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Proceedings of the Institution of Mechanical Engineers Part B.

Short communications in manufacture and design

A systems engineering approach to product modularity

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01/06/99

Abstract: Product modularity has been successfully adopted in a number of specific industries, such as computer technology and software development where it provides a number of advantages over monolithic product architectures. This paper presents initial findings from research at a range of companies within the UK where modularity is being applied or considered to address increasing product complexity and the growing need for the symbiosis of mechanical, electrical, electronic, optical, and software technologies in a wider range of manufactured products to meet discerning market requirements. The research identifies a need to address the current application of modularity within industry at three levels; a systems engineering based framework; a methodology for product modularisation; and the underlying process of modular product development. Concluding remarks highlight the issues drawn from the research and opportunities for addressing these issues.

1. INTRODUCTION

Case study research on design modularisation has been undertaken across a range of product manufacturers from automotive to scanning and sensing equipment, and manufacturing machinery. The work highlights a range of issues that must be addressed in order to introduce successful new products (1). These issues can be summarised into four main concerns to which modularity is a strategic approach.

1. Efficient deployment of stakeholder requirements
2. A rationalised introduction of new technology
3. A structured approach to dealing with complexity
4. Responsive manufacturing through flexibility/agility.

A common aspect of the research is the noticeable change in customer attitude from passivity to activity where political, social and economic factors have resulted in a lack of tolerance to mass produced 'generic' products and stimulated a demand for customised products. In addition to customer pressures companies are subject to widespread corporate concerns including product variety, product and process complexity, environmental issues, the manufacturing response, and the global nature of industrial markets presenting new opportunities and new competition.

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. In a structured attempt to meet customer requirements companies are looking at the flexibility within product and process to manage variety and complexity in an efficient and effective manner. In order to move the idea of modularity forward the concept of modularity and the characteristics of modular products that enhance product realisation are summarised. A number of principles are then presented that have been determined from the research. Subsequently the need for a structured approach to the issues presented is addressed on three levels; a framework, methodology, and process. Some initial validation results are introduced and finally concluding remarks reviews the need for modularity and highlights the opportunities for novel solutions in structuring integrated development activity for modular products and processes.

2. PRODUCT MODULARITY

Within the concept of modular products lies an opportunity to address stakeholder requirements (customer, business, supplier, legal, etc.) in a structured manner. However the potential for modular products has been largely passed over outside of a few specific industries. The use of product modules within computer and software development has proven not only to be effective but virtually essential, yet the efficacy of the approach has yet to be exploited within the rest of manufacturing industry. Constrained by engineering legacy and the lack of a broader view, modularity has been consigned to a process of decomposition or demarcation for manufacturing convenience in the form of subassemblies (2). However, the research carried out has determined that 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 functions that can be tested in isolation from the system
- 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 (3). However variety is only one aspect of product modularity. One of the most important aspects of modular products and their realisation is the potential for efficient flexibility. Modularity can be versatile, where a product or process can alter between two known states through selection of the appropriate module, and truly flexible, where uncertainty can be accommodated through the selection of an existing module or development of a new one. Modularity ultimately provides a means to address the scope of flexibility incorporated by product engineering in order to meet a broad range of customer requirements efficiently, to the flexibility afforded to manufacturing in the form of module based cells, parallel manufacture and late configuration.

3. MODULARITY PRINCIPLES

From the case study research it has been determined that regardless of the approach taken modularity exhibits a number of facts or rules that define the principles of a modular approach. An example of these principles includes:

1. Modularity is inherently based upon a mapping of functional aspects to physical entities and is governed by concepts such as the domain theory (4) and Suh's design axioms (5). The way in which this is done and the impact of particular configurations controls a product's modularity and ultimately its ability to meet requirements.
2. A number of factors have been identified that influence the mapping of physical to functional elements e.g. interactions, geometry, core business, and manufacture.
3. Some initial metrics have been developed to allow numerical measurement of advantage to be gained and suitable level of modularity though further validation is necessary.
4. Modularity has a negative effect upon assembly when a localised view of assembly operations and fixture requirements is taken. The modular assembly will always take an extra number of assembly operations.
5. 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 timeliness attributes are seen.
6. To meet changing needs in an effective and efficient way, flexibility must be introduced into the product realisation process. Modularity provides a rational product flexibility to enhance existing manufacturing flexibility solutions.
7. Modularity needs support of a system level framework in order to manage its complexity and broad ranging links and interactions. Modularity cannot be viewed as an isolated process capable of being implemented without consideration of the organisation system in which it is to fit.

4. THE MODULARITY PARADIGM

A number of the principles above show that an approach to modularity cannot be performed in isolation at a discrete point in the development process. Instead, modularity must permeate the whole process, integrating requirements, the functions to meet those requirements and the physical implementation of those functions from the perspective of a total view. To support this view a high level framework is proposed from which increasing levels of detail on processes and underlying principles can be targeted at increasing resolution of implementation. This hierarchy of modularity forms what has been termed the modularity paradigm (Fig. 1) and is the basis for any approach to meet the needs presented. A benefit of the modularity paradigm approach is that the framework and methodology provide a structure into which a company with considerable resource invested in an existing process may fit without the need for unnecessary change. The following sections will now deal with each of the three elements of the paradigm.

