaim the most desirable elements.
6. Finally, the customer benefits from a modular product by the range of product choice or customisation at no extra cost, and in significantly reduced time scales, both in terms of delivery and also development of new products. They will also gain improved quality, ease of service and replacement of parts, and a simple upgrade path.

On the negative side, the modularisation of a product will immediately increase the problems with interfaces. Module interfaces will require careful consideration as a key enabler of the technique. Though initially the extra effort up front in defining the interfaces will seem excessive it will facilitate downstream processes and will also promote the discipline of team working and simultaneous engineering by design and manufacture personnel.

It is possible to demonstrate the benefits of a modular strategy to product development and manufacture by examining a number of products that have considered modularity to be a desirable objective. None of these products were developed using strict guidelines on how to implement modularity yet they show how the consideration of a technique such as modularity may be used to promote the discipline of product and process integration.

Figure 1. shows a colour scanner from Crosfield Electronics. The company focused on a new project and developed the product to be modular. During the project the seeds of a strategy were developed to aid in the process of module definition and a means to identify and analyse module interfaces and the interactions that occur. Working with cross functional teams and ensuring up-front effort, provided Crosfield electronics with considerably less problems downstream, and iterations within product development. Other advantages include; significant reductions in part numbers and variety, assembly operations and adjustment, floor space, testing, and complexity of the product.

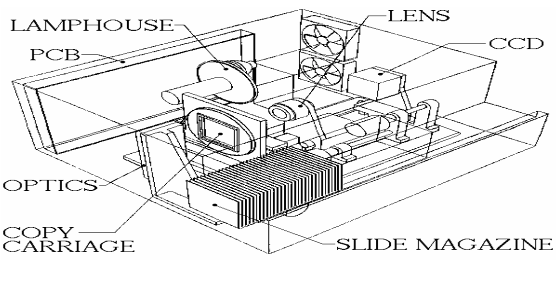

Figure 1. A modular scanner assembly.

Figure 2. shows a typical product by GMS. This illustrates a perfect opportunity for modularity. The product must be designed in this form to offer the flexibility required, but up until now the predominant way of working has been to re-engineer many parts or modules of the product, with little overall standardisation in the mechanical aspects which have proven to be secondary to the electronic concerns. The company are now into the early stages of developing a new mechatronic product, and this is being used as an opportunity to modify their development phase. They aim to take advantage of previous work and designs so modules that make up many of their products are standardised and interchangeable. A key consideration in this case is the nature of the business; GMS do not sell their products, but operate them to provide a Measurement Whilst Drilling (MWD) service, thus they must constantly be able to support existing equipment and provide for large degree of customer requirements. With a structured approach to modularisation GMS will be able to address their main concerns and also refine their overall product.

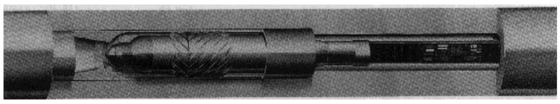

Figure 2. A modular (MWD) sensor and drilling string.

Figure 3. shows a concept for modules incorporated into a new small car. The use of modules in the automobile industry provides a number of advantages in both product and process. The assembly of the automobile benefits greatly through reduced handling, fewer process steps, and component integration, increased flexibility in tooling, equipment and processes and higher productivity through the integration of DFA, DFM, DFS, and DFE disciplines. Quality is improved, and through the ease of interchangeability of modules, so too is customer satisfaction in features and attributes.

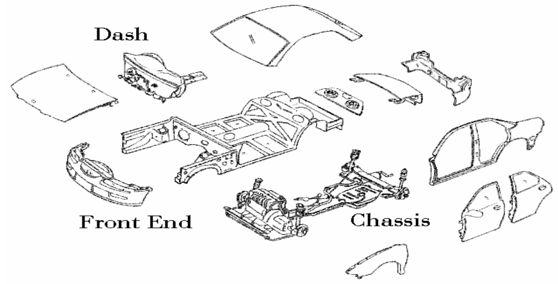

Figure 3. The modules of a small car.

Conclusion

This paper documents the initial investigations into modularisation as a technique for product development. The case studies shown offer an opportunity; to examine the benefits of having applied the technique, to apply the technique within a company who are not untypical in their current product development process, and to study a company who are examining a broader strategy in meeting customer demands for the next millennium. It has been shown that the implementation of modularisation provides many advantages over incremental design and manufacture. Modularisation, be it product wide, or company wide under the guise of the holon, directly meets the needs for custom specifications, and provides mutual benefit to the producer and the customer from the optimum development of the product through companies who are able to configure themselves to meet specific demands. The paper documents the ground work done in furthering the aim to provide guidelines or checklists for the suitability and implementation of modularisation within a context. It is believed that modularisation provides the way forward for product development, achieving a product and process that is capable of dealing with customer driven needs, and that it will prove to be an extremely valuable technique in the future manufacturing industry.

