



HAL
open science

Supporting ‘Design for Re-use’ with Modular Design

J.S. Meehan, A.H.B. Duffy, R.I. Whitfield

► **To cite this version:**

J.S. Meehan, A.H.B. Duffy, R.I. Whitfield. Supporting ‘Design for Re-use’ with Modular Design. Concurrent Engineering: Research and Applications, 2007, 15 (2), pp.141-155. 10.1177/1063293X07079319 . hal-00571210

HAL Id: hal-00571210

<https://hal.science/hal-00571210>

Submitted on 1 Mar 2011

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L’archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d’enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Supporting 'Design for Re-use' with Modular Design

J. S. Meehan, A. H. B. Duffy and R. I. Whitfield*

CAD Centre, University of Strathclyde, Glasgow, G1 1XJ, United Kingdom

Abstract: Engineering design reuse refers to the utilization of any knowledge gained from the design activity to support future design. As such, engineering design reuse approaches are concerned with the support, exploration, and enhancement of design knowledge prior, during, and after a design activity. Modular design is a product structuring principle whereby products are developed with distinct modules for rapid product development, efficient upgrades, and possible reuse (of the physical modules). The benefits of modular design center on a greater capacity for structuring component parts to better manage the relation between market requirements and the designed product. This study explores the capabilities of modular design principles to provide improved support for the engineering design reuse concept. The correlations between modular design and 'reuse' are highlighted, with the aim of identifying its potential to aid the little-supported process of design for reuse. In fulfillment of this objective the authors not only identify the requirements of design for reuse, but also propose how modular design principles can be extended to support design for reuse.

Key Words: engineering design reuse, multi viewpoints, function, working principle, solution, design structure matrix.

1. Introduction

Design for reuse, whereby current artifacts are designed with a specific emphasis on promoting, extracting, and enhancing re-usable knowledge elements, has been shown in previous studies to have the most significant impact on the realization of 'reuse' related benefits (Duffy and Ferns [1]). While their investigation limited the consideration of benefit in terms of time, quality, cost, and performance, Duffy and Ferns considered reuse in terms of domain knowledge, domain models, reuse libraries, design requirements, evolved design, domain exploration, design for reuse, and design by reuse. Interestingly however, research by one of the authors [2,3] has shown that, of all the reuse processes, design for reuse suffers from a most notable lack of support. Thus, the potential for various principles to support design for reuse was investigated as part of a project to develop a modular design method to improve support for formal design reuse.

Modular design is a natural extension of structuring principles. It involves the creation of artifact variants based on the configuration of a defined set of modules. Modules are commonly described as a group of 'functionally' or 'structurally' independent components clustered such that 'interactions are localised within each

module and interactions between modules are minimised' [4]. The principle aims to create variety, reduce complexity, and maximize kinship in designs and across product families. Owing to the fact that individual module functions and/or structures must eventually combine to realize the overall function/structure of the artifact, the modules can never truly be independent and must be defined together with the system to which they belong. Modular design research can generally be grouped into three categories: the identification of modules, the design of modules, and designing with modules. The approach outlined within this study predominantly considers issues related to the first two categories, the later is encompassed when the output of the tool is further utilized from a 'design by reuse' perspective.

1.1 The relation between modular design and reuse principles

In exploring why modular design so readily maps to the 'reuse' perspective some of the major benefits of the modular approach are considered [5–11], these include: efficient upgrades; improved design understanding; improved knowledge structures; improved knowledge management; improved knowledge utilization; rapid product development; reduction in complexity, and reduction in costs. These benefits center on a greater capacity for structuring both physical parts and artifact knowledge to better manage the relation between market requirements and the design artifact. They support increased utilization of experiential knowledge

*Author to whom correspondence should be addressed.
E-mail: ianw@cad.strath.ac.uk
Figures 3–6, 8 and 10–12 appear in color online: <http://cer.sagepub.com>

for new product development and provide an approach to actively support reuse.

However, despite the existing evidence as to its benefits, ‘little work has been done on these research issues’ [5]. In 1995, Chang [10] noted that ‘none of the design theories or tools in the mechanical world serves as an articulate procedure for designers to follow in practicing modular design.’ Despite continued developments in the field of modular design, further inadequacies were highlighted by Miller and Elgard [12] and Huang and Kusiak [13]. The later stating that ‘modularity has been treated in the literature in an abstract form’ and ‘approaches are needed to determine modules, represent modularity, optimise modular design and assess the impact of modularity on the design process, manufacturing, and management.’

2. Current approaches to modular design

Modular design principles have been applied to structure the designed product [9,13–20] and its associated production system [21–24], and have been applied to explore and identify modularity within individual products [13–15,17,18,20] or across a product family (or generations of a product family) [9,16,19]. Modular design applied across a product family is aimed at exploring the domain to identify common characteristics in the product structures that can be realized as a common module. This section considers current approaches to modular design and demonstrates their limitations in fulfilling the requirements of ‘modular design for reuse.’

2.1 Single viewpoint approaches

The majority of approaches focus solely on a particular viewpoint, generally either functionally or structurally. Existing approaches to modularity may be grouped into three distinct categories based on: function, the potential means of realizing this function, and finally on physical parts and/or components.

The focus of Kusiak and Huang [25] and Ouyang and Chenggang [26] was modularity from a functional viewpoint where sub-functions were grouped or clustered, based on their relation to one another, to form ‘functional’ modules. The realization of the defined ‘functional’ modules as physical entities is left to the designer.

Chang [10] provides examples of ‘behavioural modularity’ based on the technical solutions or means of fulfilling the functional criteria of a design. Chang focuses on the minimization of variation across a product family by reducing the ‘conceptual noise’ of technical solutions with respect to the requirements of components and/or assembly sets. Erixon’s modular

function deployment (MFD) approach [14] looks at modularity across the wider spectrum of the design process, however, the module identification phase focuses on clustering of potential technical solutions (or means) to functional objectives.

The component/part view that is termed here as ‘structural modularity’ is the focus of Gu and Hashemian [27], Kamrani [28], and Ishii and Lee [17]. The application field is often redesigning, and it is predominantly utilized in domains where the product is mature and the parts inventory stable. Gu and Ishii are seen to focus on modularity for recycling and disposal whereby well-defined physical parts are grouped into modules based on their similarity in areas, such as life span, material, maintenance level, disposal method, etc. Similarly, Masuda utilizes the modular design at a ‘structural level’ to improve the upgrade prospects of products which are technologically driven or have long in-service life spans. Kamrani, utilizes this modular approach, in well-developed design domains when technology, materials, and design are mature and subject to little flux, with the aim of maximizing kinship in terms of manufacturing requirements and assembly operations and thus capitalizing on potential process improvements.

Design for reuse, the identification, extraction, and enhancement of possible reusable knowledge fragments, requires a systematic approach to the capture and structuring of generated knowledge throughout the engineering design life-phase from its inception. Thus, owing to the potential for knowledge of different types, media, scope, and abstraction level, to exist at different levels of completeness it is surmised that it is inconceivable to utilize a single viewpoint as the basis of design for reuse [3], since reuse may be represented within the functionality of a product (without considering the working principles or physical solution), within the working principles of the product (without considering the functionality or physical solution), or within the solution (without considering functionality, or working principles). In addition, as this approach demonstrates, it is also possible to conceive of modularity across viewpoints.

2.2 Multi-viewpoint approaches

Salheih and Kamrani [20] note that the principle of modularity ‘can be applied in product design, design problems, production systems, or all three,’ thus acknowledging the need to support different views of the artifact design. Their four-step methodology covers the design process from need to concept with the aim of determining the modularity in design concepts and utilizing these modules as the basis for the allocation of development teams. The detailed design of such modules is left to the development teams. Further,

due to the need for decomposition of the design concept, the focus of their approach is predominantly towards cases of redesign and/or where the design and problem domain are well developed, documented, and understood. Thus, they observe modularity only at the 'macro level' where the granularity of design problem and process is at a relatively low level i.e., basic needs, requirements, and component types. The product's modularity is only explored in one step (Step 4: concept integration) and through one view (a low level structural view), with the previous steps being utilized as data gatherers to support this analysis.

Tseng and Jiao [29] present a case-based approach with the aim of rationalizing past designs to 'provide the designer with a set of concepts and common solutions to specify current design.' Thus, by organizing information around features common to all past designs they create a product family architecture (PFA) in which all new designs will be anchored by 'emphasising its similarities/commonalities to past designs.' The approach plans for modularity across 'views' namely the functional, technical, and the physical views of product development posited by Ulrich and Eppinger [30] and Pahl and Beitz [31]. Here, the functional 'view' deals with customer grouping, the technical view with the design of modules through the coupling of design parameter's regardless of their physical realization, and finally the physical views deal with the physical realization of the modules based on past design and process capabilities trade-offs. The three views are independent and issues relating to different business functions are dealt with in different views and mapping between the viewpoints is utilized to maintain the product family when initiating new product design.

