

EXPLORING ALTERNATIVE PRODUCT MODULARISATIONS WITH MULTI-OBJECTIVE OPTIMISATION

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ABSTRACT

This paper presents a multi-objective optimisation framework for product modularisation. At the heart of the software is a custom developed genetic algorithm that is able to generate a whole range of alternative product modularisations. Once generated, the solution set is then explored to examine the inherent trade-offs needed. In this way the decision maker is able to choose the most suitable modular architecture according to the company's strategic objectives. The focus of this paper is to illustrate the developed computerised framework using an example product: a car climate control system.

1 INTRODUCTION

Traditional product structuring tends to create a hierarchical product architecture split into sub-assemblies for the purpose of convenient assembly. On the other hand product modularity is seen as a product structuring concept, in which the product system is decomposed into smaller more manageable chunks (modules) to enable any number of strategic advantages, such as increased product variety at lower costs, outsourcing, reduced order lead-times, decoupling of design and assembly tasks, ease of product upgrade and change and ease of service and recycling. Modularity therefore represents an important means of improving competitive advantages in fast growing and changing markets. However, even for a relatively simple product there are a vast number of different ways the product can be modularised, according to the different objectives of modularisation. With each different solution there will of course be compromises that have to be made between the different objectives. Ideally these compromises should be explored before arriving at a final decision. This implies that a good set of alternative solutions can in fact be found in order to make the comparisons. However, current algorithms for product modularisation are simplistic (aggregated objective) approaches. Finding a set of optimal solutions (for comparison) with these algorithms is problematic and time-consuming.

The overall aim of this research has thus been to develop a computerised multi-objective optimisation framework for product modularisation. In the framework numerous modular design principles have been reconciled and integrated and a state-of-the-art multi-objective optimisation algorithm has been developed to perform the modularization.

2 LITERATURE

Modularity has been given many definitions over the years and a large range of measures, methods and techniques have been created in the attempt to guide the development of modular product architectures.

Generally speaking one can see a kind of general convergence towards the seminal works of Ulrich and Tung (1991), who define modularity in terms of two characteristics of product design: similarity

between the physical and functional architecture of the design and the minimisation of incidental interactions between physical components.

The first part of Ulrich's (1991) definition, relates product modularity to product functions. Similar perspectives on modularity can be seen in other works (Stone et al (1999), Baldwin and Clark (1997), Kusiak and Huang (1997), Sanchez (1999), Suh (1990) and Pahl and Beitz (1984) and Jiao and Tseng (1999). Following these works, product architecture is defined by the way in which functional elements correspond to physical components. The product architecture is said to be modular when it exhibits a one to one mapping between functional and physical elements. In a modular product functions are less integrated (spread among components), so different customer needs can be addressed by different modules, allowing a mix and match of modules to enable product variety at low costs (Ulrich (1991), Pahl and Beitz (1984)).

The second of part of the Ulrich's seminal definitions of modularity, views modularity in terms of the interaction and interface complexity (coupling) between components. Other works also support this idea (Ericsson and Erixon (1999), Newcomb et al (1996) , Gu and Solace (1999), Gershenson et al (1999), Sanchez (2000), Mikkola (2003), Kusiak (1997)). Interactions can be seen as the physical and functional relationships between the product's elements (components). Obviously, there is a need to reduce the number and complexity of these interactions between modules. This will reduce design dependencies, reduce assembly complexity and can be used in the pursuit of 'plug in- plug-out' or interchangeable modules to create a large number of product variants at low cost.

Other researchers have chosen to include other product lifecycle based aspects into their definitions of modular products. Gershenson et al. (1999) view modularity from a whole life-cycle viewpoint. Their methods have been used in pursuit of service (Gershenson and Prasad, 1997b), manufacturing (Gershenson and Prasad, 1997a), retirement (Zhang et al, 2001) and assembly (Gershenson et al, 2007) based modularity. Similarly, the bodies of work by (Gu and Solace (1999), Iksii et al (1996) and Newcomb et al (1996)) also see modularity as a means of improving various product life cycle goals.

In regards to actually creating a modular product, there have been numerous frameworks and methods developed to create optimal modular product architectures. The majority of these methods pursue a 'bottom-up' approach in which low-level product elements (components) are grouped to form larger product element (modules). The rationale for grouping has been seen to vary considerably, from a more technical perspective such as functional and physical interactions to a more strategic focus such as the similarity between various lifecycle attributes such as service and reliability, reuse and recycling, product variety, outsourcing, etc.

