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Procedia CIRP 41 (2016) 183 – 188

www.elsevier.com/locate/procedia

48th CIRP Conference on MANUFACTURING SYSTEMS - CIRP CMS 2015

Entropy based versus combinatorial product configuration complexity in mass customized manufacturing

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Abstract

Increased product differentiation in the context of mass-customized production causes significant changes in complexity of manufacturing and assembly systems. There are several approaches to defining product variety induced complexity. Our focus in this paper is to describe procedure to calculate product configuration complexity based on the Boltzmann's entropy theory. Proposed approach is applied on a realistic example of mass customized manufacture of washing machines. Subsequently, we compare obtained measures with product configuration measures based on a combinatorial method. On the basis of the computational experiments, strong correlation between the two mentioned approaches has been observed. Finally, obtained findings are commented.

Keywords: Customization; Axiomatic; Assembly; Modelling

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1. Introduction

Due to the shorter product life cycles and increasing trends of global competition, mass customized production (MCP) became one of the pillars of company’s visions. Mass customization was firstly driven and motivated by the opportunities of new flexible manufacturing technology in the early 1990s. The next wave came with the internet boom. So called internet-based mass customization was pushed thanks to the development of online configurators that made mass customization happening in a larger scale. Today's possibilities of mass customized production based on open two-way communication between producers and consumers helps to improve product innovations.

There are a number of definitions trying to describe the meaning of the term Mass Customization. One of them says that MC is a set of technologies and systems producing goods and services based on individual customer requirements [1]. Thorsten and Blecker [2] defines mass customization as a concept in which customer orders are fulfilled from a pre-engineered set of potential product variants that can be produced with a fixed order fulfillment process. However, wide practical application of this strategy is still limited to a certain level because high number of variants causes high complexity. Mass customized strategy is often criticized for the fact that customized production does not bring much bigger profit for the manufacturer compared profit of traditional mass-producer. Therefore MCP may not be the panacea for all organizations. On the other hand PCP brings many benefits to firms in terms of cost and profit because of lower inventory levels, maximum sales, elimination of material waste, high customer satisfaction and good customer retention.

The main motivation of this paper is question of Blecker at al. [3]: “Does the introduction of the new variants induce high complexity and if yes, to which extent?” To find answer to this question, the best first step is to do some research on measures of variety induced complexity in terms of MCP. The aim of this paper is to propose the possible complexity measure based on Boltzmann entropy, which has been adapted by Guenov [4] and to compare this approach with so called Combinatorial Product Configuration.

doi:10.1016/j.procir.2015.12.100

2. Related works

Every product portfolio, these days consists of increasingly complex products and complex product configurations. Business environment is unstable: responsive adaptation of the customized product configuration for higher price in expected quality is the new paradigm. Production systems should be able to cope with increased variety and therefore uncertainty to satisfy the needs of the market. Information support regarding the product variety quantification may help decision-makers at all levels of manufacturing management.

So far, several approaches have been taken in order to assess complexity of the manufacturing system. Different authors focused on partial problems – sources of complexity and covered only a partial manufacturing environment. Complexity of any system is affected by three variables, namely state of the system elements, their number and relationships among them [5]. Different definitions of manufacturing complexity have been provided so far but the very first metric is associated with the Shannon`s information theory [6] related to the amount of information (in bits) in uncertainty of information system. From this approach, it is evident, that the fewer processes, machines and/or product configurations – the lower is the overall complexity of the system. Zhu et al. [7] and Desmukh et al. [8] applied and proposed entropy based measures in terms of assembly in conjunction with part types and derived their own measures to capture the process complexity in manufacturing. Suh [9] defined complexity in relation to product design through achievement of functional and design requirements. Kim et al. [10] introduced number of metrics for complexity on the basis of system components, elements and their relations. These measures cover majority of system elements but cannot be extended to other manufacturing domains except for cell production. Frizelle and Woodcock [11] defined two original types of complexity, static and dynamic currently corresponding with structural and operational complexity. Their metrics have been further applied and even developed in the works of other authors [12-16].

Only few authors [17-19] discussed complexity sources in terms of mass customization. Therefore, structural view on the mass customized manufacturing and its product complexity is the main objective of this paper.