These approaches all support product modularity from 'design-by-reuse' perspective. They are all applied to cases of redesign or cases that do not 'include novel engineering design tasks, but systematic variant design' [18]. All require access to a significant number of past cases, and require that there is an abundance of customer and marketing information available on the product. For example Tseng and Jiao's approach is applied to the field of industrial products, due to: the availability of large repositories of product knowledge; an abundance of historical data; the ease of accurately classifying market needs; the knowledgeable customers, the limited customer base; and the incremental as opposed to innovative nature of development. These approaches attempt to explicate the underlying modularity of an existing set of past cases for utilization to support new design. Each acknowledges that there can be multiple 'views' of the artifact knowledge. The tendency is however to consider 'engineering design as a single 'view' with others representing additional phases in the life cycle of the artifact and/or life-phase objectives/requirements. By developing methods to

define and manage modularity from the higher level 'functional' requirements to 'lower level' parts, geometry and physical characteristics, the authors aim to take into account life-phase modular needs during design while utilizing the principle as a tool to extract, manage, and enhance design knowledge 'for reuse.'

2.3 Issues in modular design support for reuse

A number of issues have been raised through research into existing modular design methodologies. These include issues of knowledge management, relation definition, and the incorporation of life cycle objectives during design.

2.3.1 KNOWLEDGE MODULES

In addition to the definition of the physical module, Miller and Elgard [12] recognize the need to capture related 'knowledge modules' and abstractions of these. They express a need to explore the concept of modularity in relation to 'knowledge management and modules seen as knowledge carriers.'

Such exploration is essential to facilitate a design for reuse modular methodology as it is well documented that previous solutions are rarely wholly re-usable [3,32,33]. Without adequate provision for the knowledge related to how and why the final solution was derived, it is difficult to effectively facilitate the 'reuse' of partial solutions. Thus, as current approaches do not adequately formalize, nor maintain, the knowledge behind defined modules they are consequently too inflexible to fully support design for reuse.

2.3.2 RELATIONS

Relations both within and between modules can be considered to involve complex dependencies in terms of functional, behavioral, structural, spatial, information, energy, and material constraints. Thus, they are far more complex than the functional or physical geometry relations utilized in most approaches to modular design. Currently relations are treated as predominantly one-dimensional i.e., that a relationship exists. This treatment has resulted in documented incidents of 'false clustering' and accidental 'importance' increases of functions [18]. The researchers attribute such incidents to the facts that the algorithms are based on the quantity and not the quality of relations and their inability to incorporate constraints. Thus, it is suggested that a deeper understanding and more adequate support of: within and between module relations, and across view-point relations would aid in the management of such difficulties.

2.3.3 LIFE CYCLE OBJECTIVES

Life cycle objectives such as recycling, maintenance, assembly, and disposal are the focus of a number of

modular design approaches [27,34]. For instance, Gu et al. focus on the grouping of components with similar life spans or material compositions for recycling or disposal. Different sets of life cycle objectives are the distinct consideration of particular ‘views’ of modular design. Thus, out-with the boundaries of that particular ‘view’ the designer has, no formal mechanisms to further explore the implications of these chosen objectives and resulting trade-offs exist as the artifact definition evolves. However, a multiple viewpoint approach would allow for a ‘deeper’ understanding of how a life cycle objective related to, for instance, ‘functional’ performance impacts on, say, the ‘structural’ components and vice versa.

3. A modular design methodology for reuse

A novel ‘multi-viewpoint modular design methodology’ has been developed that aims to address the previously outlined issues for modular design support. The methodology has been developed to support the exploration and maintenance of a modular design by modeling viewpoints and perspectives of design knowledge, optimizing these models, identifying their inherent hierarchical modular structure, and then mapping between these viewpoints. The methodology has four main elements: a knowledge formalism; a matrix application; a clustering mechanism; and a mapping mechanism.

3.1 The knowledge formalism

The formalism takes a multi-viewpoint evolutionary approach (MVEA) to formalizing both current working knowledge (CWK) and domain knowledge (DK) [35]. The formalism defines design knowledge elements, and their relations, within and across different viewpoints and their evolution through the design activity. Thus, it has the ability to support and formalize knowledge of an evolving design over the viewpoints inherently adopted by the designer.

The approach allows the designer to formalize knowledge within viewpoints as concepts with attributes and constraints. The formalism also notes a causal link relation across viewpoints.

Concept constraints indicate application conditions while attribute constraints represent dependencies between individual attributes. Relations between concepts can be of a structural nature (has-kind, a-kind-of, a-part-of, has-part), or associative nature (functional-dependency, physical link) and have a direction, whereas relations between viewpoints are formalized as a causal-link.

Figure 1 depicts the views of CWK formalized as basic structures and networks illustrating how the concepts and relation knowledge interrelate within multiple viewpoints. The viewpoints are modeled as a series of structures (function, working principle, and solution) and networks (desired mode of action, actual mode of action, and construction network).

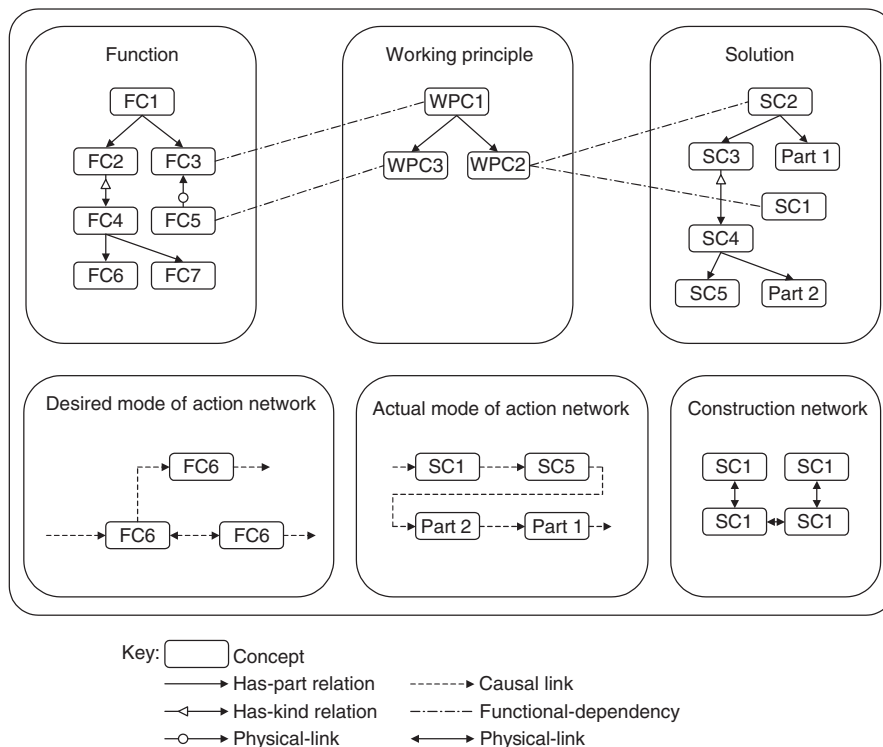


Figure 1. Multiple viewpoint current working knowledge model [35].

The structures encapsulate knowledge of the viewpoint concepts in the design and the structural relations between these; for example, the function structure defines functions concepts and their structural relations. The different notations on the relations between concepts in the structure represent different types of structural solutions.

The networks depict viewpoint concepts and their associative relations and represent a specific part of the structures, i.e., the concepts from the bottom most level of the structure (at any discrete point in time) and the associative relations between these. Associative relations represent the functioning sequence or physical attachment between concepts. Thus networks depict the most detailed and concrete viewpoint concepts and a type of associative relation between them.

3.2 The interdependency matrix application

A matrix formalism (Figure 2) was utilized as a means to represent the 'viewpoint model' of the concepts and their dependency knowledge to support its modular analysis. The matrix formalism was chosen due to 'its compactness, its ability to represent most design activity knowledge and their dependencies and its quantifiable nature' [36]. The matrix formalism is based upon the design structure matrix (DSM) [37]. The DSM has been used to represent concepts such as: tasks, resources, and parameters, as well as the inter-concept dependencies.

