CIRP Journal of Manufacturing Science and Technology xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

CIRP Journal of Manufacturing Science and Technology

journal homepage: www.elsevier.com/locate/cirpj

Product family formation by matching Bill-of-Materials trees

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ARTICLE INFO

Article history:
Received 15 April 2014
Received in revised form 16 September 2015
Accepted 28 September 2015

Keywords:
Bill-of-Materials (BOM)
Trees matching
Product family formation
Hierarchical clustering
Integer programming

ABSTRACT

Formation of product families is of great importance for manufacturing systems which rely on commonality and similarity between products for improving efficiency and productivity. Existing techniques for product family formation are based on similarity measures such as components commonality but none of them consider similarity of the product structure which directly affects the assembly system configuration and the sequence of assembly operations. A novel Bill-of-Materials (BOM) trees matching integer programming model is introduced to address commonality of components as well as their hierarchical assembly structure. A product Bill-of-Materials is a structured tree representing its components and their assembly relationships. BOMs are traditionally used for Material Requirement Planning (MRP); however, they have other useful applications in product modeling and variety management. A product BOM trees matching model, inspired by well-established techniques used in the field of biology for comparing phylogenetic trees, has been developed. Hierarchical clustering is applied to form groups of product families based on the pair-wise similarities obtained by matching BOM trees. The proposed method is applied to a case study of six centrifugal pumps for demonstration and analysis. The benefit of considering structural similarity in family formation for assembly products, in terms of having a better utilized assembly process when compared to the grouping based on plain component commonality, is highlighted.

Motivation

The variety of products has been increasing over the last few decades driven by the emergence of new materials and manufacturing technologies as well as the fierce competition among manufacturers and retailers to differentiate their products [1]. An abundance of research has been carried out to study and address product variety from various perspectives [1–5]. The notion of grouping products into families to capitalize on similarity within a class of products is considered a pre-requisite for success in managing variety [5]. It is important to identify sets of product families that share significant manufacturing resources and setup in order to maximize the manufacturing system utilization and productivity, and decrease its complexity. For instance, in a Reconfigurable Manufacturing Systems (RMS) [6], similar products are grouped together into families of products in which a customized system configuration is designed for each product family. The foundation for the success of RMS lies in recognizing homogenous sets of product families [7]. This also applies to other systems such as Cellular and Flexible Manufacturing Systems.

The Bill-of-Materials (BOM) was first introduced by Orlicky [8,9] as a product data structuring form for Material Requirements Planning (MRP) systems, commonly used in production planning and inventory control. A BOM is the list of sub-assemblies, components, parts, raw materials and the quantities required of each to produce an end product. Unordered rooted trees were used to represent BOMs [8]. Fig. 1 shows a three level BOM tree of a pilot control valve consisting of ten different components. A BOM tree of a more complex product would include more components and hierarchical levels. BOM trees have other valuable applications, in addition to their classical use in MRP. For instance, Jiao et al. [10] proposed an integrated product and production data management method for mass customization systems. They proposed a production data structure called Bill-of-Materials-and-Operations (BOMO) for unifying BOMs and routings for better production planning and control, order processing, and engineering change control. Steva et al. [11] employed BOMs along with other tools such as Design Structure Matrix (DSM) and Function Diagrams to develop a product platform identification methodology. Other applications for BOM in support of product modeling and variety

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http://dx.doi.org/10.1016/j.cirpj.2015.09.004
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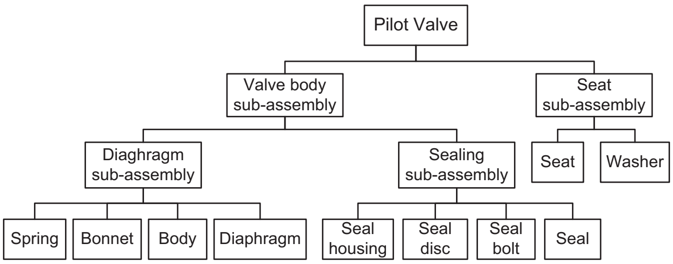

Fig. 1. BOM tree of a pilot control valve.

management, such as assemble-to-order manufacturing [12] and end-of-life decision making in Design-for-the Environment [13] have been reported.

Several grouping methods have been developed for forming product families [14–18] using similarity measures such as components commonality, reusability and operations sequence. In this paper, a novel product family formation method based on a new Bill-of-Material (BOM) trees similarity measure is proposed. Grouping based on BOM trees concurrently addresses three important grouping criteria. The first criterion is components commonality (e.g. Jaccard's [30]) which is the most commonly used criterion in product family formation. The second is the assembly structure which implies the assembly sequence. Assembly sequence is equivalent to operations sequence in manufacturing/machining which is also a major grouping criterion [15]. The third grouping criterion is the similarity in required number of components; which is an important complementary aspect to components commonality [19].