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Erlandsson, A. and Yxkull, A. 1993, Product plans and their interaction with development of the manufacturing system. N.F.M Roozenburg (ed.), *Proceedings of the 9th International Conference on Engineering Design 93*, The Hague. 580-587.

McHugh, P, Merli, G, and Wheeler, W.A. 1995, *Beyond Business Process Reengineering - Towards the Holonic Enterprise.*(J. Wiley & Sons, Chichester)

Shirley, G. 1992, Modular design and the economics of design for manufacturing. G.I. Susman (ed.), *Integrating Design and Manufacturing for Competitive Advantage*, (Oxford University Press, Oxford) 82-99.

Valckenaers, P. and Van Brussel, H. 1994, IMS TC5: Holonic Manufacturing Systems.

ENHANCED PRODUCT REALISATION THROUGH MODULAR DESIGN: An Example of Product/Process Integration.

Marshall, R., P.G. Leaney and P. Botterell, 1998. Enhanced product realisation through modular design: an example of product/process integration. *Proceedings of the SDPS/ASME/IEEE Third World Conference on Integrated Design and Process Technology,* 6-9 July. TBP.

ABSTRACT

The success of new products in the market place depends upon timeliness, cost effectiveness and quality. The realisation of such products demands an integrated, structured, requirements driven approach to their development and manufacture. Requirements can be identified from both the customer and the business enterprise and are often in opposition through the customer's desire for variety and customisation and business' desire for standardisation and rationalisation.

This paper presents design modularisation as an integrated, structured approach to these requirements. The efficacy of the approach is demonstrated through a case study of modularity applied to a measurement whilst drilling (MWD) electronic sensor for civil engineering and oil industry applications. The product presents a mixed technology platform comprising mechanical, electronic and software elements. The benefit of design modularisation is shown through improved product development, manufacture and performance. Further opportunities are identified for the development of modularity tools, their support and the investigation of modularity's analytical performance.

INTRODUCTION

Modularity has a rather unfortunate legacy in that many companies and engineers believe, incorrectly, that they understand what modularity means and that they already utilise a form of modular product architecture. In addition modularity is often seen purely as a process of decomposition or demarcation of product architecture into subassemblies (Whitney 1992). Modules have a number of characteristics that provide fundamental differences between them and convenient groups of components in a subassembly:

- Modules are hierarchical subsystems that form a product, manufacturing system, business etc.
- Modules have their main functional interactions within rather than between modules
- Modules have one or more well defined functions that can be tested in isolation from the system and are a composite of the components of the module
- Modules are independent and self contained and may be combined and configured with similar units to achieve a different overall outcome.

Modularity is typically utilised for its ability to rationalise variety through the partitioning of product functions (Pahl & Beitz 1996; Smith & Reinertsen 1991; Parnaby 1995) and allow for flexibility of application. This advantage has been applied widely throughout the electronics industry for computer manufacture. Within the automotive industry on the Max spider (Weernink 1989), and the Renault Modus (Figure 1 - Smith 1995). Also within the aerospace industry on the Joint Strike Fighter: a highly common modular range of aircraft for airforce, marine, and navy use (JSF 1997). However variety is only one aspect of product modularity. One of the key elements of modularity is its fresh approach to meeting the requirements of effective new product introduction.

THE DRIVERS FOR A FRESH APPROACH

A common aspect of businesses in today's product manufacturing industry, is the noticeable change in customer attitude from passivity to activity. In the markets in which these companies operate, political and economic factors have resulted in a combination of increased affluence of the individual and a human vanity that has developed a lack of tolerance to mass produced 'generic' products and stimulated a demand for customised products (Wright & Bourne 1988). The implications are widespread including product variety, product and process complexity, and the manufacturing response. Markets have also become global, presenting new opportunities and new competition. The global automotive industry has seen Western manufacturers under increasing pressure from Japanese industry (Clark, Fujimoto and Chew 1987; Fujimoto 1989; Altshuler, *et al.* 1984).

For much of manufacturing industry this trend is unfamiliar, and often the existing business, product, and manufacturing systems cannot deal efficiently with a demand they were not designed for. The legacy of heavy automation and mass production has hampered the response of many companies above the small craft industry to these growing stimuli. A review of the history of manufacturing has highlighted the trends that have been followed and the situation where the legacy from manufacturing solutions that were suited to the concerns of the time but no longer meet the concerns of today have to constantly redressed (Figure 2 - Warnecke 1993). Previously the demand for these products has been met by adaptation of existing products, rapid and unstructured re-engineering, ad-hoc solutions, and specially built products (Shirley & Eastman 1990).