3. Generation of all possible product configurations – methodological framework

3.1. Basic elements and preconditions

Based on our previous works [20-22], a methodological framework for generation of all possible product configurations can be presented. The framework assumes the existence of three types of so called entry components, namely stable components ’*i*’, voluntary components ’*j*’ and compulsory optional components defined by variables “*k*” and “*l*” according to combinatorial number $\binom{k}{l}$, where “*l*” is number of selected items from a collection ’*k*’, such that (unlike permutations) the order of selection does not matter. Then, configuration requirements in relation to mass customized assembly (MCA) process can be specified using these elements. Moreover, the following preconditions of MCA are assumed:

- These three types of input assembly components are defined within a single assembly node;
- The term „component“ can be understood as a physical part, property or function of the finalized product;
- MCA consists of number of assembly stations, so called nodes, localized within the multi-level network ’*r*’ where $r = 0, 1, 2, 3, ..., m$;
- If within a single assembly node is defined collection of k components, then it is allowed to select maximum $l = k – 1$ compulsory optional components and minimum $l = 1$. The summary condition is then $1 \leq l < k$;
- Set of assembly operations performed on nodes result with number of product configurations. In order to simplify a graphical representation of all possible configurations, we model on the exit from assembly node only one (customer selected) configuration as single stable component.

As it has been mentioned in the preconditions of MCA above, three types of initial assembly components can be described in detail as follows:

- Stable component ’*i*’ is the core initial assembly element and its specification and number is strictly defined, therefore no other component choice is possible; Stable component may occur as a pre-assembled component or part, standard stable component or as a set resulting component of node assembly on exit from assembly node;
- Unlimited number of stable components ’*i*’ may be further assembled with voluntary components ’*j*’. The selection of these components is voluntary (it is possible that $j = 0$).

Three types of initial components have been organized and combined using combinatorial rules in order to present a comprehensive model of options in relation to customer within any MCA. Within this conception, company decision-makers and managers are able to decide on the optimal product variety within the existing production structure.

Other generic building elements of the MCA methodological framework are as follows:

- Individual node assembly operations are carried out on layers ’t_r’, where $r = (0, 1, 2, 3, ..., m)$.
- Layers can be identified in each assembly scheme of MCP. Layer tm is the highest layer of the MCA scheme. Previous layers are derived from the final layer and the total number of layers is important when decomposing the scheme and identifying possible component configurations. The final layer of the product assembly scheme is always denoted by t_0. This layer includes final assembly node, and links all previous assembly operations. Hypothetically, layer t_0 is a starting – selection point for customer in MCA.
- Assembly branch ’*b*’ is an important element of any MCA. They are useful in identification and distribution of possible product configurations within assembly process.

Then the total number of assembly branches is equal to number of assembly nodes on the layer t_m.

- Each modular assembly chain can be further decomposed into individual non-modular assembly nodes, which is an essential attribute for future identification of possible product configurations. Decomposition of modular assembly structure into single non-modular/node operations can be seen in Fig. 1.

3.2. Framework Scenario #1 for base and voluntary component

The basic and mandatory attribute of MCA is the composition of input components entering individual non-modular assembly nodes. Each input composition consists of at least one stable assembly component in combination with at least one voluntary component. Let's denote a group of cases with the same number of stable component as class $CL_{1-\infty}$ and group of cases with the same number of voluntary components as sub-class $SCL_{1-\infty}$.The number of stable components is fixed throughout the whole assembly process. In cases when only one stable and one voluntary component enter the MCA process, in principle, we are not talking about standard assembly operation, but since this operation results with two possible product configurations, we may consider them as a choice of components and at the same time configurations, and therefore it is considered as MCA (see CL_1SCL_1).

MCP systems can be divided into make-to-stock MCP, assemble-to-order MCP, make-to-order MCP, engineer-to-order MCP, and develop-to-order MCP. The focus of this paper will be on assemble-to-order production.

Each component configuration can be assigned by a number of product variants but it has already been proven that from a practical standpoint, component configurations are much more important than component variants [23]. To prove the practical relevance of component configurations, it was necessary to investigate their dependence on the number of stable and voluntary components. For this purpose, summary fragment table of Framework Scenario #1 with product configurations and variants for product classes CL_1 to CL_6 can be used.

