Optimizing modular product design for reconfigurable manufacturing

AHMET S. YIGIT,1 A. GALIP ULSOY2 and ALI ALLAHVERDI1

1Department of Mechanical and Industrial Engineering, Kuwait University,
P.O. Box 5969 Safat 13060, Kuwait
2Department of Mechanical Engineering, The University of Michigan, Ann Arbor,
MI 48109-2125, USA

Received November 2000 and accepted May 2001

The problem of optimizing modular products in a reconfigurable manufacturing system is addressed. The problem is first posed as a generalized subset selection problem where the best subsets of module instances of unknown sizes are determined by minimizing an objective function that represents a trade-off between “the quality loss due to modularization” and the cost of reconfiguration while satisfying the problem constraints. The problem is then formulated and solved as an integer nonlinear programming problem with binary variables. The proposed method is applied to the production of a modular drive system composed of a DC motor and a ball screw. The study is a first attempt toward developing a systematic methodology for manufacturing modular products in a reconfigurable manufacturing system.

Keywords: Modular products, product design, reconfigurable manufacturing, optimization, integer programming

1. Introduction

A new manufacturing paradigm called reconfigurable manufacturing systems (RMS) is emerging to address the needs caused by rapidly changing markets and rapid introduction of new products (Koren et al., 1999). A reconfigurable manufacturing system is designed for rapid adjustment of production capacity and functionality, in response to new circumstances, by rearrangement or change of its components. These new systems provide exactly the functionality that is needed exactly when it is needed (Mehradi et al., 2000). Therefore, a RMS is designed to be easily reconfigured such that it is able to process a family of parts and accommodate new and unanticipated changes in the product design and processing needs.

The utility of a RMS is greatly increased if it is designed for production of modular products, where the combinations of individual modules form the product. The term modularity is used to describe the use of common units to create product variants (Huang and Kusiak, 1998). Through modularity, the number of parts to be manufactured for a product family may be significantly reduced while achieving sufficient variety by combination of different modules (see Fig. 1). In general each module may have more than one instance. The different instances provide the sizes and capabilities that are required by the desired product variety, and together they form the part family. The modular products in the part family are all the variants (i.e., $A_i + B_j$; $i = 1, 2, 3; j = 1, 2$) shown in Fig. 1. A particular configuration of the RMS for a particular module can then be used to produce a particular instance of the part family (see Fig. 2). The first production line (RMS-A) can be quickly and cost effectively reconfigured, as needed in response to market demand to produce any instance of module A (i.e., $A_i$; $i = 1, 2, 3$). Similarly, the second production
line (RMS-B) can be reconfigured to produce either B1 or B2. This enables the manufacturer to be responsive to changing and unpredictable demand. It also requires that the product be designed in a modular manner (i.e., as the combination of two modules $A_i$ and $B_i$ in this example).

The Nippondenso panel meter design (Aoki, 1980) is cited in Kusiak (1999) as a powerful example that clearly illustrates the benefits of modularity. The old panel meter was redesigned with six standard modules. Through redesign the number of parts was significantly reduced; e.g., the number of voltage regulators was reduced from 20 to three, the number of bimetals was reduced from eight to four and so on. The combination of six modules resulted in 288 different models, of which 40 were produced. (With the previously considered number of alternatives, the number of possible models were 23040.) As this example illustrates, the benefits of modularity include: economies of scale; increased feasibility of product/component change; increased product variety; reduced lead time; easier product diagnosis, decoupled risks, maintenance, repair and disposal.

Despite these clear benefits, a formal theoretical approach to modularity is still lacking (Kusiak, 1999), and designers are often skeptical regarding the advantages of modularity. This is largely due to the inferior performance obtained by modular designs compared to their custom built optimal alternatives (Cakmakci and Ulsoy, 2000; Ulrich and Seering, 1989). Recently, there have been some attempts to address various issues in modular product design such as planning for commonality, optimizing the degree of commonality and finding the optimum settings for the common modules (Fujita et al., 1999; Gonzales-Zugasti and Otto, 2000; Martin and Ishii, 1997). Fujita et al. (1999) proposed an optimization approach to designing modular products from existing modules using an integer-programming formulation. Gonzales-Zugasti and Otto (2000) presented a general method for designing families of products built onto modular platforms. These modular platforms allow for the use of both existing and new modules. Optimizing modular products in a RMS has not been addressed before. As mentioned above, in RMS each module instance required for a particular product variant is produced by a different configuration. Therefore, the design of modular products should consider the cost of reconfiguration, in addition to other issues related to modularity.

This paper addresses the problem of manufacturing modular products in a RMS environment. For a modular product that is to be manufactured in a RMS, the performance of a custom built alternative can be approached if the number of module instances (i.e., different sizes or capabilities) is increased indefinitely. However, this is neither practical, nor economical since each instant requires a different configuration. Therefore, a major issue in designing and manufacturing modular products in a RMS is to determine optimum number of module instances and the selection of the optimum subset of module instances from a large (possibly infinite) number of

![Fig. 1. A typical modular product with two types of modules.](image1)

![Fig. 2. Manufacturing a modular product on a reconfigurable manufacturing system.](image2)