Pimmler and Eppinger, 1994 use a clustering approach based on functional interactions between components. Single objective mathematical optimisation models have also been developed; such as the method of Gu and Sosale (1999) who have developed a heuristic and non-linear optimisation model to optimise a weighted sum of numerous lifecycle objectives. Similarly Kreng (2004) uses a non-linear optimisation GA based weighted sum approach to modularise to a number of strategic modular drivers and functional/ physical interactions. Manual heuristic based methods have also been developed. Erixon and Ericsson's (1996) Modular Function Deployment (MFD) uses a comprehensive list of modular drivers which can be used to evaluate candidate modules. Stone et al (2000) work from a functional basis using energy, signal of material flows between components and use a set of heuristics to form modules.

3 OVERVIEW OF THE COMPUTER AIDED MODULARISATION FRAMEWORK

In summary and as depicted in figure 1 the computer aided modularity optimisation (CAMO) framework has four main steps: 1) product decomposition 2) interaction analysis 3) formation of modular architectures 4) scenario analysis. The important aspect of the framework is that it presents a novel multi-objective approach to product modularisation, in which a whole set of alternative modular product architectures are generated in one single run of the algorithm without the need to set up preference weights for the various objectives. The solution set can then be further analysed to choose the best compromise solution.

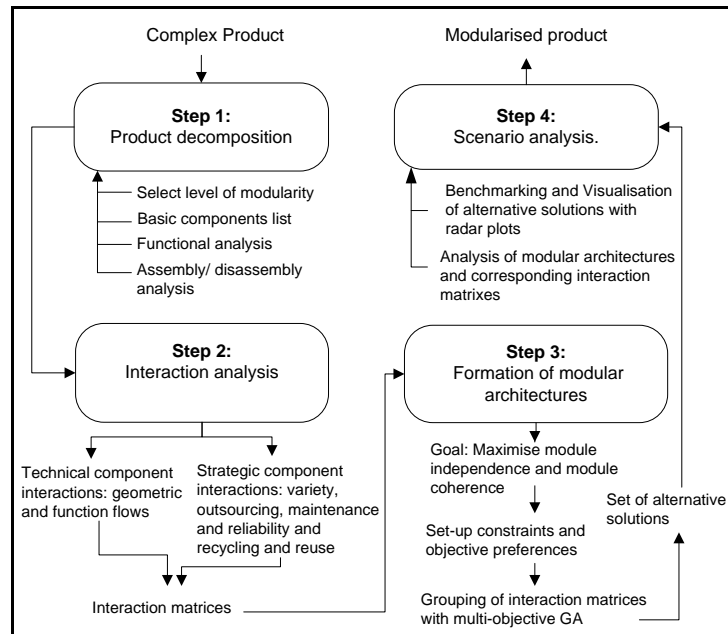


Figure 1: Overview of framework

4 PRODUCT MODULARISATION WITH THE FRAMEWORK: CAR CLIMATE CONTROL SYSTEM

The car climate control system is a fairly complex system that is comprised of various technologies that must be split across numerous geometric locations within the car. This makes the climate control system an ideal case example to assess the potential of the developed modularity framework. The case study is in fact built upon the works of Pimmler and Eppinger (1994) who look at the clustering of highly interactive components to improve product development. However unlike Pimmler and Eppinger, for this study it has been presumed that there is more than one strategic objective for modularisation of the system; these are loose coupling, function binding, variety, outsourcing, maintenance and reliability, and recycling and reuse. In the next sub-sections of this paper the four steps of the framework will be described using the climate control system as an example.

4.1 Step 1 and 2: Product Analysis

Essentially with the framework we are grouping basic product components into larger product sub-systems (modules). That is to break the product down into smaller elements (components) and group them to form larger elements (modules). To do this requires a decomposition approach to indentify the basic components before their interactions (physical, functional and strategic) can be documented. For each modularity objective an evaluation form has been developed.

4.2 Step 3 and 4: Exploration of Different Modularisations Scenarios

A Multi-objective grouping algorithm is applied to find optimal modular architectures (solutions) through manipulation of the data in the various matrices. Each solution is found by varying the membership of components to modules, in each of the interaction matrixes, such that the developed modularity metrics are maximised for the different objectives. Of course it will often be impossible to simultaneously maximise every objective, so different trade-off solutions are produced. In the framework the modular solutions

formed from the matrices are represented by radar plots as shown in the figure 2a. These plots give the user a suitable means for making comparisons between different solutions and exploring different modularisation scenarios. To support this exploration stage a product modularisation objective hierarchy has been developed (as seen in figure 2b). By changing the preferences at the various levels of the hierarchy corresponding solutions can be visualised in real time i.e solutions that best match the preferences given are presented to the user of further analysis. By exploring the solutions in this manner the decision maker is then able to make a more informed decision on the most suitable modular structure for the product.

