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Optimum granularity level of modular product design architecture

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ABSTRACT

In modular architectures, Design Structure Matrix (DSM) is used to cluster product components into modules with minimum interfaces externally and maximum internal integration between components. However, DSM is a flat connectivity map that does not capture the layered nature of the product structure. Hierarchical clustering (cladistics) is proposed to automatically build product hierarchical architecture from DSM. The resulting clustering tree represents product architecture while its depth represents its granularity. The optimum granularity level and number of modules are determined, indicating the potential product and process platforms. A case study of automobile body-in-white of 38 components is used to demonstrate the capabilities and superior results quality of the presented technique.

1. Introduction

Products architecture defines the functions of its components and the topology of their interfaces. Products architecture facilitates further detailed design, testing, and planning of its manufacture and material supply chain of those components [1]. In an era characterized by proliferation of product variety and mass customization, establishing families of parts/products and product/process platforms are effective solutions for product design and manufacturing [2]. A modular architecture defines the appropriate product structure consisting of a group of modules with distinguishable functions and minimum interaction with the rest of the product [3]. Many types of modularity can be identified [4,5] including: (1) bus modularity where all modules are connected to a single common module, (2) sectional modularity where product variants are built from specific combinations of modules having a unified interface, (3) scalable modularity where some scalable components are combined with standard components.

The depth of the architecture hierarchy of components, modules and subassemblies defines its level of detailed description or *granularity* (Fig. 1). It has important implications on all subsequent activities throughout the product life cycle. Shared common product modules across many product variants, known as product platforms, capitalize on commonality and similarity to approach the economy of scale while offering a range of differentiated variants to enable economies of scope. Success in achieving these objectives depends on the appropriate identification of common and different modules and their interactions. The appropriate level of aggregation and granularity should, therefore, be carefully considered when families of products are formed [6].

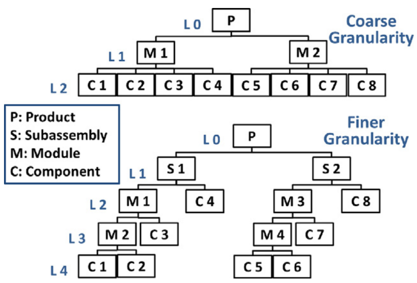

Fig. 1. Different levels of product architecture granularity.

Chiriac et al. [7] analyzed many product architectures with one and two levels of granularity to identify the effect on the quality of product modularity. They concluded that modularity has a unidirectional relationship with granularity and indicated a need to investigate the appropriate granularity level for a given product design to optimize system modularity.

This paper introduces a new model capable of determining the appropriate level of granularity for a product design, as well as the structure of its architecture based on the interactions among its components. The model also includes a new clustering tool to group components into modules in a hierarchical structure which reveals product architecture.

2. Product modularity incorporation

Product components are usually grouped into modules that are assembled using a specific design architecture to facilitate future design changes, product variety management, mass customization and manufacturing processes using delayed product differentiation [8]. The Design Structure Matrix (DSM) is the most common tool used to represent interactions among components (component-based DSM) in a product [9]. DSM elements are usually represented by binary numbers where ‘1’ indicates interaction and ‘0’ indicates lack of it. Grouping product components into modules can be accomplished by clustering DSM into blocks consisting mostly of ‘1’ elements.

There are few techniques to cluster DSM for modularity, which differ mainly in the clustering objective. Coordination cost minimization is one of the first clustering methods [10] in which each DSM element is placed in an individual cluster, then components are

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coordinated across modules to minimize the cost of being inside and outside a cluster. The maximum number of components in a cluster was predetermined to prevent forming large clusters and optimization was performed using simulated annealing.

Clustered DSM can be compared to a targeted DSM topology using another objective function called Minimal Description Length (MDL) [11] which finds mismatching elements between the two topologies. The objective of clustering was to minimize MDL using GAs where chromosomes are formulated to represent components combinations in clusters generations. The number of clusters is determined a priori based on the DSM structure.

Clustering Efficiency (CE) index is another clustering objective that evaluates a weighed count of zero elements inside clusters and the non-zero elements outside clusters using neural network optimization for clusters generation with a predefined number of clusters otherwise the model would form fewer clusters than desired [12,13].

Measures other than clustering can be used for quantifying efficiency of modularity and alternative designs evaluation. Modularity performance is a normalized index [14], with value from 0 to 1. It is used to compare number of interfaces, connections and dependencies among the product components to the minimum and maximum possible number of interfaces. A value of '0' indicates a fully integrated design, while modularity improves as it approaches '1'. Another similar modality index is more detailed as it counts the interactions between the composed modules taking into consideration intra-relationships between components in a module and components of the other modules [7]. It was also modified to count inter-relationships among components within modules [15]. A components similarity approach was used to present a relative modularity measure [16] in which the ratio of the sum of similarities within modules to the total similarity in the whole DSM matrix is added to the ratio of the sum of dependencies within modules to the total dependency. The concept of the smoothness of product change from one product generation to another was introduced through a coupling index, which is indirectly related to quantifying modularity [17] which measures the strength of relationships among product modules. The stronger the coupling, the more difficult are changes, and hence more modularity is needed to weaken the existing components' coupling.

