J. ENG. DESIGN, 2002, VOL. 13, NO. 4, 293–303

Holonic Product Design: a process for modular product realization

R. MARSHALL†* and P. G. LEANEY*‡

This paper introduces a fresh perspective on product modularization and proposes a process for modular product realization called Holonic Product Design (HPD). The holon has recently been adopted from Arthur Koestler's work to represent subsystem entities within manufacturing systems and the enterprise chain. In addition, it has been embraced as a philosophy for change that attempts to fashion modern manufacturing businesses and manufacturing activity. This paper demonstrates the holon as being equally valid as an approach to product development. Through research at a number of UK companies, HPD is developed and presented as a structured approach to product realisation. Addressing a total view through systems engineering, HPD provides an accessible and customizable modular product development workbook. The efficacy of the new approach is demonstrated through the initial results from an HPD case study. Further work remains in refining the integration of HPD elements and thoroughly testing the approach through a full new product development process.

1. Introduction

The aims of this paper are to

1. present the case for a modularity-based process for enhanced product development;
2. present the modularity paradigm and explain its structure and how it supports Holonic Product Design (HPD);
3. highlight some key features of the HPD workbook; and
4. finally present some initial validation work at a small UK company and conclude.

Case study research on design modularisation has been undertaken across a broad range and scale of product manufacturers. The work carried out highlights a range of issues that must be addressed in order to introduce successful new products (Marshall 1998). These issues can be summarised into four main concerns to which modularity is a strategic approach.

- Efficient development of stakeholder requirements.
- A rationalized introduction of new technology.
- A structured approach to dealing with complexity.
- Responsive manufacturing through flexibility/agility.

Revision received 4 September 2001.

† Department of Design and Technology, Loughborough University, Loughborough, Leicestershire, LE11 3TU, UK.
‡ Wolfson School of Mechanical and Manufacturing Engineering, Loughborough University, Loughborough, Leicestershire, LE11 3TU, UK.
* To whom correpondence should be addressed.

Journal of Engineering Design
ISSN 0954-4828 print/ISSN 1466–1387 online © 2002 Taylor & Francis Ltd
http://www.tandf.co.uk/journals
DOI: 10.1080/09544820210000508 3 9

This paper will now discuss some of the characteristics of modular products that enhance product realization and highlight why modularity might be a strategic approach to meeting the issues presented.

2. Product modularity

Modular product architectures are not new and have seen successful application, but have been largely passed over outside of a few specific industries. 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 (Whitney 1992). However, the research carried out (Marshall 1998) has determined that modules have a number of characteristics fundamentally different to subassemblies:

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

It is believed that the lack of modularity application is due to its initial perception as a tool to rationalize variety through the partitioning of product functions (Pahl and Beitz 1996). However, variety is only one aspect of product modularity. One of the most important aspects of modular product development is the potential for efficient flexibility. Modularity ultimately provides a means to address product flexibility, in order to efficiently meet a broad range of customer requirements, and manufacturing flexibility in the form of cells, parallelism, and late configuration.

3. Holons and holonic manufacturing

The term holon is derived from two observations by Koestler (1967). The first is from Simon (1962) and is based on the parable of the two watchmakers. The parable concludes that a purely sequential assembly process is highly prone to disturbance, and that greater robustness, ease of maintenance and repair can be obtained through the use of subassemblies, a point echoed by Hansen (1970) when dealing with mechanical adjustments. The second is the relativity of hierarchies. Intermediary structures such as subassemblies have characteristics associated with 'parts' and also with 'wholes' depending on the way in which they are viewed. To represent these 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.

Holons have already been adopted at an organisational level in the form of Holonic manufacturing systems (HMS). HMS are part of the Intelligent Manufacturing Systems (IMS) programme that addresses the so-called 'fragility' of today's manufacturing systems (Valckenaers and Van Brussel 1994). However, taking a system-wide approach to manufacturing enterprise organization and operation requires equal consideration of the product system. In the same way that flexible manufacturing solutions are facilitated through the use of flexible designs (Barnett *et al.* 1995) so too holonic manufacturing concepts can be facilitated through holonic product design. Indeed, parallels can be drawn between the issues and requirements for modules and those for holons. The literature from various areas of design and manufacturing highlights the trend towards distributed, co-operative and intelligent modules but also highlights the need to bridge the gap between the analytical nature of these observations and the design/synthesis of artefacts (Suh 1990, Valckenaers 1993, Rzevski 1998, Wynns 1999).

4. Modularity principles

Case study research has determined that regardless of the approach taken modularity exhibits a number or facts or rules that define the principles of a modular approach (Marshall and Leaney 1999). An example of these principles includes the following.