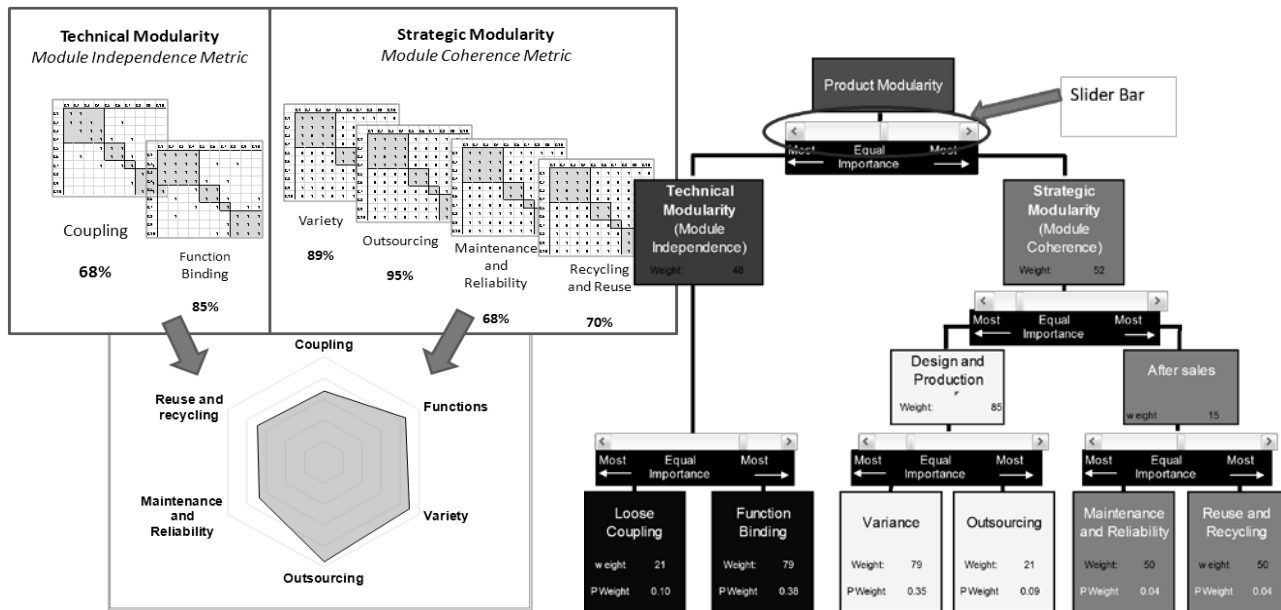


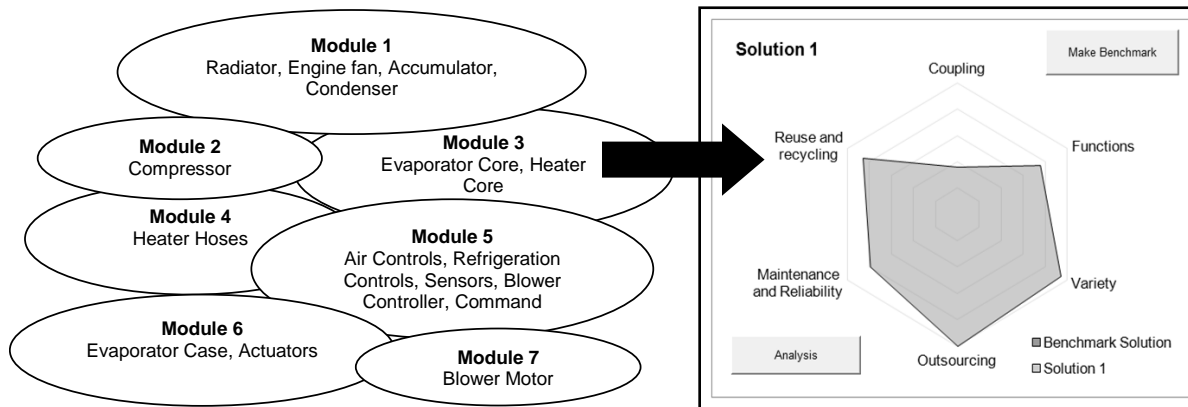
Figure 2: a) Radar plots of solutions and b) objective hierarchy for setting preferences

5 RECOMMENDED MODULARISATION OF CLIMATE CONTROL SYSTEM

The chosen modular solution for the climate control system is seen in figures 3 and 4. Although this is a hypothetical decision, it is a solution that offers good performance in most of the modularisation objectives. The relatively poor performance of the ‘loose coupling’ can be ‘tackled’ by the careful design of the interfaces between modules.