Roobeek and Abbing (1988), and Rogers (1990) have identified a number of limiting factors such as increasing product complexity, poor integration and support of computer systems and tools that have constrained the manufacturing response. Drucker (1990) provides an analogy between today's manufacturing factories and a cumbersome battleship navigating in adverse conditions. Whereas a post modern factory would be a flotilla of smaller vessels or modules which serve to compliment each other whilst moving in the same direction. Such an organisation would not only be more flexible but allow rapid design changes in response to demand.

In a structured attempt to meet customer requirements companies are looking at the flexibility within product and process to manage variety. Potential lies within combinations of philosophies from custom manufacture to mass production through mass customisation. Moving from economies of scale to possibilities within economies of scope (Roobeek & Abbing 1988). Modularity is a key aspect of a mass customisation approach.

Case study research of a number of complex product manufacturers has provided a snap-shot of these concerns (Marshall 1998). Four broad issues are presented to which modularity presents an efficient and effective approach are now considered in turn.

1. Efficient deployment of customer requirements
2. A rationalised introduction of new technology
3. A structured approach to dealing with complexity
4. Flexible or agile manufacturing.

CUSTOMER REQUIREMENTS

The meeting of customer requirements is a fundamental aspect of successful product development. The consideration of requirements highlights two issues. The first is the process of managing the requirements, distilling the information from the customer into a product specification. The second is the realisation of these requirements into a completed product or a variety of products. These can be further broken down into:

- Identification and selection of customers to be served

- The identification and selection of their requirements
- The interpretation, deployment and use of requirements in a product development process
- Increasing product variety without unnecessary variety of components, designs, and processes
- Managing the complexity of products and the accommodation of new technologies
- Maintaining a low product cost, by keeping design, production, service and disposal costs low
- Minimising the time of development for new products and delivery time for ordered products.

Requirements management is an increasingly important aspect of product development however it is often an area typically in need of a more structured approach. To this end, systems engineering provides a fresh perspective, focusing development activity on meeting customer needs. SE also provides a framework for tools such as modularity and other formal methods. SE then provides the linking mechanism, facilitated through IT and CIM, to allow requirements to be identified, documented, analysed and distributed throughout the development process into the physical and functional implementation of the product.

NEW TECHNOLOGY

Meeting customer requirements increasingly requires a constant upgrade through the integration of new technology. New technology meets customer requirements and must be managed within the variety of products. This is especially true for electronic systems where technology life is often very short. To the customer this means that improved performance from upgraded technology and new technology is more easily available and affordable. However technology advances rapidly render technology obsolete. Companies must consider the implications for backward compatability and the constraints this will place upon development.

Upgrade and new technology integration also present time scale concerns. Product development for upgrade requires considerable resource and timescales can often be greater than those for a generation of new technology to be developed. Upgrade also commands development costs and effort equivalent to new product introduction.

COMPLEXITY

The natural consequence of meeting customer requirements and maintaining a level of technology raises yet another issue, that of complexity (Syan 1994). Modern product systems typically incorporate a greater number of features, include inherently more complex technologies, and combine a greater number of technologies in a single system than ever before. Products are typically combinations of technologies, and are structured from components to the completed product (Figure 3). Hence it becomes increasingly true that market success depends on the ability of the manufacturer to integrate all such technologies (Tomkinson & Horne 1996).

Management of complexity involves not only product complexity but also development and manufacturing process complexity. The co-ordination across departments, suppliers and with customers requires considerable planning and control especially when combined with modern industrial pressures for reduced costs and lead times (Groover 1987). An issue directly addressed by product and process integration through the total view of systems engineering.

FLEXIBILITY

The traditional response of industry to the issues of variety and complexity is typically that of flexible manufacturing solutions to what are seen as manufacturing problems. Manufacturing flexibility in this context refers to flexible facilities and tooling, and if taken in isolation only addresses the problem in the short term with associated high monetary and complexity costs. Alternatively systems engineering presents a total view. The application of flexibility to the product and process will facilitate manufacturing flexibility, and the use of flexible systems will then aid the overall design to manufacture process (Marshall & Leaney 1995). Agile manufacturing embodies the application of flexibility and process integration, lead time reduction, and more enterprise-wide philosophy of concurrent and systems engineering. On analysis it offers similar goals as mass customisation, holonic manufacturing and the fractal factory (Gould 1997).