For brevity, Figure 2 illustrates the three structures combined. The row and column headings represent either: a functional conceptualization; a working principle conceptualization; and a solution conceptualization. The relation between concepts is used to represent either 'within' or 'across structure dependencies' (in terms of the shape), and the strength of the relationship as defined by the designers. A viewpoint model is created for the differing viewpoints of interest throughout the design phase, i.e., function, working principle, solution. Within the viewpoint model, the matrix rows and columns represent the same concepts (in the same order) and dependencies within the matrix itself.

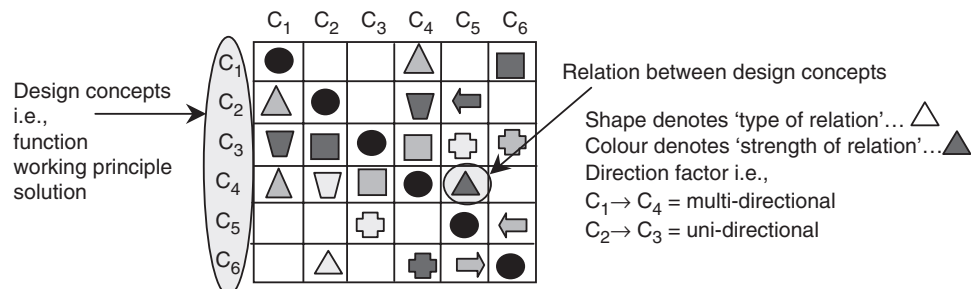


Figure 2. An interdependency matrix application.

The limitations of the matrix formalism restricts its application to modeling one structure (function, working principle, solution) due to the potential inconsistencies in concepts and dependencies. The implementation of the matrix formalism within this research does however allow different perspectives of a viewpoint to be considered simultaneously. Figure 3(a)–(c) for example (adapted from [38]) illustrates three different perspectives (material, information, energy) of the function viewpoint. The matrix implementation allows this flexibility to consider different perspectives of each type of concept in a similar approach to that proposed by Pimmler and Eppinger [39], but not restricted to four perspectives, in addition to being able to view combined perspectives of any of the other perspectives, Figure 3(d).

It is important to note that modularity from one perspective (Figure 3(a)) may not result with modularity from another perspective (Figure 3(b)). The focus for a modular design practitioner is to determine the optimum modularity with respect to one, or a number of perspectives across different viewpoints of design.

3.3 The clustering mechanism

A clustering criterion was produced that represents the summation of the dependencies both above and below the diagonal multiplied by the distance from the diagonal on the basis of their weight. The focus of minimizing the clustering criterion is therefore to re-sequence the concepts to get the dependencies as close to the diagonal as possible. Minimizing the clustering criterion minimizes the distance of the dependencies from the diagonal, with the result that the dependencies are clustered around the diagonal. No changes to the information relating to either the concepts or their dependencies are made during the optimization process.

$$\text{Clustering criterion} = \sum_{i=1}^N \sum_{j=1}^N (|j-i| \times w_{i,j}) \quad (1)$$

where N is the number of concepts in the matrix, i and j are the row and column indices, and $w_{i,j}$ are the dependency weights.

The difficulty in optimizing the DSM lies in the need to be able to deal with discrete, multi-modal, noisy, and multi-criteria solution spaces that are common within the DSM [40]. Re-sequencing the order of activities in order to minimize the clustering criterion is known to be an NP-complete problem [41], hence the use of a stochastic optimization tool, such as a genetic algorithm (GA) is necessary. The general procedure for GAs developed by Goldberg [42], has been used to enable the evolution of optimal modular structures [36].

The objective of the GA in this particular application is to minimize the value for the clustering criterion – Equation (1) by varying the sequence of concepts within the matrix.

Figure 4 illustrates the output from the optimization of each of the individual perspectives for the functional viewpoint model. In each case, the sequence of functional concepts has been changed in order to cluster the dependencies around the diagonal. It can also be seen that the optimum clustering differs for each perspective due to the differing nature of the dependencies, with the combined perspective, Figure 4(d) illustrating the optimum

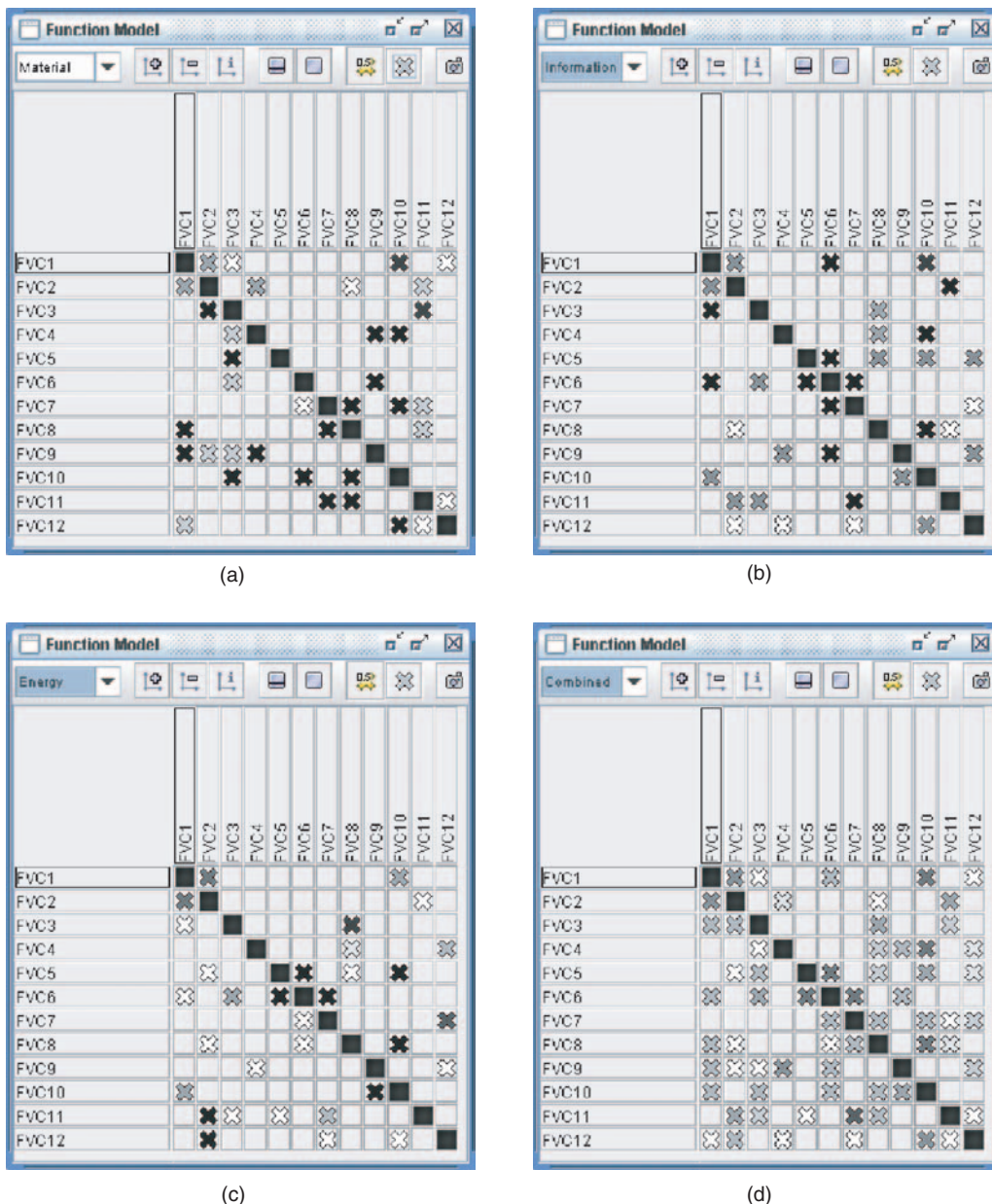


Figure 3. Material, information, energy and combined perspectives of the function viewpoint model.

clustering for the material, information, and energy perspectives.

Once the clustering criterion has been minimized for a given matrix, the module identification mechanism is used to address the difficulties associated with identifying modules. The module identification mechanism consists of two parts: the module strength indicator (MSI) function and a module structure matrix (MSM).