3.3. Framework Scenario #2 for base, voluntary and compulsory optional components

On the base of above presented Scenario #1 methodology, methodological framework for identification of all possible product configurations is different than previously published works, since another type of optional component have not yet been considered. Therefore, theoretical assumptions of the Framework Scenario #1 for the generation of all possible product configurations have been defined while compulsory optional components were involved. Assumption of the above presented Framework Scenario #1 methodology underlying our previous work have been extended with new rules while the principle remains on the growing variety defined also as variety induced complexity.

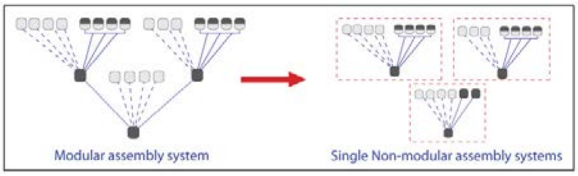


Fig. 1. Decomposition of modular assembly into non-modular assembly systems.

For the new component – compulsory optional component, there are three possible, so called selection rules when identifying different combinations:

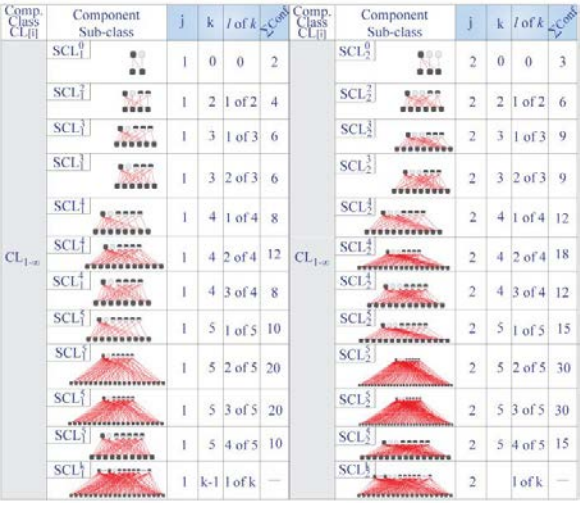
- Definition of exact number of components '*l*' to be chosen from a collection of compulsory optional components '*k*' (Individual selectivity rule): exactly *l* of *k*;
- Maximum number of components '*l*' to be chosen from the available compulsory optional components '*k*' (Maximum selectivity rule): max. *l* of *k*;
- Minimum number of components '*l*' to be chosen from the available compulsory optional components '*k*' (Minimum selectivity rule): min. *l* of *k*;

In order to present the framework, a summary fragment table of the Framework Scenario #2 with component configurations of product classes CL_1 to CL_6 can be seen in Fig. 2.

4. Entropy based product configuration complexity

Configurations of product in terms of MCP can be also modeled by means of axiomatic design. In such a case we transform the specific customer product requirements into a design solution in the form of customized product.

According to the Axiomatic design (AD) definition [9], design process is present in four main domains: customer, physical, process and functional. After several iterations, design process transforms customer needs (CN) into functional requirements (FR) and constraints (Cs), which are



Comp. Class CL[i]	Component Sub-class	j	k	*l* of *k*	ΣConf	Comp. Class CL[i]	Component Sub-class	j	k	*l* of *k*	ΣConf
$CL_{1-\infty}$	SCL_1^0	1	0	0	2	$CL_{1-\infty}$	SCL_2^0	2	0	0	3
	SCL_1^2	1	2	1 of 2	4		SCL_2^2	2	2	1 of 2	6
	SCL_1^3	1	3	1 of 3	6		SCL_2^3	2	3	1 of 3	9
	SCL_1^3	1	3	2 of 3	6		SCL_2^3	2	3	2 of 3	9
	SCL_1^4	1	4	1 of 4	8		SCL_2^4	2	4	1 of 4	12
	SCL_1^4	1	4	2 of 4	12		SCL_2^4	2	4	2 of 4	18
	SCL_1^4	1	4	3 of 4	8		SCL_2^4	2	4	3 of 4	12
	SCL_1^5	1	5	1 of 5	10		SCL_2^5	2	5	1 of 5	15
	SCL_1^5	1	5	2 of 5	20		SCL_2^5	2	5	2 of 5	30
	SCL_1^5	1	5	3 of 5	20		SCL_2^5	2	5	3 of 5	30
	SCL_1^5	1	5	4 of 5	10		SCL_2^5	2	5	4 of 5	15
	SCL_1^k	1	k-1	1 of k	—		SCL_2^k	2		1 of k	—