1. Modularity is inherently based upon a mapping of functional aspects to physical entities and is governed by concepts such as the domain theory (Andraesen 1980, 1999) the work of Hubka and Eder (1998, 1996) and Suh's design axioms (Suh 1990). The nature of this mapping and the ultimate configuration 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 (see section 6.2).
3. Some initial metrics have been developed to allow numerical measurement of advantage to be gained and suitable level of modularity, although further validation is necessary.
4. Modularity has a negative effect upon assembly when a localized view of assembly operations and fixture requirements is taken. The modular assembly will always take an extra number of assembly operations.
5. A total view of assembly highlights the overall beneficial effects of modularity. By using parallel assembly, total cycle time is reduced and further positive impacts upon flexibility and timeliness attributes are seen.
6. Modularity provides a rational product flexibility to enhance existing manufacturing flexibility solutions.
7. Modularity needs the 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 buisness context in which it is to fit.

5. Holonic Product Design

The principles above highlight the systemic nature of modularity. In addition, analysis of the work of exponents of modularity such as Ulrich and Eppinger (1995) supports the need for an equally systemic approach addressing a broader scope suited to the needs identified. Thus, HPD embodies a generic approach 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 (figure 1) (Marshall and Leaney 1999) and is largely implementation-independent. The paradigm consists of three levels and combines elements of best practice from systems engineering (SE) standards

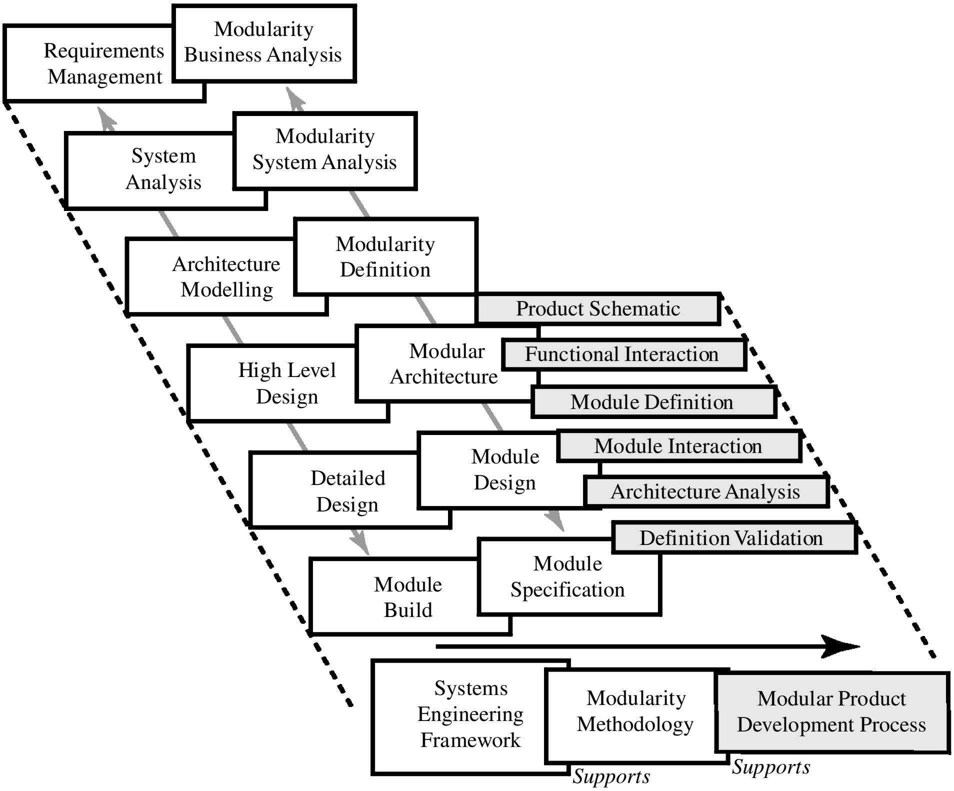


Figure 1. The modularity paradigm.

IEEE 1220 (IEEE 1995), EIA 632 (EIA 1997) and design standards such as BS7000 pt2 (BS7000 1997). HPD has been developed in a workbook form (Marshall 1999) as a pragmatic implementation of the modularity paradigm and addresses the development of modular products in conjunction with the process and organizational issues that accompany them.