The MSI function was derived to support the determination of the inherent modularity within the product structure and is represented within Equation (2), which provides the designer with an indication of the relative modularity of the potential

clustered sequence, with respect to its concepts' internal and external dependencies.

$$MSI = \frac{\sum_{i=n_1}^{n_2} \sum_{j=n_1}^{n_2} w_{ij}}{(n_2 - n_1)^2 - (n_2 - n_1)} - \left(\frac{\sum_{i=0}^{n_1} \sum_{j=n_1}^{n_2} w_{ij} + w_{j,i}}{2 \times (n_1 \times (n_2 - n_1))} + \frac{\sum_{i=n_2}^N \sum_{j=n_1}^{n_2} w_{ij} + w_{j,i}}{2 \times ((N - n_2) \times (n_2 - n_1))} \right) \quad (2)$$

where i is the row index; j is the column index; n_1 is the index of first component in module; n_2 is the index of last component in module; N is the number of concepts in the matrix; and $w_{i,j}$ is the weight of the dependency at row i and column j .

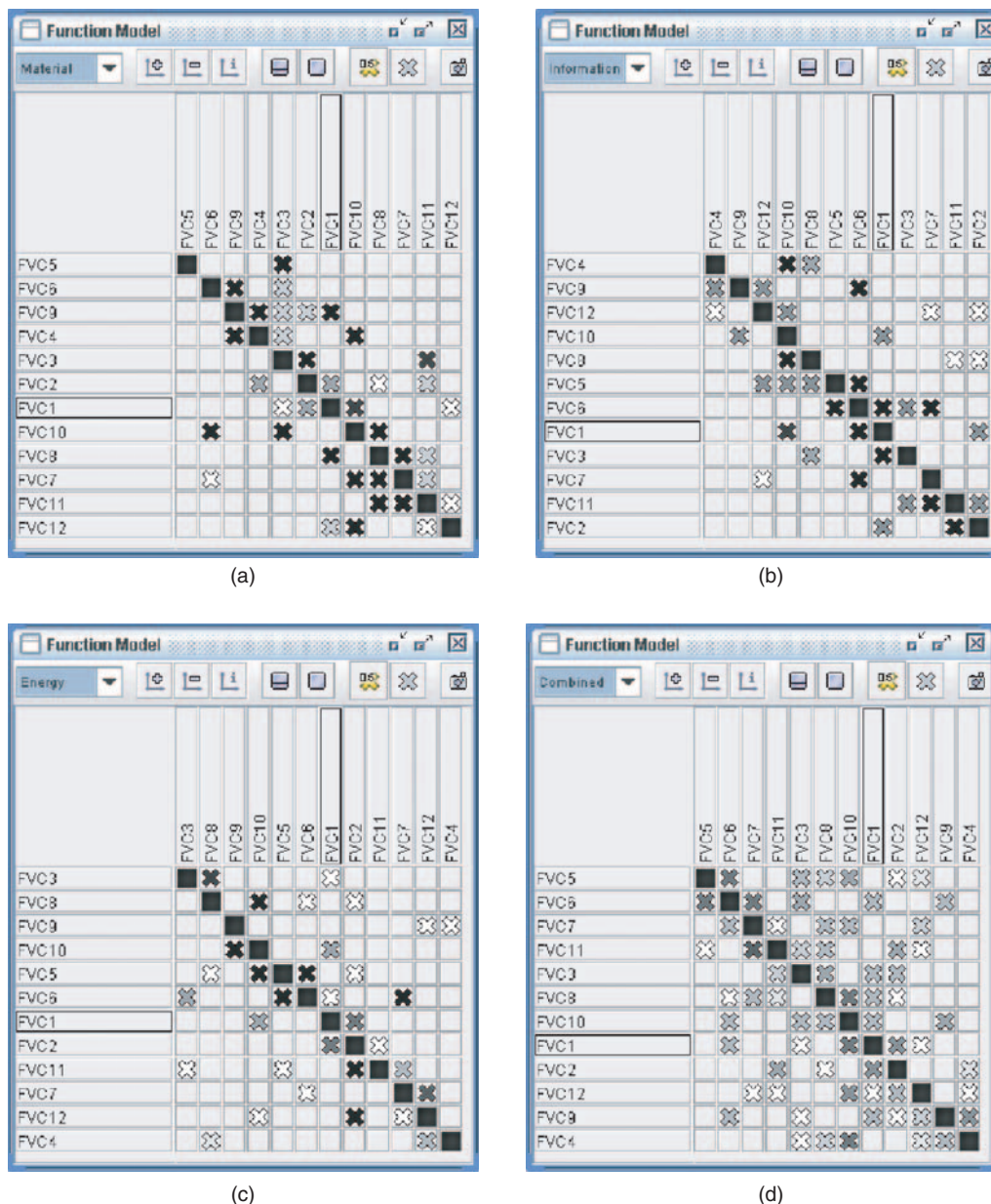


Figure 4. Optimized material, information, energy, and combined perspectives of the function viewpoint model.

The MSI technique results in an alternative representation of the DSM. The resulting MSM, uses a variation in color to depict the relative modularity of all available component modules. Thus, the MSM exposes the boundaries of any existing modular structure based on the given dependencies. The MSM identifies inherent hierarchical modularity within highly constrained problems with densely populated dependency matrices that otherwise may not have been readily apparent. In general, an optimized viewpoint model is the expected basis for visualizing the MSM, however Figure 5 illustrates the inherent modularity of the original perspectives of the functional viewpoint model from Figure 3. Equation (2) is applied to all possible concept groupings within the viewpoint model to determine the inherent modularity in the overall structure.

Figure 5 depicts concept groupings with different values of MSI. The figure illustrates that for each perspective of the functional viewpoint, the modularity is relatively weak, with strong modules defined between FVC7 and FVC8 for the material perspective, and between FVC5, FVC6, and FVC7 for the information, energy, and combined perspectives.

The optimized viewpoint models within Figure 4 were used as the basis of the MSI, the results of which can be seen within Figure 6. The inherent modularity resulting from the optimized viewpoints is clearer with the MSM exposing the boundaries of any existing modular structure based on the given dependencies and the resulting MSI values. The MSM within Figure 6(d) highlights inherent modularity within highly constrained problems with densely populated dependency matrices

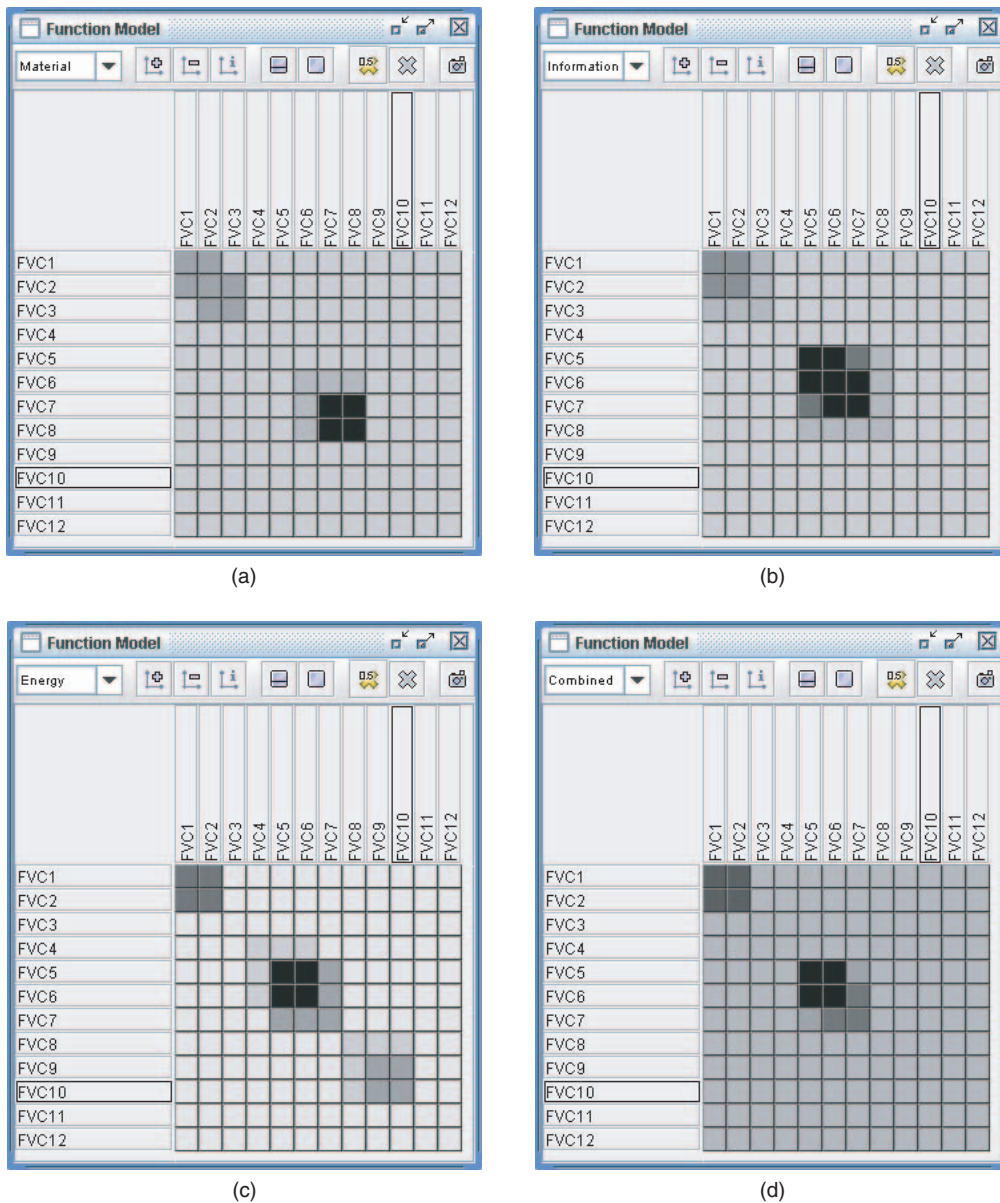


Figure 5. Initial module structure matrices for material, information, energy, and combined perspectives of the function viewpoint model.

that otherwise may not have been readily apparent – see for example Figure 5(d).