Fig. 2. Fragment of Framework scenario #2 for product classes $CL_{1-\infty}$.

later transformed into design parameters (DP). Within a design hierarchy, the dependencies between the FRs and DP can be represented by the following equation:

$$FR = [A]DP, \tag{1}$$

where each element of the matrix [A] can be expressed as coupling of each FR with each DP. Equation 1 can be understood as choosing the right set of DPs to satisfy given FRs. Therefore each element of the matrix indicates dependency of FR on DP. If the value of any interaction element refers to ’0’, then FR does not depend on the DP, and vice versa for ’X’. Depending on the type of the resulting design matrix [A], three types of designs exist: uncoupled, decoupled and coupled design. In our approach the coupled design will be employed.

In order to transform individual non-modular assembly nodes into such design matrix the following procedure will be used. Let’s say we have, according to FS1, two stable (S) and two voluntary components (VO), then number of resulting configurations equals 4 (see Fig. 3 a). For this module, we categorize 4 FRs and 3 DPs (see Fig. 3b). The number of DPs equals 3 because all stable components are represented by single - joint DP. Subsequently, coupled design matrix for this composition of initial assembly components and related product configurations can be created (see Fig. 3c).

4.1. Proposed approach to measure configuration complexity through Boltzmann's entropy

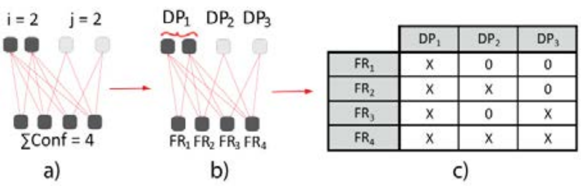
The newly applied complexity measure developed by Guenov [4] is based on AD principles and is originally derived from Boltzmann's entropy (see e.g. [24]). Guenov proposed, in this context, three complexity indicators. One of them (so called Systems Design Complexity (SDC)) measure, is the most suitable to measure product configuration complexity. It can be expressed as follows:

$$SDC = \sum N_j ln N_j, \tag{2}$$

where N_j represents number of couplings per single design parameter.

Then, for each assembly sub-scenario with all three component types and for arbitrary $CL_{1-\infty}$, a SDC value can be determined. Selected results for $CL_{1-\infty}$ are shown in Table 1 to compare SDC value with related product configurations.

4.2. Feed and transfer complexities



	DP₁	DP₂	DP₃
FR₁	X	0	0
FR₂	X	X	0
FR₃	X	0	X
FR₄	X	X	X

Fig. 3. Transformation of assembly node with 2S and 2VO components into a coupled design matrix.

Table 1. Fragment of CC and SDC values for one and two VO components

S	VO	CO	Condition for CO	ΣConf	SDC
$CL_{1-\infty}$	1	0	0	2	1,4
		2	1 out of 2	4	9,7
		3	1 out of 3	6	18,2
			2 out of 3	6	30,7
		4	1 out of 4	8	27,7
			2 out of 4	12	83,6
			3 out of 4	8	65,2
		5	1 out of 5	10	38,0
			2 out of 5	20	166,1
			3 out of 5	20	232,0
			4 out of 5	10	114,3
		6	1 out of 6	12	48,9
			2 out of 6	30	280,8
			3 out of 6	40	567,7
			4 out of 6	30	502,1
			5 out of 6	12	178,7
		o	*l* out of *k*	-	-
	2	0	0	3	6,1
		2	1 out of 2	6	28,4
		3	1 out of 3	9	51,2
			2 out of 3	9	73,5
		4	1 out of 4	12	76,3
			2 out of 4	18	190,8
			3 out of 4	12	142,2
		5	1 out of 5	15	90,4
			2 out of 5	30	371,0
			3 out of 5	30	482,0
			4 out of 5	15	235,8
		2	1 out of 6	18	131,4
			2 out of 6	45	619,1
			3 out of 6	60	1153,0
			4 out of 6	45	987,6
			5 out of 6	18	355,4
		0	*l* out of *k*	-	-

According to Hu et al. [25], complexity of individual assembly stations is obtained as a weighed sum of complexities associated with every upstream assembly activities, as can be seen in Fig. 4. Feed complexity exists due to the product configurations added on the previous stations and these affect subsequent processes at stations and configuration selections.

