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# Using Axiomatic Design and Entropy to Measure Complexity in Mass Customization

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**Abstract**

Nowadays, complexity issues in mass customized manufacturing are considered as topical problem. Especially, product variety induced complexity is frequently discussed in recent research works. Our focus in this paper is based on an exploration of product variety induced complexity based on axiomatic design and entropy theories. For this purpose we propose to adopt previously developed complexity measures based on so called degree of disorder. Our approach consists of transformation of graphical representation describing relation between input components of assembly node and numbers of related product configurations into design matrix of coupled design. Subsequently, we apply the measures to enumerate product variety induced complexity. Finally, we analyze mutual relations between numbers of possible product configurations and obtained values of the complexity measures.

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*Keywords:* Product configuration; Axiomatic design; Degree of disorder

## 1. Introduction

Mass customization (MC) strategy is considered to be one of the important contemporary market mentalities, comprising a set of methods and tools, by which manufacturing and service companies can increase their competitiveness and industries can ensure their long-term profitability. The focus of MC strategy is on variety and customization of company product portfolio through flexibility and responsiveness. This can be achieved only with product families and standardized modules ready to be assembled based on customer specifications and requirements. Such an organization must be flexible and adaptive. Manufacturers of customized products are confident that if they find the right balance between product variety offer and customer requirements, it will allow them to maintain or even increase market share. Recent research studies revealed that the increasing number of product alternatives is directly related to an increase of the number of modules integrated into these varieties of products. This fact negatively affects a complexity of the product and generates turbulences in the manufacturing systems, leading to higher direct production costs. Taking this into account, the success of MC strategy depends, apart from other factors, on the balance between product variety induced complexity and usability of mass customized manufacturing system. To solve this problem it is expected to develop suitable methods for the measurement of product variety induced complexity. The main scope of this paper is to propose and describe a model for complexity measurement and investigate the possibilities of using axiomatic design and entropy for quantifying product variety induced complexity. In this context, a methodological framework including definition of minimal preconditions of Mass Customized Assembly (MCA) and suitable complexity measures (Configuration complexity and Axiomatic Design (AD) based complexity) for system designs will be developed in this paper.

## 2. Related work

Mass customized manufacturing is concerned not only with production processes but influences overall set of enterprise processes. Complexity of these processes in terms of MC strategy increases due to higher dynamics of relations among system components. One of the complexity sources lies in the product configuration structure and system design. There are several approaches to explore the impact of a


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product variety on manufacturing complexity, see for example [1-3]. According to the very first complexity theory adopted from information theory by Shannon [4] the most significant source of complexity is entropy. Information entropy is defined as amount of information within a system to describe the uncertainty of system states. When fewer possible states exist less information is needed to describe the system, and therefore there is less uncertainty entropy in the system. People tend to understand complexity in terms physical things, but it must be viewed from the functional perspective or domain [5]. In other words – what we want to achieve as functional requirements (FRs) and how to achieve it through design parameters (DPs). AD theory defines complexity as a measure of unpredictability of the ability to satisfy a given FR [5]. This complexity is present in all systems as a continuum. Any system or product has therefore a minimum set of independent requirements characterizing its functional need.

Applications of AD in various areas of manufacturing, decision-making appeared in literature. A hierarchical knowledge base system has been built with use of independence axiom by Chen et al. [6]. Chuang and Jiang [7] used fuzzy logic as the membership function of DP. Yi and Park [8] developed an application to enumerate and evaluate the design process according to the independence axiom of AD theory. Moreover, a component-oriented approach based on the AD has been proposed and a V-Model was extended to address component-level issues [9]. Finally, Lindkvist and Soderberk [10] applied AD and robust design to compare different assembly concept alternatives. Authors [11-13] proposed complexity/vulnerability indicators intended to measure coupling complexity in design matrices applicable during the early stages of the product design. This paper applies information coupling complexity into variety induced complexity and its management. In this context, according to Matt [14], a significant research has been carried out in the design of assembly systems for high product variety. On the other hand a number of systems have been designed without having a theoretical framework for complexity [5]. Systems where customer requirements are unpredictable are becoming more complicated even with fundamental applications of complexity management in these companies. Complexity is therefore an important problem since out-of-control complexity can bring undesired design consequences and therefore, unsatisfied customer requirements [15]. Manufacturing complexity from design perspective aimed at product alternatives is also a widely discussed topic. Piller [16], for example, proved that the extent of offered variety determines the complexity, which in turn affects the time and additional cost invested in product configurations.

Only a limited number of papers addressed complexity issues in terms of mass customization so far. Therefore, our ambition in this paper is to present an approach to quantify product variety induced complexity based on combinatorial rules and to compare it with complexity based on existing Boltzmann's statistical concept in the design matrix. For this purpose we adopt previously developed complexity measures based on the so called Degree of disorder. In order to compare this approach to complexity with numbers of possible product configurations, we firstly need to describe the way to calculate combinatorial product complexity.

## 3. Combinatorial product configuration complexity

### *3.1. Basic preconditions and notation*

Based on our previous works [17, 18], a methodological framework for the generation of all possible product configurations (PCs) will be briefly outlined. The framework consists of entry components as basic elements for the calculation of PCs. Exactly three types of initial assembly components can be identified within a Mass customized assembly (MCA). A component, in this context can be understood as a part, module, and group of products, property or other characteristic of the final product. Initial assembly components are divided into the three categories, namely stable components, voluntary components and compulsory optional components. Any MCA structure consists of a number of assembly stations – nodes. These can be identified within a multi-level network $t_r$, where $r = 0, 1, 2, 3,\ldots,m$, while $t_0$ identifies a final level of structure. Each assembly node understood as an individual assembly operation results with a single product, but in a long run the same node can produce a number of different product configurations depending on the number and composition of an entry components. Final products in the downstream assembly node are considered as the stable components for s subsequent operations. The number of product configurations brings uncertainty and thus complexity in these systems.

In order to formalize the three types of initial assembly components the following notation can be used:

Stable components and their number '$i$' is an obligatory initial assembly element as they are uniquely determined. An unlimited number of stable components may be further assembled with a number '$j$' of voluntary components. The selection of these components is voluntary (it is possible that $j=0$). A number '$k$' compulsory optional components is limited in selection. They are optional, but with minimum and maximum requirements '$l$' on a selection by customer, where $1 \le l < k$.

Additional individual building elements of a MCA are assembly branches in MCA assembly structure. They are important for identification and distribution of possible product configurations within an assembly process. Assembly branches can be identified on the highest layer of the model decomposition.

The three types of initial components have been combined using combinatorial rules in order to present a comprehensive model of options in relation to customer within any MCA, as presented in Fig. 1 in the form of bipartite graph. Based on this model, company decision-makers and managers are able to decide on the optimal product variety within an existing production structure or design.

### *3.2. Methodological Framework Scenario #1(FS1) for base and voluntary optional components*

The basic precondition of any MCA is the composition of initial assembly components on entry to assembly node-