5. A SYSTEMS FRAMEWORK

The need to approach the realisation of modular products from the perspective of a total view has been highlighted. Systems engineering provides this perspective through a structured and requirements driven approach to the lifecycle development of products and their associated processes. Systems engineering structures the development process through a series of phases that address the management of stakeholder requirements, the analysis of functions to meet those requirements, and finally a physical analysis that maps functions to physical elements. In addition, it provides

validation and verification at each phase (6). This structured approach begins to address the issues presented with complexity, requirements, technology and flexibility from a top down perspective. Thus systems engineering addresses the needs for a modularity framework, supporting modular product realisation throughout the product lifecycle and its accommodation of a methodology and underlying principles.

However it is proposed that traditional approaches to systems engineering e.g. Blanchard and Fabrycky (7), miss an opportunity to provide a true total view of product and process integration through consideration of manufacturing as the consequence of design. An approach to modularity is proposed from the perspective of integrated product and process development (IPPD) and the IPPD tenets proposed by the Department of Defence (DoD) (8). Such an approach encourages the traditional aspects of systems engineering but combines them with a truly integrated development of the product and the means by which it is developed and manufactured (9). By taking design to manufacture as a single process, modularity can be better accommodated into the framework through reflection of its impact upon modular product architectures and modular based working practices and manufacturing processes.

6. A MODULARITY METHODOLOGY

The methodology provides a basis for a modular product development process and is necessary to relate the high level framework to the actual process of engineering the product. Exponents of modularity and their implementations such as modular function deployment (MFD) (10, 11) have realised its potential and have defined appropriate guidelines and processes for its application. However, an analysis of their work further highlights the requirement for the proposed three level approach addressing a broader scope suited to the needs identified.

The methodology, through its framework, must relate actions to stakeholder requirements, and consider the implications that any product module is always going to function as part of a higher integrated system. In addition the same holds true for any process module. In the same way that quality function deployment (QFD) can provide a linking mechanism between the various stages of the product life 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. Thus the processes carried out in one aspect of module realisation must be addressed in the context of the lifecycle. The phases of the methodology (Fig. 1) focus on establishing a corporate stance on modularity to guide the strategic modular intent of the company and carrying this intent throughout the product lifecycle. These phases are now expanded:

- Modularity business analysis develops a business strategy for modularity, sets strategic goals and ensures management buy-in. Examples may include make / buy decisions or whether modularity is being used to provide an upgrade path or for rationalised variety.
- Modularity system analysis sets the system attributes for module development such as the level of modularity (LOM) (e.g. many modules of similar complexity to one complex core module with a few custom feature modules).
- Modularity definition involves identifying the characteristics that define the modules and ultimately the modular product. Characteristics could include number of modules, key elements, specific functionality etc.
- Modular architecture addresses the definition of the product architecture (e.g. interface boundaries, core and variant modules etc.) based on the level of modularity to provide an architectural plan for design and manufacture.

- Module design involves the concept and detail design of each module and the interfaces between modules.
- Module specification formalises the module designs, the interface plan, the assembly processes, servicing plans and routes for upgrade.

7. A MODULAR PRODUCT DEVELOPMENT PROCESS

The actual process of developing modular products deals with the engineering processes involved in converting the results of the early phases of the methodology into product and process specifications. A preliminary outline of this process has been developed in response to the needs of the case studies and within the scope of the paradigm. Figure 1 shows these stages and their approximate timing with respect to the framework and methodology. An important aspect of this process is the focus on interactions thus the need for two stages of interaction analysis to ensure that modules can ultimately function as an integrated whole.

8. INITIAL VALIDATION

Some initial validation has been carried out through a project based at Sperry-Sun Drilling Services, UK (SSDS) who manufacture test equipment for down-hole drilling applications. The paradigm was used to help shape the business strategy for modularity and introduce a new development strategy. The strategy was then applied to two new products. Initial findings highlight the responsiveness of the approach reducing repetition of work and of functionality. Modules have allowed reuse and standardisation of service offered in a rationalised manner. Manufacture has also benefited through a reduction in part numbers and part variety, lead times (from 12-20 weeks to 6-8) and increases in quality (2.5% rejects to 1.2%). 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.

9. CONCLUDING REMARKS

The research has identified a need within industry to which modularity offers an approach that provides a timely opportunity to drive integrated product / process development in meeting stakeholder requirements. This need, summarised in the introduction as four interrelated concerns, demands a structured and requirements focussed view. It is proposed that a systems level view provides this perspective. The systems engineering framework provides the top-down context and rationale for modularity whereas practitioners require tools and techniques to address their bottom-up implementation. Thus a tiered paradigm has been proposed to target the appropriate perspective, detail, and approach to each level. The systems engineering framework supports a modularity methodology and specific engineering process that details the processes of defining, realising and implementing modular products. This paradigm then supports the principles of modularity that can be carried over regardless of application and can be used to determine metrics for control and support of the methodology. To validate this model ongoing research is being carried out into embodying the paradigm into a form accessible by the practitioners of modularity and with all necessary tools for implementation and support of the process. Some initial positive validation results have been summarised through an implementation within industry though this is to be later expanded to an assessment of the approach in terms of its applicability, accessibility and its overall scope.

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FIGURES

Fig. 1 The Modularity Paradigm.