According to the previous scheme, transfer complexity C_{01} can only flow from upstream to downstream, but not in the opposite direction. So called feed complexity C_{11} can only be added at a current station without any transferring behaviour. Then the total complexity is always the sum of feed/node complexity and transfer complexity from all upstream assembly stations. The principle is further applied on the calculation total model complexity for SDC measure. Configuration complexity adopts the multiplication principle of upstream and downstream stations till the lowest layer model decomposition.

Fig. 4. Complexity aggregation according to [25].

5. Case application of entropy-based and combinatorial product configuration complexities

In order to proof the relevance of the above presented methodological framework and new complexity principles, the proposed measures have been applied and verified on a model of washing machine MCA (Fig. 5). Customized assembly branches on the basis of two determining stable input components A_1 for top-loading and A_2 for front-loading machine option. The second type is voluntary component $B_{1\text{-}3}$, $C_{1\text{-}4}$, $D_{1\text{-}4}$, $E_{1\text{-}3}$, $H_{1\text{-}2}$, $I_{1\text{-}2}$ and they offer so called standard option. This option is automatically selected in cases when any of the non-standard options is selected. The last component type – compulsory optional $F_{1\text{-}4}$, $G_{1\text{-}5}$ are components with obligation to choose at least one component option of all possible within appropriate assembly module.

5.1. Comparison of case assembly branches

The attention was focused on transformation of the case application on a structured assembly model where individual branches and assembly nodes are represented by appropriate Configurations complexity (CC) and AD based SDC values from upstream stations up to the final station. Subsequently, value of CC and SDC have been determined for 3 selected branches, as depicted in Fig. 5 and Fig. 6. The three observed case assembly branches can be seen in Fig. 6.

On the basis of the above described methodology on CC and newly provided AD based measure principles, an important attribute regarding the complexity values have been obtained.

As can be seen on the three graphs in Fig. 7, Fig. 8 and Fig. 9 for CC and SDC values, complexity reaches the highest values towards downstream stations The only difference between the two measures is that the CC, or number of available product configurations is multiplied by the subsequent downstream product configurations and therefore, CC complexity curves grow exponentially larger than curves of SDC which grow incrementally due to addition of only feed complexity to the upstream transfers.

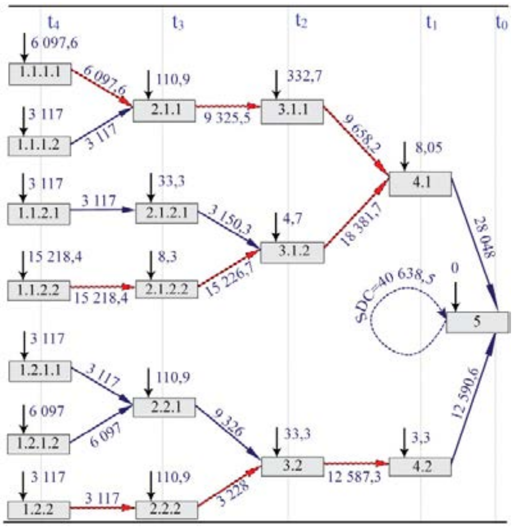


Fig. 6. Summary feed SDC values of the MCA model.

5.2. End-station values of CC and SDC

Finally, summary values of CC and SDC have been obtained. It has been performed through the application of the above mentioned principles for cumulating SDC values from entry station at layer t_4 to the lowest layer of the model t_0, as seen in Fig. 6. In case when two or more branches join at a certain assembly node, all upstream SDC transfer values and the feed complexity are summed at this node. This way a summary value of 40 638,5 bits has been calculated. For the calculation of CC values, the same rules can be applied, except for the summation. When two or more branches are joined at a certain assembly node, all upstream CC transferred values and the appropriate feed complexity are multiplied. Subsequently, a summary value of available product configurations of the case model has been obtained as the sum of both, Branch #1 and Branch #2. The model offers 543 581 819 633 664 configurations in total.

