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ENHANCED PRODUCT REALISATION THROUGH MODULAR DESIGN: AN EXAMPLE OF PRODUCT/PROCESS INTEGRATION.

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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 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 interactions within rather than between modules
- 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) 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 (Weermink 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.

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 & Chew 1987; Fujimoto 1989).

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 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. 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 integration of new technology. New technology however 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 improved performance from upgraded and new technology is more easily available and affordable. However technology advances rapidly render technology obsolete. Companies must consider the implications for backward compatibility 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 technology level raises the issue of complexity (Syan 1994). Modern product systems 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 market success increasingly depends on the ability of the manufacturer to integrate 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 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 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).

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. 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.

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 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 modularity (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. 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). This methodology for modularity must cover a number of key aspects:

- It must complement existing product introduction processes providing guidance and highlighting key elements without undue reengineering and without masking any successful existing elements.
• 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
• efficient and effective requirements management
• the operation / integration of design and manufacture
• the provision and enhancement of product support
• the implications for 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. 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. 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:

• 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.
• Module interfaces and their timing to ensure interface details can be used for module definition.
• 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. 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 subsequent 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 manufacturing strategy for modular products. As before, a generic basis is established and modular specific considerations related to it 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 company organisation and working practice
• 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
- evolved to incorporate improved and new technologies
- the ability to be combined to provide variety of service
- backward compatibility with existing products.

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. 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. The strategy 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 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 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 effectively and efficiently.

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 / 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. The introduction of 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 technical specification was signed off, 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 are 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 straightforward 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 reuse 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 preemptively 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...
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 result is greater reliability, service, and 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.

REFERENCES

FIGURES

Fig. 1 The Renault Modus.

Fig. 2 Development Stages in Manufacturing Technology (Warnecke 1993).

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.