These issues are now addressed through the modularity paradigm (Figure 4) working from a systems framework, through a modularity methodology to a process for modular product development.

A SYSTEMS FRAMEWORK

For such a broad scope of issues to be addressed it is important to take a total view. Systems engineering provides this perspective through a comprehensive approach to the life cycle development of complex products and/or processes. Though the application of modularity primarily concerns the early phases of development, it has implications for the whole of the product life cycle. From an analysis of systems engineering and modularity it is proposed that both address the complexity of product and process from the inclusion of new technology and the strive to meet customer requirements. Thus a systems engineering framework provides the ideal carrier for modular product development and its wide ranging impact on all aspects of the business and the customer.

Upon examination the systems engineering process relates strongly to a broad process for module development: accumulation of requirements, identification of the product’s functions and possible combinations of products, identification of product elements for module definition, detail module design and production.. A modular development process will also require consideration of the operation of individual modules and also their operation as a whole product.

However it is proposed that traditional approaches to systems engineering e.g. Blanchard and Fabrycky 1990, miss an opportunity to provide a true total view of product and process integration through consideration of manufacturing as the consequence of design. A modular design methodology will address this issue through the consideration of manufacturing issues as part of a concept of design to manufacture as a single process.

A MODULARITY METHODOLOGY

Modular product design or modularity presents an opportunity to the developers of predominantly complex products to meet the issues presented, in a way that does not impose penalties upon the company. Exponents of the concept of modularity (Smith & Reinertsen 1991; Ulrich & Eppinger 1995; Pahl & Beitz 1996; Erixon 1996) have realised its potential and some have defined appropriate guidelines and processes for its application. An analysis of their work highlights an opportunity to further the overall concept through clarification and the provision of a more comprehensive process and support mechanism to provide a truly fresh approach to product realisation (Marshall 1998).

Modularity is more than just a design technique. It impacts upon the whole of the product life cycle. In the same way that QFD can provide a linking mechanism between the various stages of this cycle. Modularity is developed as a linking methodology supported by a systems level framework for product realisation to provide an integrated and structured product modularisation process (Figure 4). The process relates to the specific application of modularity to a product, but through the methodology and framework also embodies the support of the product and its processes.

The methodology for modularity must cover a number of key aspects:

- It must be translucent and flexible in that it must be able to overlay an existing product introduction process without

undue reengineering and without masking any successful aspects of the existing process. However it cannot be transparent as it must make definite changes and highlight key processes.
- Consideration is given to the details of implementation and how the material may be best presented to maximise the clarity of the message, the ease of use, and the support of industrial concerns.

The methodology, through its framework, must relate actions to customer requirements, and consider the implications that any module element is always going to function as part of a higher integrated system. This framework will support the needs of the whole organisation equally through the importance of:

- corporate strategies and goals
- the need for efficient and effective requirements management
- the operation and integration of design and manufacture
- the provision and enhancement of product support
- and the implications for product takeback, recycling and disposal.

In addition the framework acts as a carrier for other techniques, such as DFMA, QFD, FA, VE etc., that are beneficial to specific issues within modularity and also to product realisation in general.

A MODULAR PRODUCT DESIGN PROCESS

Within the methodology, modularity is developed into a process that continues the aims of the methodology and ultimately the framework. This new process is based upon existing best practice and shares a level of commonality that facilitates its integration into industry. The process presents a generic platform upon which all of the diverse factors to which modularity may be applied can be built. Modularity presents a number of implementation aspects that require careful consideration for each specific application. Based upon the findings that modularity is applicable at a number of levels and that each implementation scenario will be unique, a form of self analysis is implemented to allow the process to be analysed for applicability and tailored to suit the individual circumstances of the user. Analysis also identifies a number of specific issues to address:

- The opportunity presented by manufacturing as an integral part of the design process and the competitive advantage the use of modular product and manufacturing processes presents.
- The attention to module interfaces and their timing to ensure that interface details can be used for module definition.
- The acknowledgement of manufacturing paradigms such as holonic manufacturing and the fractal factory and the mutual benefit that may be drawn from their ties to a modular product architecture.

HOLONIC PRODUCT DESIGN

The framework, methodology and process have been embodied in a Holonic Product Design (HPD) workbook in order to provide guidance for companies seeking modularity in a clear, concise and accessible manner. The HPD workbook presents the framework and methodology through seven clear sections to enable companies to address the four broad issues presented earlier.