The previous review of clustering techniques and modularity measures reveals two points:

(1) The objective function for DSM clustering is related to the interactions inside and outside the resulting clusters. Chiriac et al. [7] compared many modularity indices, and results were similar for the same product. Therefore, modularity indices with the simplest formulation would be preferable. In this paper, a simpler formula of the clustering efficiency (CE) index [12] is adopted.
(2) DSM clustering techniques reveal only one dimensional modules formation, even when compared to bus modularity architecture. Yu et al. [11] imposed bus architecture on the clustering process by utilizing former designer knowledge. Hence, the true nature of product architecture and its granularity is difficult to recognize using only clustered DSM, especially for large complex systems [13], without human input.

This paper introduces a new DSM clustering technique for modularity. It finds an optimal granulated modular and hierarchical architecture without imposing any modularity structure or predefining the number of modules or number of components per module.

3. Product architecture granularity model

The new model adopts hierarchal clustering to best divide a DSM into modular architecture. Cladistics, a classification tool extensively used in Biology [18,19], reveals the evolution hypothesis and speciation scheme of a studied group of entities. Cladistics was first introduced to the world of artifacts and used to reveal the evolution and co-development of products and manufacturing systems by ElMaraghy et al. [20]. This powerful computational analysis results in useful graphical clusters representation called cladogram (Fig. 2), which shows how different entities can be grouped based on the commonality and differentiation of their characters. A handful of specialized software are dedicated for cladogram construction such as Hennig86, PAUP, NONA, PeeWee and Phylip that can cluster large data sets very fast [21]. NONA is used in this paper for cladogram construction.

Cladogram construction, however, has to be modified for use in DSM clustering. In the original cladistics techniques, clustering is based on entities characters, while a DSM represents relationships and connections among entities. The existence of relationships between components will be considered their characters/features to be used for cladistics clustering. For correct results, the self-relationships of components to themselves are taken into consideration by the '1' diagonal elements of the original DSM in Fig. 2. A cladogram would reveal the proposed hierarchal architecture of such components starting with a common root where the whole product appears and ending with cladogram terminals of individual components. The long inclined line at the left hand side of the cladogram, at each branching node, represents the beginning of a new granularity level. The example in Fig. 2 results in possibly three granularity levels below each branching node. This excludes the lowest node at which individual components appear since it does not represent useful modularity information. The only useful information for product architecture construction is the topology of the cladogram. The distribution of characters/connections on the cladogram was the result of the parsimony analysis; however it is not useful for further granularity analysis of the product architecture.

To determine the optimum granularity level on a cladogram, a simple modularity index is used to specify the depth of the cladogram topology equivalent to the granularity level corresponding to the best modularity index. The developed modularity index (MI) has the same premise of the clustering efficiency (CE) index [12], both aim to reduce the number of blank '0' cells inside obtained clusters, and the '1' cells outside them. However the MI results in integers that can be easily understood compared to the very small fractions that result from using CE. In the particular used case study in this paper, the body-in-white, MI = 2/CE, when CE weight factors are taken equal to 0.5. The MI is the sum of the number of intra-relationships among modules and the number of missed inter-relationships among components of these modules. MI is expressed as:

$$\mathrm{MI} = I + Z \quad (1)$$

where I is the number of '1' elements in the DSM outside developed clusters, and Z is the zero elements of those clusters (referred to as S_{in} and S_{out} in [12]). The smallest MI corresponds to the best clustering. MI value changes according to the granularity level of the formed clusters. In the example shown in Fig. 2, the first granularity level divides product components into two branches and consequently two clusters/modules – module {C,D,E,F,A} and module {B}. When DSM is re-shuffled to reflect component re-arrangement at the cladogram terminals, the boundaries of clustered modules can be defined and MI can then be calculated. For level 1, MI = 10 since there are 2 intra-relationships between the two modules and 8 non-existing inter-relationships inside the modules. The second level scores MI = 6 based on three modules: {C,D,E}, {F,A} and module {B}. The last level scores MI = 10 based on four modules: {C,D}, {E}, {F,A} and module {B}. The shown example in Fig. 2 has an optimum granularity level of 2 since it has the least MI = 6. The best architecture can then be extracted from the cladogram at the optimum granularity level, which is the granularity map of the analyzed product (Fig. 2). Level 2 illustrates the hierarchical relationship between the three resulting clusters. Module {C,D,E} and module {F,A} are assembled to form sub-assembly {C,D,E,F,A} to which module {B} is added later. This product architecture decomposition is shown in Fig. 2.