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Process modularity of mass customized manufacturing systems: principles, measures and assessment

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Abstract

Process modularity in terms of mass customized manufacturing is considered as a key criterion in designing process architecture. The impact of process modularity on effectiveness of mass customized can be almost predicted based upon experience with traditional mass production. This study firstly analyses relationship between product modularity and process modularity. Then, in order to identify possible tolls for process modularity management, potential process modularity indices are compared and assessed on testing examples. Subsequently, theoretical principles for designing manufacturing and assembly process structures are formulated. The results showed that management of process architecture in mass customized environment might not be conducted in isolation from management of product development.

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Keywords: Process modularity; Product modularity; Mass customization; Manufacturing systems; Modularity indices

1. Introduction

There is no doubt that mass customization (MC) is becoming increasingly important model for a broad range of different industrial sectors. MC means, in simplified terms, to offer customized products on a large scale and in a responsive manner so that almost every customer can find products that satisfy their specific needs at a reasonable price and delivery promptness [1], [2].These customer expectations are what ultimately motivate manufacturers to prioritize both delivery fulfillment times as well as cost. There are several key elements that we should focus on to achieve these objectives. One of them is product standardization and modularization, by which manufacturers can produce compatible modules concurrently and modify those into different functional variants[3], [4], [5]. Several authors, e.g. [6], [7], [8] stated that modularity-based approaches in manufacturing that include particularly product modularity and process modularity can improve MC capability and are strong enablers of mass customization.

In this context, this paper explores a possibility to measure process modularity and proposes principles that can be used for designing and assessment of manufacturing process structures. For this purpose, firstly, potential indices are compared and assessed on testing examples. Subsequently, theoretical principles for designing manufacturing and assembly process structures are formulated. Finally, some pertinent comments are made.

2. Related work

Starr [9] in his pioneering work depicted that modular production is a practical concept making use of standardized and interchangeable parts and organizing manufacturing process to satisfy the variety request by producing so called combinatorial outputs. Later, he emphasized how mass customization is related to modularity issues [10]. Calcagno [11] argued that there is a need to measure a degree at which a manufacturing system is modular. In this context, definition concepts of process modularity seem to be important. Process

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modularity for mass customization is defined by Abdelkafi [12] as the degree to which the production process on the shop floor can be broken down into independent sub-processes called process modules. Langlois [13] identifies modularity as a very general set of principles for managing complexity. According to Tihonen et al. [14] the complexity of production is directly related to the degree of modularity of the product. Obviously, many others definitions of the process modularity and product modularity are more or less beholden to different types of products. In the context of mass customization, product modularization and process modularization is also related to the term 'product configuration'. However, there are also several definitions of product configuration (see e.g., [15], [16], [17], [18], [19]).

During the past decades research on process modularity dealing with its different facets attracted the attention of numerous researchers. In fact, majority of those studies was related to functional modularity [20], [21]. The presented approach in this paper is focused on structural problems in process modularization and is directly related with the domain of the modularity in design of systems, discussed, e.g., by Pandremenos et al. [22] and Huang and Kusiak [23].

3. Proposed indices for measurement of process modularity

Due to the absence of process modularity measures, we propose to consider and, subsequently, adopt selected product modularity measures for this purpose. They are namely: *Module Independence* (MI), *Average Ratio of Potential* (ARP), and *Singular Value Modularity Index* (SMI).A short description of the indicators is further presented.

3.1. The Module Independence and the Average Ratio of Potential

Blackenfelt [24] proposed two indicators for product modularity measurement:

a) The Module Independence - MI, which is calculated through the formula given below:

$$MI = \frac{\textit{the sum of relations inside all modules}}{\textit{the sum of all relations}}. \quad (1)$$

If MI= 0, then it means full modularity is achieved; if 1, then structure is non-modular.

b) The Average Ratio of Potential. This indicator is expressed as follows:

$$ARP = \frac{\frac{\text{the sum of relations inside all modules}}{\text{the sum of the potential relations inside the modules}}}{\text{the number of modules}} \quad (2)$$

ARP is only modification of indicator MI, therefore, for this reason this indicator will not be further tested for process modularity measurement.

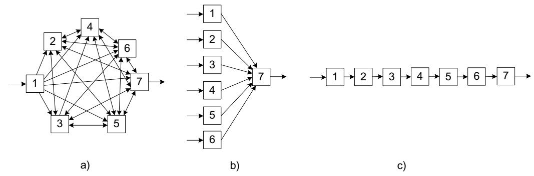

Fig. 1. (a) Fully integral system (INT) that means non-modular system; (b) bus-modular system (BUS); (c) fully modular system (MOD).

3.2. Singular Value Modularity Index

This index called Singular Value Modularity Index denoted as SMI has been used to quantify the degree of modularity of a product on its internal structure [25]. SMI is theoretically bounded between 0 and 1. An SMI closer to 1 indicates a higher degree of modularity. SMI closer to 0 indicates a more integral system. For its enumeration the following formula is used:

$$SMI = 1 - \frac{1}{N \cdot \sigma_1} \sum_{i=1}^{N-1} \sigma_i (\sigma_i - \sigma_{i+1}), \quad (3)$$

where:

N – is the number of components of the system

σ_i– represents singular values, *i=1,2,…, N* ordered in decreasing magnitude.

Holta et al. [25] demonstrated applicability of the index SMI through three typical component structures, which are shown in theFig. 1.

In order to enumerate the modularity index, firstly design structure matrixes are created (see Table 1 a), from which singular values are calculated (see Table 1 b).

Table 1 a) Design structure matrixes; b) Singular values

a)

b)

INT system structure

	1	2	3	4	5	6	7
1	0	1	1	1	1	1	1
2	1	0	1	1	1	1	1
3	1	1	0	1	1	1	1
4	1	1	1	0	1	1	1
5	1	1	1	1	0	1	1
6	1	1	1	1	1	0	1
7	1	1	1	1	1	1	0

σ_1= 6.000
σ_2= 1.000
σ_3= 1.000
σ_4= 1.000
σ_5= 1.000
σ_6= 1.000
σ_7= 1.000

BUSsystem structure

	1	2	3	4	5	6	7
1	0	0	0	0	0	0	1
2	0	0	0	0	0	0	1
3	0	0	0	0	0	0	1
4	0	0	0	0	0	0	1
5	0	0	0	0	0	0	1
6	0	0	0	0	0	0	1
7	1	1	1	1	1	1	0

σ_1= 2.449
σ_2= 2.449
σ_3= 0.000
σ_4= 0.000
σ_5= 0.000
σ_6= 0.000
σ_7= 0.000

MODsystem structure