The workbook begins by introducing the product introduction process (PIP) based on BS EN ISO 9000 and BS 7000 Part 2 in order to establish a baseline for integration of the workbook methodology. Detail of the generic processes is kept to a minimum focusing on key points that can be extracted to relate to a company's existing process. The next section relates the generic product introduction process to the holonic product design (HPD) methodology, highlighting the influences of HPD at various stages throughout the generic PIP. The format of three phases presented by BS 7000 Part 2 is maintained to allow companies to partition the process into broad steps of product introduction for simplified integration and to allow personnel responsible for each area to have ownership of the respective changes.

Having introduced the PIP the workbook goes on to detail the mechanics of designing for modular products, and how this process fits into the HPD methodology and subsequently the generic PIP. Designing for modular products provides guidance on the each stage of the process and the new issues that must be dealt with for a successful modular design. Material is presented in a neutral and flexible way in order to allow the process to be adapted and integrated into a wide range of industrial scenarios.

The following section provides detail on the manufacturing strategy for modular products. As before, a generic basis is established and modular specific considerations related to this basis for ease of integration into an existing strategy.
Specific attention is given to cellular manufacture and its relationship of cells to modules and the implications for stages of the lifecycle beyond manufacture.

The next section presents a self assessment to allow the HPD technique to be integrated into current practice within the company. The self assessment provides simple evaluations to aid companies to:

- Clarify reasons for the change to modular product architectures
- Clarify business strategy and corporate objectives
- Define the required company organisation and working practices
- Provide a platform on which to base the framework of the new HPD methodology
- Examine existing and future products and their features for suitability to modularity
- Provide guidance on the level of modularity suited to the product and the company.

Results from this section provide a clear understanding of what is wanted in terms of company goals and a modular product. In addition, the self analysis provides a list of benchmarks, priorities and relevant guidelines to the specific needs of the company in question.

Final sections of the workbook address maintaining the HPD methodology through a series of checklists and relating guidelines. The aim of these is to ensure that the HPD process is followed and to provide guidance to the employees embarking on a new process and dealing with product architecture in an unfamiliar manner. The guidance ensures that the best practice of HPD is instilled within the employees and yet does not try to adhere them to rules which are not always practical. These sections also present the underlying essence of modularity in highly accessible and user friendly elements that facilitate integration and acceptance. Again, the checklists and guidelines are company customisable to allow beneficial aspects to be adopted where appropriate.

CASE STUDY

In order to evaluate the modularity methodology it was implemented within a development process at a company called Sperry-Sun Drilling Services. Sperry-Sun Drilling Services (SSDS), Cheltenham are a small company of around 70 employees, and are the UK arm of a much larger corporation (2500 employees) based in Houston, USA. SSDS design, manufacture, test, service and support a number of products that are used in an ever diversifying market, under increasingly harsh environmental conditions. Products consist of electronic sensors and instrumentation for civil engineering and oil industry applications (Figure 5). The applications are primarily in the form of measurement whilst drilling (MWD) operations and the products are designed to allow these measurements to be taken in order to determine a range of information such as direction of drilling and the formation being drilled through.

The products are operated by the company as a service to the customer. Over time the customer needs have grown as new applications have been envisaged and the requirements on performance have increased. In order to meet the needs of the customer the company has developed a range of products. These products exhibit a number of characteristics:

- They have been developed in response to specific customer needs
- They have evolved to incorporate improved and / or new technologies
- They can be used in combination to provide a variety of service
- They are backwardly compatible with existing products already in service.

The development of this product range directly met customer needs but led to a situation that posed a number of difficulties to both SSDS and for the operators of their products. The constraint of backward compatibility, has over time, presented a problem with the number of interfaces required to ensure compatibility between products of differing ages. This was not a problem when the number of product options was low, but with the increase in possible combinations and a likely continued increase in the future, the situation became prohibitive to both business and operator needs. Coupled with this was an unstructured and somewhat ad-hoc design of products. Presenting problems with; part standardisation, increased stock holding, product re-engineering, poor time management, and continued 'fire-fighting'.

The solution to this, and a number of specific technical needs was the development and implementation of a new product development strategy that mapped out the needs of both the business and customer, and provided a framework for dealing with a number of issues including customer requirements, increasing product and process complexity, and the introduction of new technology. The product development strategy was to be based on the HPD methodology, and be linked with business objectives and a strong quality management process.

The framework for a successful product development strategy was put in place by the definition of SSDS's business objectives and corporate mission statement. The focus was understanding and exceeding the customer's expectations and providing benefit to the business as a whole in a continuous improvement culture.

The case study now follows the implementation of the strategy to two core products in need of replacement. The 150º C (operating temperature capability) directional gamma whilst drilling (D(G)WD) system, or specifically the pressure case directional (PCD) and pressure case gamma (PCG) probes. Figures 6 & 7 highlight the finished product modules and their constituent elements.