The MSM provides an indication of the existing modularity within the design artifact. The designer is free to adapt the module configuration within the boundaries of the inherent modularity identified.

3.4 The mapping mechanism

The three elements of the methodology described within Sections 3.1–3.3 are applicable to each of the design viewpoints separately. This results in the definition of a modular structure for individual viewpoints but not for the identification of the overall modularity of the product structure or maintenance of the modularity across viewpoints of the product structure. However, to

support the evolution of the modular design there is a requirement to map between the individual viewpoints. Thus, a mapping mechanism is defined to support cross-viewpoint modular development and analysis.

The mapping mechanism is a key element in providing a coherent and integrated framework required to support the capture and exploration of knowledge from multiple viewpoints and to evolve the modular solution from the abstract (function) to the concrete (solution) – Figure 7. When utilized within a design by reuse scenario, the mechanism could facilitate the analysis of the impact of design changes and support partial reuse of the design solutions (modules) and their associated knowledge.

The mapping mechanism uses a knowledge and matrix formalism similar to that within Section 3.1, and an

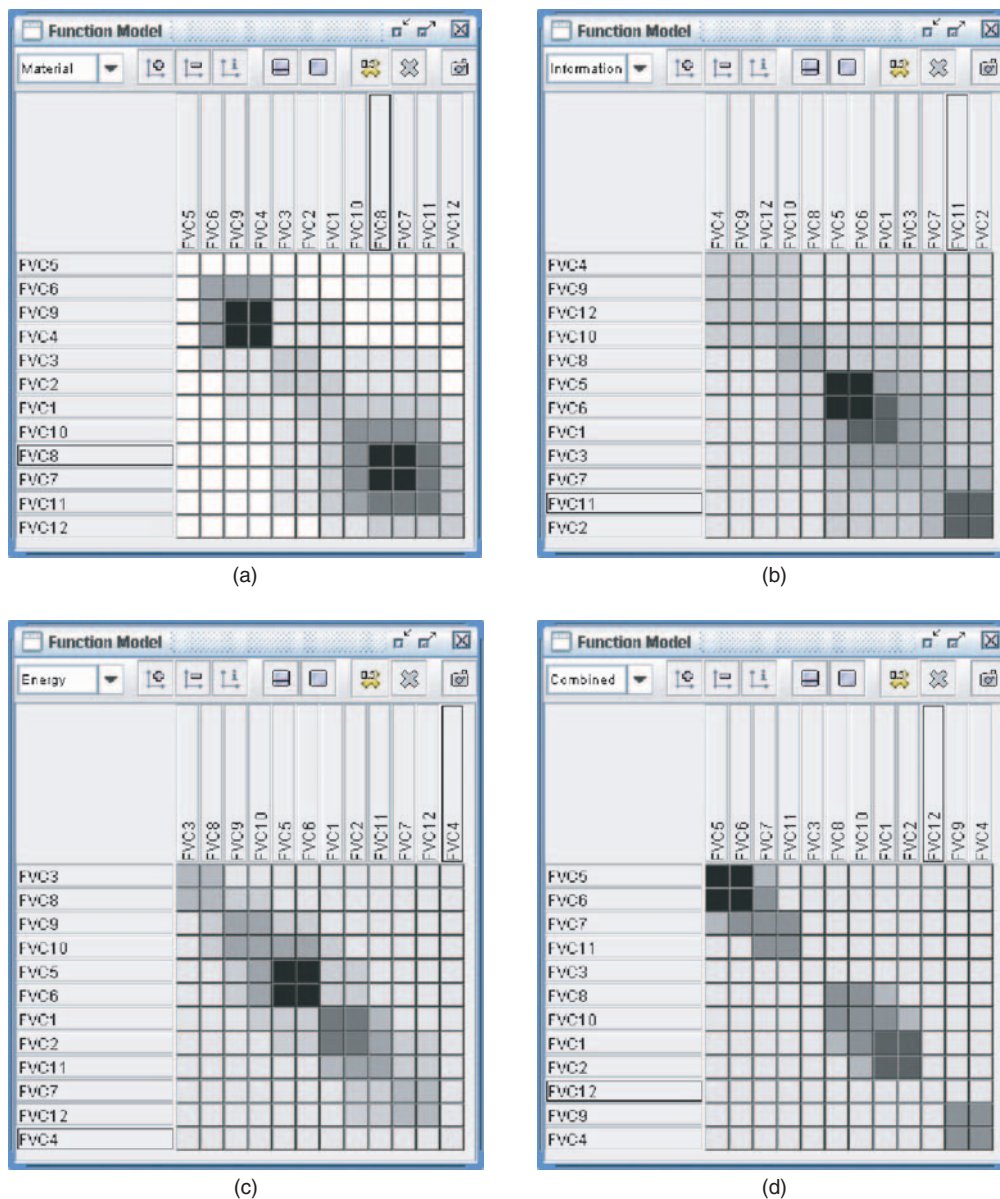


Figure 6. Optimized module structure matrices for material, information, energy, and combined perspectives of the function viewpoint model.

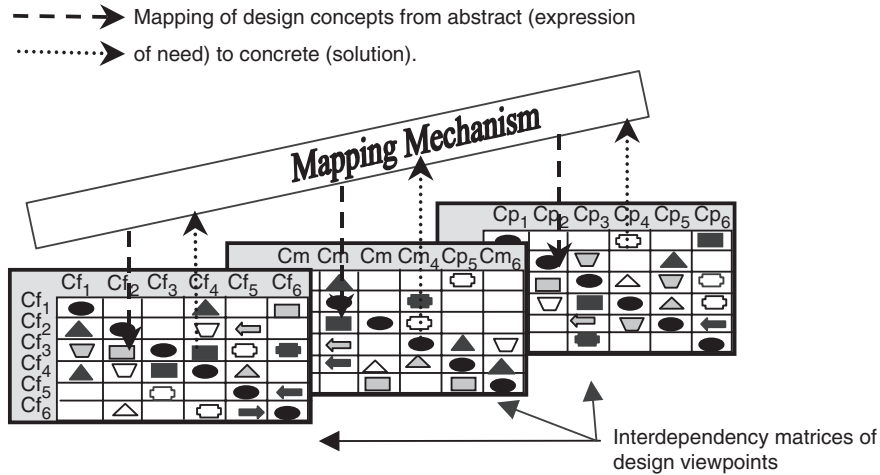


Figure 7. Mapping mechanism.

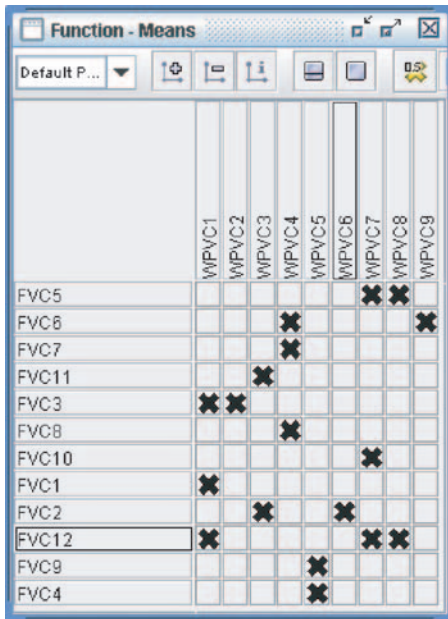


Figure 8. The cross-viewpoint matrix between function and working principle.

optimization mechanism. However, the focus here is on concepts and their cross-viewpoint dependencies, termed causal-link dependencies that represent the mapping of concepts between viewpoints as they progress from the abstract to the concrete. A causal-link dependency can exist between any two concepts across any two of the three viewpoints of the design knowledge posited here. The resulting model is termed a cross-viewpoint model and an implementation of the model can be seen in Figure 8 for the links between the functional viewpoint and the working principle viewpoint.