The chosen modular product architecture has been compared with the existing modular structure in currently manufactured climate control systems. The information regarding this current modular structure comes from Nepal (2005), who performed the same case study with a number of tier one automotive suppliers. Nepal discusses that the current climate control system was not systematically modularised in the past, and hence very few modules existed.

When comparing this existing product structure to the new one proposed in the figure 3 it can be seen that there are fewer modules in the existing product. This structure may well be optimal for assembly time, and reduces the interface complexity needed between modules. However, a number of issues may arise from this configuration. When this existing configuration is evaluated using the CAMO framework, it can clearly be seen that, although the module independence (coupling and function) is high, the modularisation objective achievements for the various strategic considerations are considerably lower than the chosen modular configuration. For example, the large front end module (module 1) will have poor performance in terms of maintainability because not all the components have common maintenance requirements. The cost of implementing and managing product variety is also going to be higher because, de-



pending upon the vehicle type and size, there may be different requirements for the type of controls, cases and connectors i.e. to make the whole module a variant, the costs will be considerably higher than splitting the modules further into common and variant modules. These costs are of course difficult to quantify as, like other frameworks, the framework does not contain any detailed means of module cost analysis. Yet, it can be implied the CAMO framework does provide a clear insight into how costs may be affected by looking closely at how the chosen configurations respond to the different modularisation objectives.

Figure 3: Recommended modularisation of car climate control system

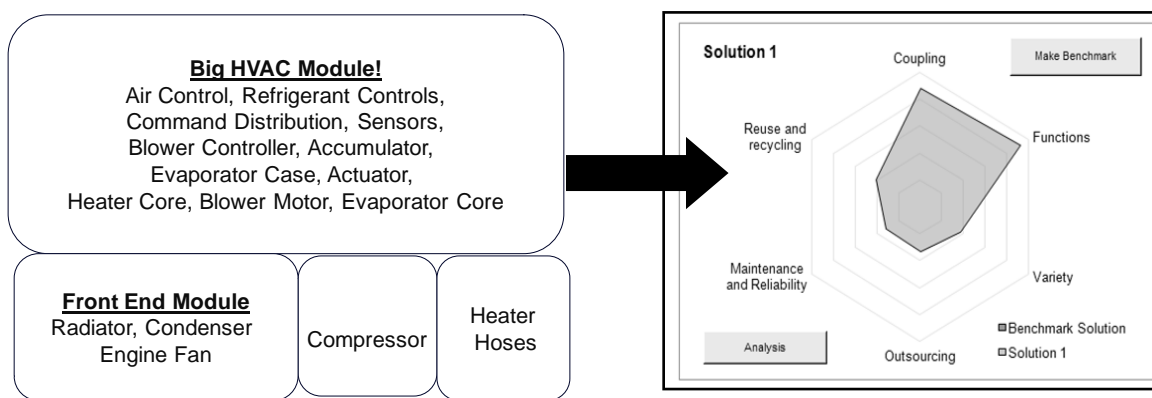


Figure 4: Existing modularisation of car climate control system

6 CONCLUSIONS

In this paper product modularity has been defined as a complex configuration problem in which the product system is decomposed into smaller more manageable chunks (modules) to enable any number of strategic advantages. However, the majority of previous modularity optimisation methods have used simplistic optimisation models to handle a inherently complex multi-objectives problem. Furthermore it is argued that in any complex decision making process alternative solutions should be considered before a

final choice is made. With the framework presented in this paper a whole set of alternative modular architectures can be generated and a trade-off analysis can then be carried to help identify the best compromise solution according to the companies strategic goals. The framework therefore provides a more logical, structured and less ambiguous approach to creating optimal module product architectures.

The focus of this paper has been to show the application of the framework on an example product: the car climate control system. When considering multiple modularity drivers it is clear that the current climate control modules are not optimal and it has been shown that more 'optimal' modular architectures are possible and should be further explored.

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