The process truly began with the inclusion of the modularity goal as part of the corporate objectives. This step ensured that there was a company-wide 'buy-in' of the concept and that it provided a universal platform for the integration of disciplines and the utilisation of resource in achieving business goals in an effective and efficient manner. A concurrent engineering environment was facilitated through a total quality management (TQM) philosophy and the use of multi-disciplinary teams, the co-location of employees in related functions, and the encouragement of co-operation and communication between all departments.

The detail implementation of a modular strategy was initiated with the analysis of the existing products and the documentation of key elements within them. This analysis aimed to ensure backward compatibility with existing products to maintain high customer confidence but to also identify possibilities for standardisation and rationalisation. The analysis identified a number of elements that required consideration:

1. A high degree of functional, but low physical, commonality between the two products
2. A distinct common and dedicated split of functional areas
3. No real justification for the low physical commonality
4. Possibilities for novel design changes to improve performance and ease of manufacture
5. A possibility to introduce a new standard to the product range whilst still maintaining backward compatibility
6. A starting point for a new company platform and philosophy. There was an opportunity to provide a generic platform for future products. This coupled with the business changes and focus, presented itself as a new company philosophy for understanding and exceeding customer requirements.

In addition to the identification of key elements, a level of modularity was determined to include a generic platform element and to develop modules at a mechanical and electronic package level. Thus electronics packages could be developed within constraints by separate teams, in parallel to the mechanical design based around the same constraints. This provided a benchmark guide for product development, and allowed parallel development of the associated modules.
The culmination of this concept phase of development was the generation of a technical specification document. This document was refined to meet the needs of the new product development process. The new specifications showed a systems engineering influence by providing an up-front record of requirements, and traceability to who generated those requirements.

Once the requirements were signed off in the technical specification the requirements were used to develop a rough layout of the product. The layout provided information on key features, constraints and provided sufficient detail for the team to determine possibilities for modularity. Possibilities related to existing and future product requirements to ensure compatibility and extended life. The criteria used for module identification were primarily those presented below:

1. Standardisation was used to provide a generic product element that covered the common functional areas. This generic element could then be used as a platform for future products
2. Manufacture was addressed through the commonality elements, complementing the common areas of functionality with common areas of mechanical and electronic design
3. Localisation of change was considered important in allowing existing products to be upgraded through the retro-fit of new modules
4. Supplier capability allowed modules to be sourced completely from one supplier increasing economies of scale, reducing overheads, and providing a better relationship with the suppliers.

In addition to module identification, interfaces were also identified and analysed. This was especially important between the generic platform module and the dedicated variant elements. The capability for a new interface standard was also included to enhance the flexibility of the design, improve ease of operator use, and reduce complexity and stockholding.

Once module concepts were agreed, a rough geometric layout was performed to ensure module fit, and compatibility with the existing equipment and products. Finally the proposed modules were checked against the technical specification to ensure that the requirements were being met at an early stage when changes were relatively straight forward and economic. Once signed-off the product went onto detail design.

In addition to the specific modular features of the strategy there were a number of complementary initiatives to improve the development process. Component standardisation was employed wherever possible to ease manufacture and assembly, reduce stock holding and part inventories, and provide greater economies of scale. Total procurement was employed to source modules complete from individual suppliers. This was accompanied by a rationalisation of the supplier base and a shifting of responsibility of component quality from SSDS to the suppliers. Manufacturing input is now much earlier in the development process including the manufacture of prototype products, as oppose to engineering, so that production problems can be identified early.

CASE STUDY FINDINGS

The benefits gained from the implementation of the new modular strategy have been widespread. New product development is much simplified and responsive. The re-use of modules reduces the engineering effort required to realise a new product and ensures that the customers needs are met quickly. Design changes and upgrades have also benefited in the same way through forward compatibility and the ability to upgrade selective modules, addressing customer requirements pre-emptively and allowing existing products to be upgraded with greater efficiency.

Complexity has been addressed through decomposition into modules, partitioning of dedicated and common areas and a reduction in interfaces and provision of generic modules. This has improved management, design, manufacture, service and use of the product.

Modules have simplified and allowed more efficient manufacturing and assembly tasks. This has been achieved through the early involvement of manufacturing but also a reduction in part numbers and part variety, thus reducing stock holding, parts inventory, lead times (from 12-20 weeks to 6-8) and increases the economies of scale and quality (2.5% rejects to 1.2%) for part orders. Assembly sequences are generic across the majority of products and variety can be introduced late on in the assembly process providing a flexibility to the build plan. Testing is simplified as modules can be tested separately and also by the supplier ($190,000 saving). There are also less varieties of products to test and a reduced requirement for test tooling and facilities.