By utilizing the near-optimum concept order returned for the more abstract view (from Figure 6(d)) and optimizing the concept order in the more concrete viewpoint in relation to these, the designer can maintain the modular solution across viewpoints of the design.

Once an optimum sequence for the working principle concepts has been created, the process is repeated from Section 3.2, with the creation of an interdependency matrix for the working principle viewpoint using the concept sequence generated. The process is repeated until the concepts being represented are concrete, i.e., the solution viewpoint. Progressing in this manner results with the production of a design artifact that is modular both within and across viewpoints.

3.5 Application

As the methodology was developed to support improved engineering design reuse, the procedural knowledge is defined based on its application within a current design activity (i.e., for reuse). The application process of the above methodology involves an iterative application loop which supports the generation of modules as the design evolves from the abstract to the concrete as shown in Figure 9.

In the first instance, the designer creates a function viewpoint model that embodies the designer's initial ideas of the functions that the design has to fulfil and the interdependencies between these. This model is utilized as the basis to support a modular analysis of the generated design knowledge from the function viewpoint. The analysis begins with the designer checking all the function concepts and their related dependencies. The designer queries whether each function concept has a dependency with one or more of the other concepts in the model. A concept that has no dependencies with other concepts of the same type may represent unnecessary duplication, diversity, and/or complexity in the product structure. The designer can choose to discard the concept, maintain the concept, and update the dependency knowledge associated with it to more adequately reflect its status within the generated design knowledge, or maintain the concept as a standalone entity. The process is repeated until all the

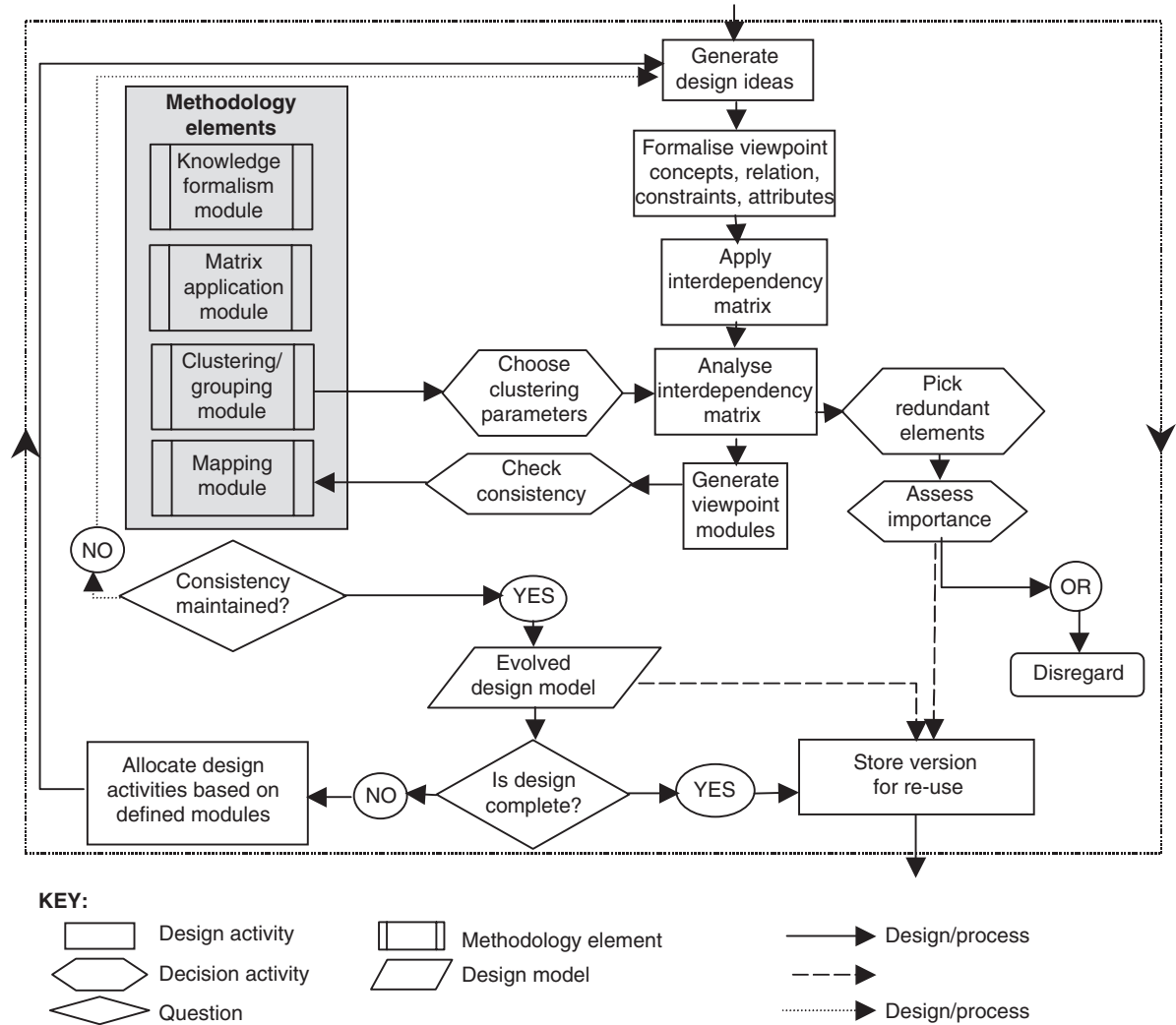


Figure 9. Methodology application process.

remaining function viewpoint concepts have been verified.

On completion of the function viewpoint model verification process, the designer uses the GA to generate an optimized function viewpoint model. The concept groupings defined in this model can be utilized as the basis to define and allocate further design tasks required to evolve the design activity and its associated knowledge, for example, the function concept groupings may be utilized as the basis to define the boundaries for individual designers and/or design teams, to research potential working principle or solution concepts to realize these functional groups. However, in complex or highly constrained problems, the concept grouping boundaries may not always be clearly visible from the optimized function viewpoint model and the designer may apply the module identification mechanism to facilitate this process.

The designer then proceeds by generating knowledge of the working principle concepts required to realize the function concept groupings. The working

principle concepts can be analyzed both as an individual model of a viewpoint (a working principle viewpoint model) and with respect to its capabilities to maintain the modular solution. The analysis of the working principle viewpoint model is carried out through the same process as the one described earlier for the function viewpoint model. The analysis results in knowledge of optimum working principle groupings on which to base further design tasks and research required to support the realization of these groupings as structural entities, i.e., solution concepts or parts.

The mapping mechanism analyzes the working principle concepts that have been defined by the designer to realize the function concepts. As such, the results (the concept order) defined in the optimized function viewpoint model is utilized as the basis for the analysis. A matrix formalism is applied to both the function and working principle concepts. The cross-viewpoint dependencies between these are defined and represented within the matrix body. The analysis begins

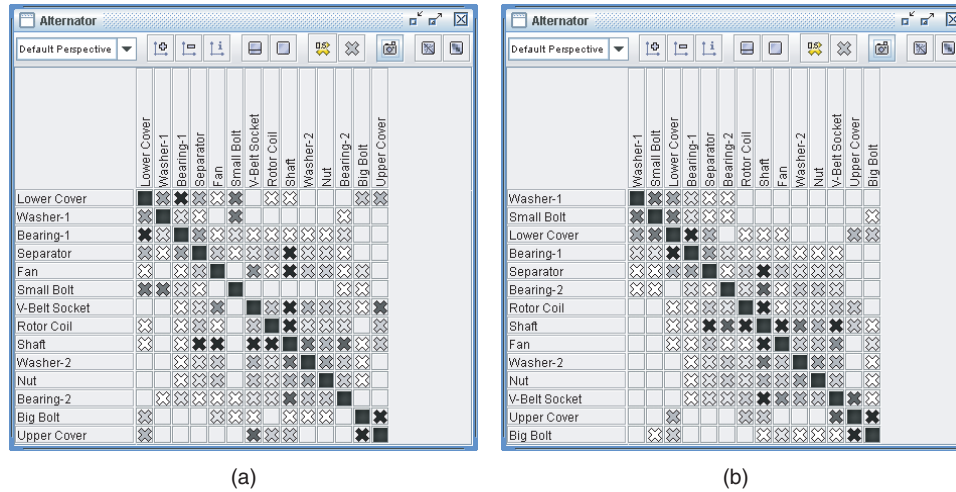


Figure 10. Solution viewpoint model for alternator.

with the designer checking all the dependencies between the function and working principle concepts. The designer queries if the concepts in each viewpoint have at least one more working dependency with the concepts from the alternative viewpoint, i.e., whether each working principle concept realizes (or partially realizes) a function concept and whether each function concept is realized by at least one working principle concept. Each concept in a preceding, more abstract viewpoint should be realized by one or more concepts in the following more concrete viewpoint to maintain the integrity of the design.