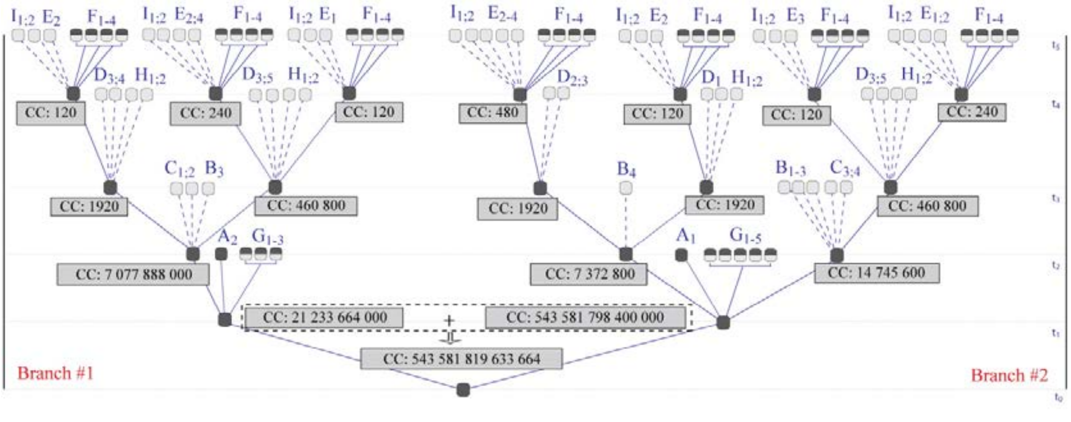


Fig. 5. Model of MCA with CC values for individual nodes and summary CC value.

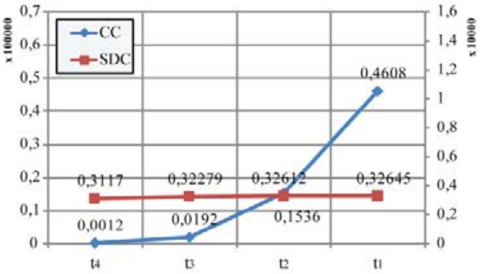


Fig. 7. CC and SDC values of the stations 1.1.1.1; 2.1.1; 3.1.1; 4.1.

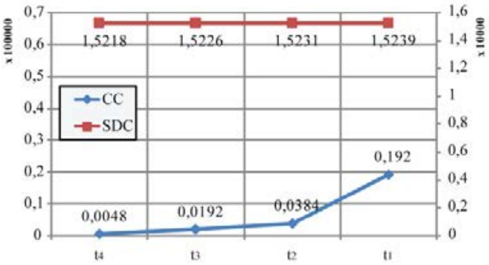


Fig. 8. CC and SDC values of the stations 1.1.2.2; 2.1.2.2; 3.1.2; 4.1.

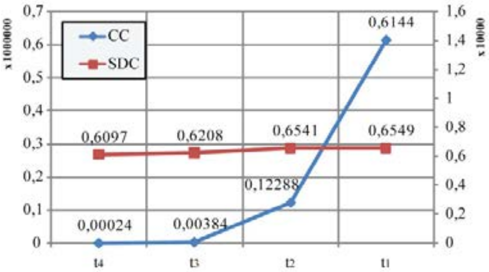


Fig. 9. CC and SDC values of the stations 1.2.2; 2.2.2; 3.2; 4.2.

6. Conclusions

The two individual measures for structural design have been applied and compared in order to catch growing trend of available product configurations or variety in terms of assemble-to-order concept of MCM. Both measures fulfilled two main requirements – simplicity of application and accuracy for early stage of complex systems design and decision-making.

However, based on the comparison of the measures, it is possible to identify significant differences between them. SDC indicator in our case assembly grows incrementally from entry stations at layer t_4 to the lowest layer t_0, what is empirically understandable, while CC indicator is based on multiplications of possible configurations and therefore, grows exponentially. Accordingly, the practicability of SDC is undoubted.

Acknowledgements

This paper has been supported by KEGA project no. 078TUKE-4/2015 granted by the Ministry of Education of the Slovak Republic.

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