Another important practical advantage for BOM tree is that it is a widely-accepted product representation format used by almost all manufacturing companies. BOMs are accessible and ready-to-use product representation format. BOM data can be extracted from Material Requirement Planning modules of the Enterprise Resource Planning (ERP) systems, such as ECi M1 and, Infor VISUAL and E2 shop, used by production facilities to collect, store and manage data from various business activities including product planning and control, supply chain and inventory management. Accordingly, it is a practical and industrially friendly to use BOMs for grouping instead of specifically developing three separate similarity measures for each of the above mentioned criteria and aggregating them.

A few approaches have been developed in literature for measuring distances between trees of BOM, based on graph difference operations, linear algebra and integer programming [20–23], for applications such as product design retrieval and constructing Generic Bill-of-Materials (GBOM). Kashkoush and ElMaraghy have developed a BOM trees matching method based on Trees Reconciliation [24,25] which is a well-studied phylogenetic tree reconstruction technique used in many biological research fields such as developmental biology, parasitology, molecular systematic, and biogeography [26–29]. A new BOM matching measure is proposed due to some limitations of the previously developed tree reconciliation-based method, to be discussed later in the Literature review section. The new measure is based on a tree matching measure commonly used in phylogenetics known as Robinson–Foulds (RF) distance [30]. An enhanced and modified version (RF-BOM) is developed in this paper for comparing BOM trees. A novel integer programming model was formulated and implemented to formally define and calculate the new measure of distance between any given pair of BOM trees. Average linkage hierarchical clustering is then used to construct clustering trees based on the pairwise similarity distances obtained from BOM matching.

This paper is organized as follows: in the Literature review section, research work related to product family formation as well as BOM trees matching is reviewed. The current research scope and used assumptions are defined in the Research scope and assumptions section. The Proposed product family formation method section introduces the proposed product family formation method based on the new BOM trees matching measure. The Case study section applies this method to a set of chemical processing centrifugal pumps for demonstration and analysis and also compares the results with grouping results based on Jaccard's commonality measure [31]. The Discussion section provides a discussion of the development and significance of the proposed method. Finally, summary and conclusions are outlined in the Conclusion section.

Literature review

Product family formation

An extensive amount of research has been conducted on the subject of clustering products into groups using different titles such as products grouping, product family formation and parts-machines grouping [32–36]. State-of-the-art product family formation methods primarily use average linkage hierarchical clustering to group products into a binary rooted tree called Dendrogram. The main difference between these methods is the similarity measures on which the clustering is based. Abdi and Labib [37] used operational similarities between products calculated using Jaccard's similarity coefficient [31] which is a commonly used similarity coefficient for parts-cells formation in cellular manufacturing. Goyal et al. [15] proposed a similarity coefficient based on operations sequence. Galan et al. [14] used five similarity coefficients; modularity, commonality, compatibility, reusability and demand. Analytic Hierarchy Process (AHP) [38] is used to aggregate the five similarity coefficients into one single coefficient. Eguia et al. [17] addressed the product family formation for disassembly systems using a similarity coefficient employing the following information: (a) types and quantities of the products to disassemble within a certain time horizon, (b) existing reconfigurable machine tools and available modules library, (c) operations and processing times required to disassemble each product type, and (d) machines and modules required for each disassembly task.

Considering alternative process plans, Rakesh et al. [7] proposed a modified average linkage hierarchical clustering algorithm based on Jaccard's similarity coefficient. Navaei and ElMaraghy [32] used a similarity measure based on the required machines. The authors considered a case where alternative machines are available for performing each operation. Abdi [36] proposed a conceptual framework for product family formation using Analytical Network Process (ANP) [39], which is an extended form of the AHP that allows more interrelationships among decision elements. Abdi's framework incorporates six major clustering criteria mainly related to manufacturing operations and market requirements, where each major criterion is further broken down into more elements that affect product family formation and selection. Pattanaik and Kumar [16] implemented a multi-objective (bi-criterion) Genetic Algorithm [40] to cluster products based on a pre-defined number of clusters using two similarity coefficients; components commonality and demand.

The similarity in product assembly structure should be taken into consideration whenever components commonality is used as a similarity measure for an assembly application. Products sharing many common components may have considerably different product structures. Grouping such products into one family is not sufficient as they have differences in type and sequence of required