5.1. *Systems engineering framework and modularity methodology*

These areas are not covered in detail here but aim to meet the need for a total view and a means of relating this view to the actual process of engineering the product. The framework supports an approach to modularity from the perspective of intergrated product and process development (IPPD) (Schumaker and Thomas 1998), where the traditional aspects of systems engineering are combined with a truly integrated product and the means by which it is developed and manufactured (Stevens *et al*. 1998). In the same way that quality function deployment (QFD) can provide a linking mechanism between the various stages of the product lifecycle, HPD embodies a linking methodolgy supported by a systems-level framework for product realization to provide an integrated and structured product modularization process. Thus, the processes carried out in one aspect of module realization must be addressed in the context of the lifecycle. The phases of the methodology (figure 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.

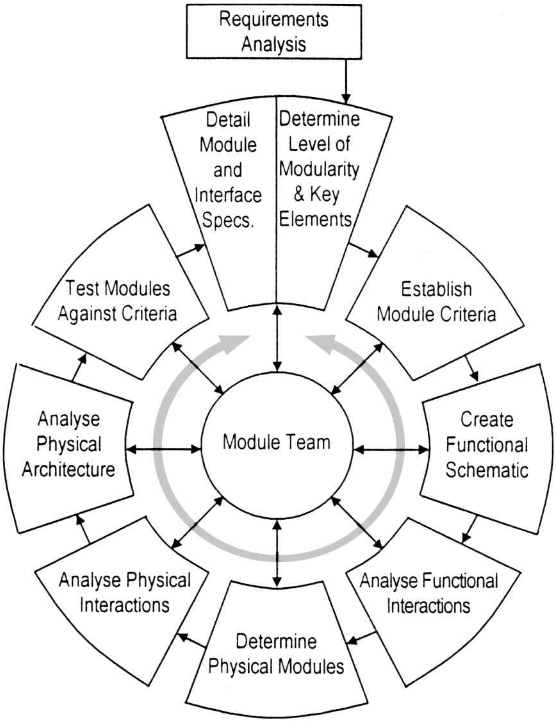


Figure 2. The modular product development process flow.

5.2. Modular product development process

The actual process of developing modular products deals with the engineering activity involved in converting the results of the early phases of the methodology into product and process specifications. The process (figure 2) was developed to maintain the structured approach outlined by the systems framework by ensuring stakeholder requirements, through module criteria, to permeate the process and to provide traceability for all development decisions. The process then follows a classical functional analysis/physical analysis structure to provide a largely unconstrained environment for the designer, in order to encourage innovation and the opportunity to foster an approach to modularity that is not constrained by legacy designs. The two key stages in this process concern interaction analysis, and are performed twice—once at a functional stage, and again at a physical stage to ensure the optimum consideration of interface interactions.

6. Key features of HPD

6.1. Level of modularity

One of the initial requirements for the modular design process is the level to which the modular architecture is to be taken. Case study work undertaken by the authors has shown that for a modular product there are several dimensions to the implementation of modularity. This application difference of modularity has been named the level of modularity (LOM), and is classified as a combination of 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 many functions.
2. *Resolution*—the number of modules in the product. The number of modules often relates to 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.

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 effect of the LOM has been identified through several additional factors.

1. The LOM gives a basis for development to maximize the ability to utilize 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. Although 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. The greater the number of common modules the more efficient the manufacture. Also, complex modules will naturally be more complex to manufacture.
4. The LOM will also affect complexity, robustness (both in quality and flexibility), and cost.

6.2. *Module definition*

Module definition is a complex and largely intuitive process. However, there are a number of factors that may be considered to aid in the process, as follows.

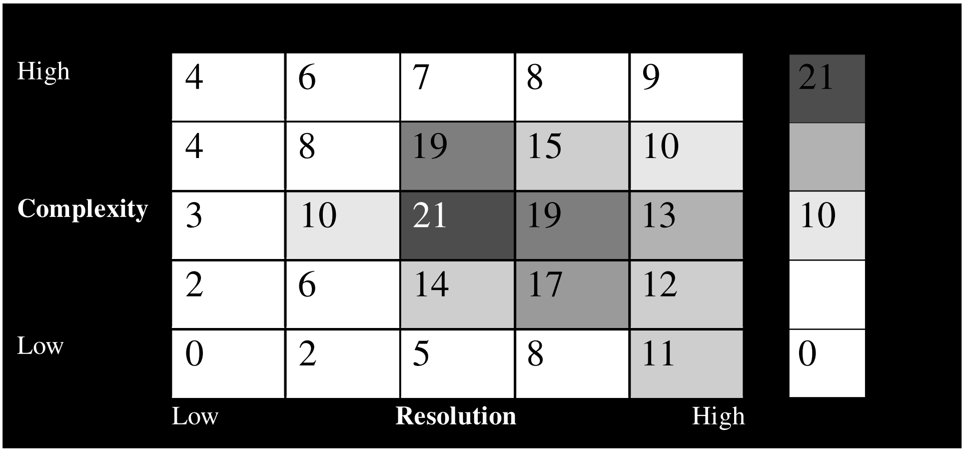
- Interactions—interactions between elements that are critical may benefit from the elements being grouped, as may interactions utilizing mechanical movement which is not sympathetic to being made to function across interfaces. Electronic interactions are more sympathetic to separation and may even benefit from being in separate modules, as in multiplexed systems.
- Geometric location—integrating elements that require precise geometric alignment will benefit from being in the same module, as control of the alignment is done in a localized area or by a single component.
- Function deployment—when a single physical 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 utilize 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 which provide variety when configured with this generic architecture. Also, designs should consider existing and 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 processes such as injection moulding or casting. Such groupings may also be mirrored through modular assembly cells. In addition, elements composed of the same material may be grouped to aid manufacturing and also recycling. Groups can also be formed that encapsulate features of the product that allows for these to be introduced to the assembly process late on—i.e. late configuration.
- Failure modes and effect analyses (FMEA)—if product or process FMEA studies are carried out or previous data are available, the results may aid element grouping with a view to minimizing the failures and their consequence.