The implementation of the process has also seen some general benefits including administration and documentation overheads reduced, a closer knit and more motivated development operation with engineers more appreciative of functions outside their own and an emphasis on finding and addressing problems early on.

CONCLUSIONS

The case study presented in one example of a number of similar studies that have shown that modularity confers a range of product and process based enhancements that together form a package for meeting current and future requirements and pressures.

- Manufacturing industry faces a number of challenges from the customer. It has been shown that the main issues are how to meet increasingly specific customer demands without the added burdens this can place upon development and production costs, time and quality.
- Modularity within a systems engineering context has been proposed as a strategic approach.
- Modularity provides product variety to the customer. However the variety can be offered efficiently through a limited number of modules and the use of common modules. Variety can also be introduced without unnecessary reengineering, in reduced timescales and at lower cost.
- Modularity allows customers to control the variety, providing flexibility in operation but also in support through improved serviceability and upgrade.
- Modularity presents an opportunity to manage process complexity and combine teams with the modules for which they are responsible. Requirements for modules to integrate together then encourages integration across teams and presents a greater system for efficient and effective product development.
- Modularity addresses product complexity through decomposition of systems, partitioning of functions, analysis of interactions and modular assembly. The resulting effect is greater product reliability, service, and product upgrade.
- Modularity allows more efficient and effective manufacture and assembly. Part standardisation addresses quality, economies of scale and improved supplier relations. Processes can be structured around the product, modules assembled in parallel, testing can be done on individual modules, variety introduced late and thus orders rapidly fulfilled.
- Modularity also provides structure to the application of other related processes such as DFA, value engineering and group technology.

FURTHER OPPORTUNITIES

Primarily the work on modularity has addressed the need for a modular approach and the specific process or methodology to meet those needs. Further work is targeted at providing supporting tools for the process through examination of a computer based systems engineering environment. The case study material is also to be accompanied by modelling and analysis of the performance of modularity through various software tools.

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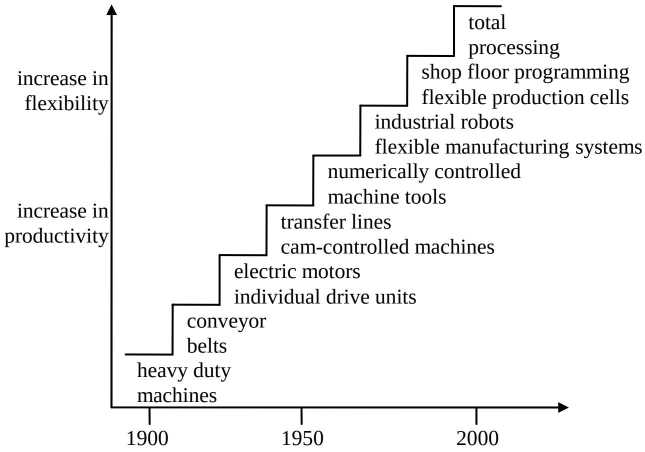

Fig. 2 Development Stages in Manufacturing Technology (Warnecke 1993).

FIGURES

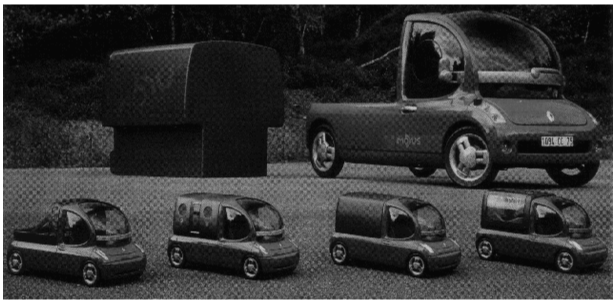

Fig. 1 The Renault Modus.

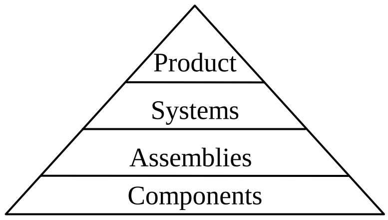

Fig. 3 The Product Hierarchy.

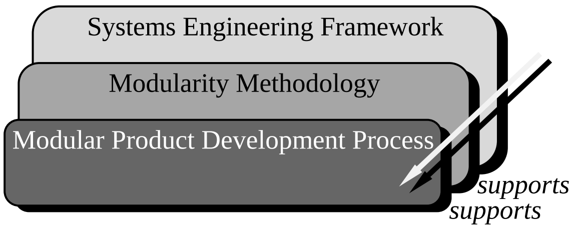

Fig. 4 The Modularity Paradigm.