The designer may then optimize the working principle viewpoint with respect to the objective of maintaining the modular structure of the function viewpoint. The resulting optimized cross-viewpoint model can be utilized to assess the performance of the working principle concepts with respect to their capabilities to maintain the modular solution. If the modular solution is maintained in this way, the designer can utilize the findings to define further design tasks necessary to evolve the design activity and consequently its associated knowledge.

The process is repeated for the individual solution viewpoint and a mapping from the working principle viewpoint to the solution viewpoint. This application to the function, working principle, and solution viewpoints represents one cycle of the methodology itself. However, the design activity is an iterative process and the designer's knowledge of a design from a particular viewpoint evolves as the design progresses.

Figure 10(a) illustrates the relationships between components for an alternator (adapted from Sosale et al. [4]) represented within the solution viewpoint. For a more detailed presentation of the approach across the three viewpoints for the modular design of an integrated technology mast, and a battle-group thermal imager, see Smith [38].

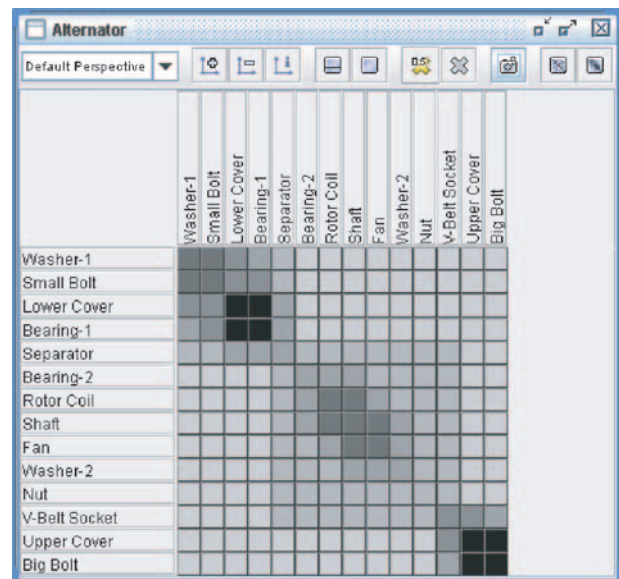
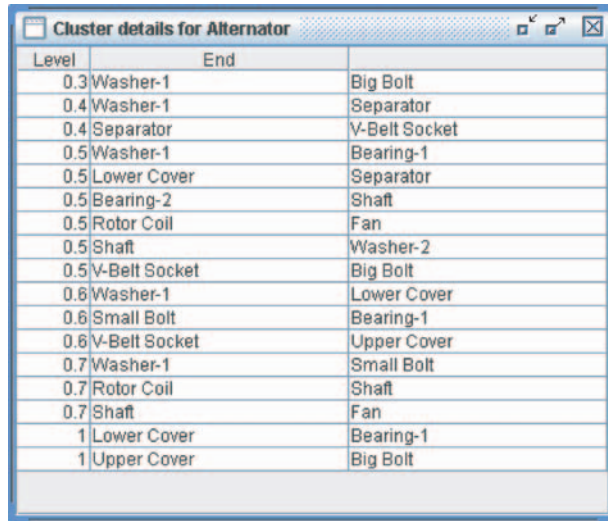


Figure 11. Optimized alternator module structure matrix for solution viewpoint.

The structure of the alternator is defined by the arbitrary sequence provided within the original work [4]. The initial value for the clustering criterion (from Equation (1)) is 153.8.

Figure 10(b) represents the optimized matrix for the solution viewpoint with a new clustering criterion value of 118.2. It is however difficult from the structuring of the dependencies to clearly identify any significant component groupings within the optimized matrix without further consideration.

The MSI function was calculated for the optimized matrix within Figure 10(b), and used to produce an MSM – Figure 11. The application of the approach has illustrated that a number of strong module candidates exist within the proposed structure in addition to highlighting the inherent modularity of the artifact.



Level	End	
0.3	Washer-1	Big Bolt
0.4	Washer-1	Separator
0.4	Separator	V-Belt Socket
0.5	Washer-1	Bearing-1
0.5	Lower Cover	Separator
0.5	Bearing-2	Shaft
0.5	Rotor Coil	Fan
0.5	Shaft	Washer-2
0.5	V-Belt Socket	Big Bolt
0.6	Washer-1	Lower Cover
0.6	Small Bolt	Bearing-1
0.6	V-Belt Socket	Upper Cover
0.7	Washer-1	Small Bolt
0.7	Rotor Coil	Shaft
0.7	Shaft	Fan
1	Lower Cover	Bearing-1
1	Upper Cover	Big Bolt

Figure 12. Module catalogue for alternator.

Figure 12 catalogues the potential modules within the alternator structure at the differing module strengths highlighted within the MSM. These modules are based on the boundaries of the colored groupings. Such modularity is not immediately evident from the dependencies of the optimized matrix within Figure 10(b).

Conclusions

A novel multi-viewpoint modular design methodology has been developed, based on modular design support for engineering design reuse, to fulfil the objective of developing and defining a multi-viewpoint modular design methodology. The methodology was developed with the aim of addressing the limitations of existing modular design approaches and satisfying the identified requirements. The overall idea of the methodology is to support the designer in creating and maintaining a modular design solution throughout the evolution of the design process. As such, the methodology embodies the concept of knowledge modularity. The methodology has been developed to support the designer in modeling evolutionary design knowledge for analysis, modular optimization to identify inherent modularity and map between design viewpoints to maintain the modular solution.

The multi-viewpoint modular design methodology embodies four main elements: a modeling formalism, an optimization mechanism, a module identification mechanism, and a viewpoint mapping mechanism. The overall methodology defines the declarative and procedural knowledge required to fuse the methodology elements into a coherent framework and provide

an articulate procedure for designers to follow in practice.

The methodology was developed within the aim of addressing the limitations of existing modular design approaches and satisfying the identified requirements. To fulfil the objective of evaluating the functionality of the developed approach, it was partially realized within a computational environment and implemented within two industry-based engineering design processes [36,38]. The results of both implementations identified potential improvements in the modularity of the designs. In addition, the methodology was deemed by the industrial partners involved to provide an articulate procedure for practising designers [38].

Acknowledgments

The authors would like to acknowledge the Forward Design Group (FDG) within BAE Systems Marine Ltd., in particular to Mr Charles Nisbet who instigated the collaborative work; and to Dr Phil Jones for presenting the opportunity to undertake the case study with the Battle Group Thermal Imager (BGTI) team at Thales Optronics Ltd. The authors would also like to acknowledge EPSRC for their financial support during this study. The opinions expressed are those of the authors and should not be construed to represent the views of either BAE Systems Ltd. or Thales Optronics Ltd. This study was based on the PhD of our friend and colleague Dr Joanne Meehan who died on the 22nd of October 2004.

References

1. Duffy, A.H.B. and Ferns, A.F. (1999). An Analysis of Design Re-use Benefits, In: *12th International Conference on Engineering Design*, 24–26 August 1999, Munich, Germany.
2. Duffy, A.H.B., Smith, J.S. and Duffy, S.M. (1998). Design Reuse Research – A Computational Perspective, *Engineering Design Conference on Design Reuse*, Brunel University, UK, pp. 43–56.
3. Smith, J.S. and Duffy, A.H.B. (2001). Re-using Knowledge – Why, What and Where, In: *13th International Conference on Engineering Design*, Glasgow, UK.
4. Sosale, S., Hashemian, M. and Gu, P. (1997). Product Modularisation for Re-use and Recycling, *Concurrent Product Design and Environmentally Conscious Manufacturing*, Minneapolis, USA: ASME.
5. O'Grady, P. and Liang, W.Y. (1998). An Object Oriented Approach to Design with Modules, *Computer Integrated Manufacturing Systems*, **11**(4): 267–283.
6. Miller, T.D. (1999). Modular Engineering in Production Plants, In: *12th International Conference on Engineering Design*, Munich, Germany.