Once elements have been grouped into modules, interactions between modules should be identified. It cannot be assumed that the interactions will be purely combinations of those between functions determined previously. Module interactions are at a higher level than functional interactions and will arise due to the physical implementation of the functional elements or due to the geometric arrangement of the modules. These interactions probably will not appear on the schematic and must be identified to ensure that any detrimental effects may be removed. The outcome of this process provides input for detail specifications to be drawn up for modules and interfaces. 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 teams that are closely tied, or even a single team. Modules that have few or no interactions can be developed by independent teams or outside suppliers.

6.3. Self-analysis

HPD's pragmatic approach also provides the ability to tailor the process and means by which the user may determine metrics from which they can base decisions. Kohlhase and Birkhofer (1996) echo this need through their evaluation of modular structures. HPD provides a set of simple self-analysis, checklists, and distilled guidelines for quick reference (Marshall 1999). One such analysis concerns implementation and aims to identify a guideline for an appropriate LOM. The analysis is performed through answering the seven question shown below.



High	4	6	7	8	9	21
	4	8	19	15	10	
Complexity	3	10	21	19	13	10
	2	6	14	17	12	
Low	0	2	5	8	11	0
	Low		**Resolution**		High	

Figure 3. Level of modularity graph.

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?

The results from the analysis provide a LOM metric. The score indicates a degree of modularity on a scale of 0–21, ranging from a low level to a high level. The metric can then be used to determine a broad level of complexity and resolution using the LOM Graph for guidance (figure 3). The LOM graph represents a 'hot-spot' for optimum LOM and highlights the benefit of a balance within the modular architecture.

A further aid to determining the appropriate LOM is the permutation chart (table 1). The 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. The actual implications of composition, complexity, and resolution can be mapped and a 3-digit value determined that represents the desired LOM. An example of its use may see a value of 003 representing a modern personal computer or 301 an automobile. However, this particular analysis is very subjective and is highly dependent on its context. Answers may vary depending on whether the product is considered in isolation or part of an existing product family. Thus any conclusions derived from this analysis should only form part of an important discussion on the level of modularity suited to the company's products.

7. Initial implementation

Initial validation has been carried out through a project based at Sperry-Sun Drilling Services, UK (SSDS), which manufactures test equipment for down-hole

Classifications Solutions	0	1	2	3
Composition	Integrated common element(s)	No common element, all variant modules	Only a common layout principle	Modular common element(s)
Complexity	Mixed complexity levels in modules	Low level of complexity in most modules	High level of complexity in most modules	Medium level of complexity in most modules
Resolution	Only a small number (2–4) of variant modules	A high number (10+) of variant modules	A medium number (5–10) of variant modules	A variable number of modules to meet requirements

Table 1. Module permutation chart.

drilling applications. A version of HPD was used to aid the development of a new business strategy that used modularity as a strategic tool in shaping the company's long-term goals. Within this strategy, HPD was used to develop two new products. 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 realize a new product and ensures that the customer's 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 been 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 in economies of scale and 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 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 varities 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 to a closer knit and more motivated development operation with engineers more appreciative of functions outside of their own, and an emphasis on finding and addressing problems early on.