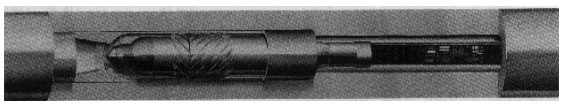

Fig. 5 A MWD Pulser and Probe.

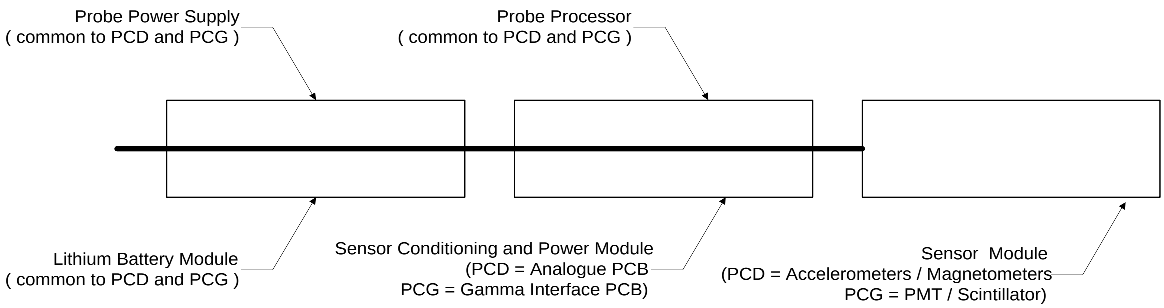

Fig. 6 PCD / PCG Module Organisation.

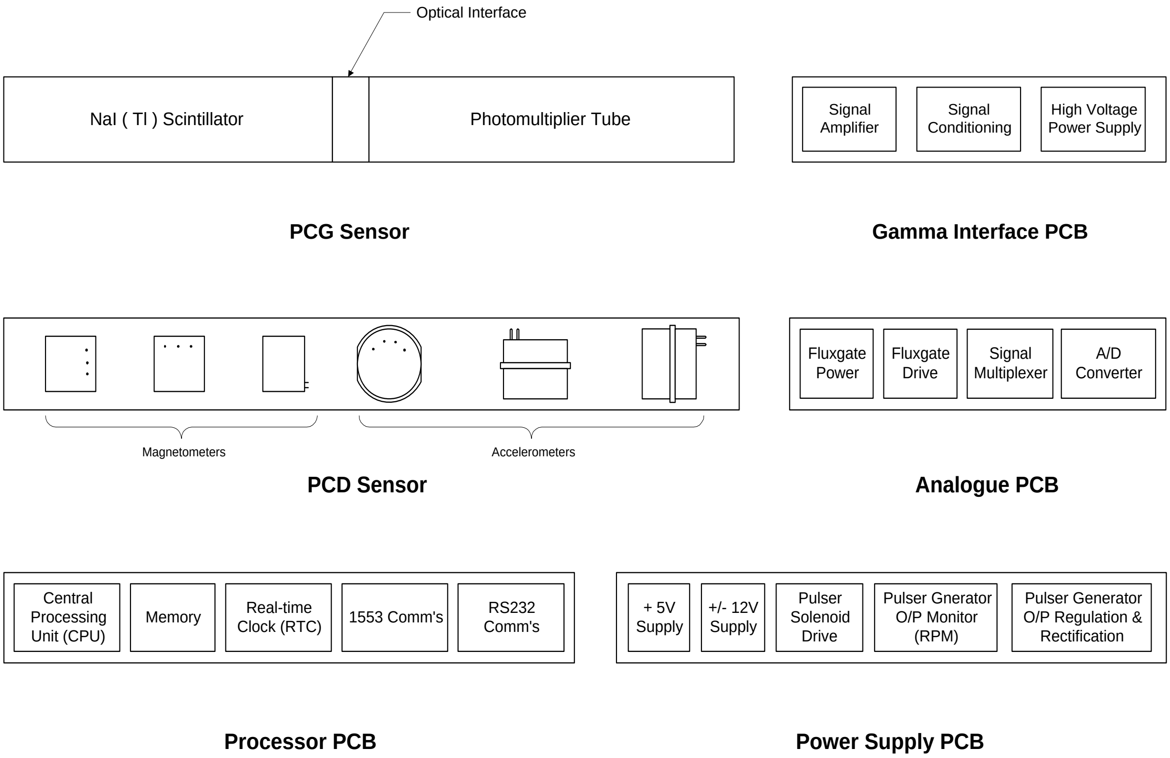

Fig. 7 PCD / PCG Module Detail.