7. Elgard, P. and Miller, T.D. (1998). Designing Product Families. Design for Integration in Manufacturing, In: *13th IPS Research Seminar*, Fugsloe: Aalborg University.
8. Galvin, P. (1999). Product Modularity, Information Structures and the Diffusion of Innovation, *International Journal of Technology Management*, **17**(5): 467–479.
9. Muffato, M. (1999). Introducing a Platform Strategy in Product Development, *International Journal of Production Economics*, **60**: 145–153.
10. Chang, W. (1995). Design-in Modularity with Conceptual Robustness, *Design Engineering Technical Conferences*, Boston, Massachusetts: ASME.
11. Smith, R.P. and Reinertsen, D.G. (1997). *Developing Products in Half the Time – New Rules, New Tools*, New Jersey, USA: John Wiley and Sons.
12. Miller, T.D. and Elgard, P. (1998). Defining Modules, Modularity and Modularisation – Evolution of the Concept in a Historical Perspective, In: *13th IPS Research Seminar*, Fugsloe: Aalborg University.
13. Huang, C.C. and Kusiak, A. (1998). Modularity in Design of Products and Systems, *IEEE Transactions on Systems, Man, and Cybernetics - Part A: Systems and Humans*, **28**(1): 66–77.
14. Erixon, G. (1996). Modular Function Deployment, In: *2nd WDK Workshop on Product Structuring*, Delft, Netherlands.
15. Gershenson, J.K. and Prasad, G.J. (1997). Product Modularity and its Effect on Service and Maintenance, In: *Proceedings of the 1997 Maintenance and Reliability Conference*, Knoxville, Tennessee, USA.
16. Gonzalez-Zugasti, J.P. and Otto, K.N. (2000). Modular Platform-Based Product Family Design, In: *Computers and Information in Engineering Conference*, Baltimore, Maryland, USA: ASME.
17. Ishii, K. and Lee, B.H. (1995). Design for Product Retirement and Modularity Based on Technology Life-cycle, *Manufacturing Science and Engineering*, **3**(2): 921–933.
18. Jarventausta, S. and Pulkkinen, A. (2001). Enhancing Product Modularisation with Multiple Views of Decomposition and Clustering, In: *Design for Configuration 5th WDK Workshop on Product Structuring*, Heidelberg, Germany: Springer Verlag.
19. Otto, K. (2001). A Process of Modularizing Product Families, In: *the 13th International Conference on Engineering Design*, Glasgow, UK: IMechE Professional Engineering Publications.
20. Salheih, S.M. and Kamrani, A.K. (1999). Macro Level Product Development using Design for Modularity, *Robotics and Computer Integrated Manufacturing*, **15**(4): 319–329.
21. He, D.W. and Kusiak, A. (1998). Designing an Assembly Line for Modular Products, *Computers and Industrial Engineering*, **34**(1): 37–52.
22. Miller, T.D. (1999). Modular Engineering of Production Plants, In: *ICED – International Conference of Engineering Design*, Munich, Germany.
23. Rogers, G.C. and Bottaci, L. (1997). Modular Production Systems: A New Manufacturing Paradigm, *International Journal of Intelligent Manufacturing*, **8**(2): 147–156.
24. Zhou, J. and Irani, S.A. (2000). *Design of Modular Layouts for Fabrication-Based Assembly Facilities*, Department of Industrial Welding and Systems Engineering, 210 Baker Systems Building, Columbus OH43210: The Ohio State University.
25. Kusiak, A. and Huang, C. (1996). Development of Modular Products, *IEEE Transactions of Components, Packaging and Manufacturing Technology*, **19**(4): 523–538.
26. Ouyang, M. and Chenggang, L. (1996). Intelligent CAD Approach for Modular Design, Washington, USA: SPIE – The International Society for Optical Engineering.
27. Gu, P. and Hashemian, M. (1997). An Integrated Modular Design Methodology for Life-cycle Engineering, *CIRP Annals*, **46**(1): 71–74.
28. Kamrani, A.K. (1997). Modular Design Methodology for Complex Parts, In: *6th IIE Annual Engineering Research Conference*, Florida, USA.
29. Tseng, M.M. and Jiao, J. (1997). Case Based Evolutionary Design for Mass Customisation, *Computers and Industrial Engineering*, **33**(1-2): 319–323.
30. Ulrich, K.T. and Eppinger, S.D. (1995). *Product Design and Development*, New York, USA: McGraw Hill.
31. Pahl, G. and Beitz, W. (1996). *Engineering Design – A Systematic Approach*, Heidelberg, Germany: Springer Verlag.
32. Finger, S. (1998). Design Re-use and Design Research, In: *Design Reuse Engineering Design Conference*, UK: Brunel University.
33. Mostow, J. and Barley, M. (1993). Automated Reuse of Design Plans, *Artificial Intelligence for Engineering Design, Analysis, and Manufacturing*, **7**(1): 2–15.
34. Jiao, J. and Tseng, M.M. (1999). A Methodology of Developing Product Family Architecture for Mass Customisation, *Journal of Intelligent Manufacturing*, **10**(1): 3–20.
35. Zhang, Y. (1998). *Design Knowledge Structuring*, Glasgow: University of Strathclyde, p. 40.
36. Whitfield, R.I., Smith, J.S. and Duffy, A.H.B. (2002). Identifying Component Modules, *Artificial Intelligence in Design (AID'02)*, Cambridge, UK.
37. Steward, D.V. (1981). The Design Structure System: A Method for Managing the Design of Complex Systems, *IEEE Transactions: Engineering Management*, **28**(EM): 71–74.
38. Smith, J.S. (2002). *A Multiple Viewpoint Modular Design Methodology*, in *Design Manufacture and Engineering Management*, Glasgow: University of Strathclyde, p. 213.
39. Pimpler, T.U. and Eppinger, S.D. (1994). Integration Analysis and Product Decompositions, In: *ASME Design Theory and Methodology Conference*, Minneapolis, USA.
40. Todd, D. (1997). Multiple Criteria Genetic Algorithms in Engineering Design and Operation, In: *Engineering Design Centre*, University of Newcastle upon Tyne: Newcastle upon Tyne.
41. McCulley, C. and Bloebaum, C.L. (1996). A Genetic Tool for Optimal Design Sequencing in Complex Engineering Systems, *Structural and Multidisciplinary Optimisation*, **12**(2–3): 186–201.
42. Golberg, D.E. (1989). *Genetic Algorithms in Search, Optimisation and Machine Learning*, Massachusetts: Addison-Wesley.

Joanne Meehan



Joanne Meehan was a research fellow in the CAD Centre, University of Strathclyde. She undertook a Master's degree in Product Design Engineering at the University of Strathclyde. Following completion of her first degree, she completed her PhD to develop a methodology and tool for establishing functional, behavioral, and structural modularity, and

used the methodology to facilitate design re-use. Her research interests included modular design, design re-use, product structuring, knowledge management, and design methodologies.

Alex Duffy



Alex Duffy is presently a professor and director of the CAD Centre, as well as Director of Research within the department of Design Manufacture and Engineering Management at the University of Strathclyde. He lectures in engineering design, design management, product development, knowledge intensive CAD, advanced computational techniques, and data-

bases. His main research interests have been the application of knowledge-based techniques in conceptual design, product and domain knowledge modeling,

machine learning techniques and design re-use, performance measurement, process optimization, design productivity, sketching and vague geometric modeling, and design co-ordination. He has published over 160 papers, is the editor of the *Journal of Engineering Design*, and is on the board of numerous journals and conferences in engineering design and artificial intelligence in design. He is currently the President of the Design Society, an international body encompassing all aspects and disciplines of design.

Robert Ian Whitfield



Robert Ian Whitfield is a Senior Research Fellow at the CAD Centre at the University of Strathclyde. In 1991 he gained a BEng (Honours) degree in Mechanical Engineering from Newcastle upon Tyne Polytechnic. Following graduation he then carried out a PhD research project investigating modes of operation of turbo-generator

rotor bearings. He then continued working within the fields of hydrodynamics and rotor-dynamics for a further 18 months at Parsons Power Generation Systems. On moving to the CAD Centre, he chaired the technical committee of the VRShips-ROPAX project that was responsible for the design, development, and implementation of a distributed virtual platform integration platform. He is currently co-ordinating and undertaking research within a number of European Union FP6 and EPSRC research projects. His research interests include design co-ordination, integration, decision support, process optimization, and parametric design.