8. Concluding remarks

The concerns summarized at the beginning of this paper relating to variety, complexity, and flexibility demand a structured requirements-driven approach to product realization. Modularity offers this approach, providing a timely opportunity to drive integrated product/process development. To these ends, Holonic Product

Design has been developed as a highly pragmatic approach embodying this total view with the core concepts of modularity and the autonomy, flexibility and co-operative nature of holons. Thus, a tiered paradigm has been proposed to target the appropriate perspective, detail, and approach to each level. 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, the work was embodied within a Holonic Product Design Workbook (Marshall 1999), accessible by the practitioners of modularity and with all the necessary tools for implementation and support of the process. An initial implementation of the workbook has produced some positive results and also opportunities for refinement and a planned expanded assessment of the approach in terms of its applicability, accessibility and overall scope.

References

Andreasen, M. M., 1980, *Machine design methods based on a systematic approach—contribution to a design theory*. PhD thesis, Lund Institute of Technology, Sweden.

Andreasen, M. M., 1998, Conceptual design capture. In: *Design Reuse: Proceedings of the Engineering Design Conference*, edited by S. Sivaloganathan and T. M. M. Shanin (London: Professional Engineering Publishing), pp. 21–30.

Barnett, L., Leaney, P. G. and Matke, J., 1995, Striving for manufacturing flexibility in body construction. Proceedings of the IMechE AutoTech/95 Conference, Birmingham, UK, C498/3/140.

BS 7000, 1997, BS 7000, Design Management Systems Part 2. *Guide to Managing the Design of Manufactured Products* (London: BSI).

Cross, N., 1989, *Engineering Design Methods* (Chichester: John Wiley & Sons).

EIA, 1997, *EIA 632 Processes For Engineering a System*. Electronics Industry Association.

Hansen, F., 1979, *Adjustment of Precision Mechanisms* (London: Iliffe Books).

Hubka, V. and Eder, W. E., 1988, *Theory of Technical Systems* (New York: Springer-Verlag).

Hubka, V. and Eder, W. E., 1996, *Design Science: Introduction to the Needs, Scope and Organisation of Engineering Design Knowledge* (London: Springer-Verlag).

IEEE, 1995, IEEE Std 1220-1994. *IEEE trial-use standard for application and management of the systems engineering process*. The Institute of Electrical and Electronics Engineers, Inc., New York, USA.

Koestler, A., 1967, *The Ghost in the Machine* (London: Hutchinson).

Kohlhase, N. and Birkhofer, H., 1996, Development of modular structures: the prerequisite for successful modular products, *Journal of Engineering Design*, 7(3), pp. 279–291.

Marshall, R., 1998, *Design modularisation: a systems engineering based methodology for enhanced product realisation*. PhD thesis, Loughborough University, UK.

Marshall, R., 1999, *Holonic Product Design: A Workbook V1.3*. (URL: http://info.ac.uk/departments/en/research/cae/res_int/ipps/mod3.htm).

Marshall, R. and Leaney, P. G., 1999, A systems engineering approach to product modularity. *Journal of Engineering Manufacture, IMechE Proceedings Part B*, **213**(8), 847–851.

Pahl, G. and Beitz, W., 1996, *Engineering Design: a Systematic Approach*, 2nd revised edition (London: Springer Verlag).

Rzevski, G., 1998, Engineering design for the next millennium: the challenge of artificial intelligence. The 86th Thomas Hawksley Memorial Lecture, IMechE, 9 December.

Shumaker, G. S. and Thomas, R. E., 1998, Integrated processes in defence manufacturing. In: *Integrated Product and Process Development: Methods Tools and Technologies*, edited by J. M. Usher, U. Roy and H. R. Parsaei (New York: John Wiley & Sons), pp. 281–308.

Simon, H. J., 1962, The architecture of complexity. *Proceedings of the American Philosphical Society*, **106**(6).

Stevens, R., Brook, P., Jackson, K. and Arnold, S., 1998, *Systems Engineering: Coping with Complexity* (London: Prentice-Hall).

Suh, N. P., 1990, *The Principles of Design* (London: Oxford University Press).

ULRICH, K. T. and EPPINGER, S. D., 1995, *Product Design and Development* (New York: McGraw-Hill).

VALCKENAERS, P., 1993, *Flexibility for integrated production automation*. PhD Thesis, KU-Leuven.

VALCKENAERS, P. and VAN BRUSSEL, H., 1994, Holonic manufacturing systems: system components of autonomous modules and their distributed control. IMS TC5: Holonic Manufacturing Systems Deliverable of WP6.

WHITNEY, D. E., 1992, *Systematic Design of Modular Products at Telemechanique*. (URL: http://web.mit.edu/ctpid/www/Whitney/europe.html).

WYNNS, J., 1999, *Reference architecture for holonic manufacturing systems—the key to support evolution and reconfiguration*. PhD Thesis, KU-Leuven.