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Reliability-oriented complexity analysis of manufacturing systems based on fuzzy axiomatic domain mapping

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Abstract

Decreasing the complexity is the effective way to improve the reliability of manufacturing systems. However, the research on the reliability oriented complexity analysis for manufacturing system is rare. A reliable manufacturing system is a prerequisite to ensure the well-designed products be manufactured faultlessly. In this context, this paper proposes an axiomatic complexity analysis model of manufacturing system based on the fuzzy axiomatic domain mapping. Firstly, in terms of the uncertainty of domain mapping information, the fuzzy evaluation matrix for complexity which integrated the weights of experts is constructed based on triangular fuzzy numbers. Secondly, considering the influence of the design parameters (DPs) on the functional requirements (FRs), a quantitative computation approach to manufacturing system complexity is achieved by means of fuzzy evaluation matrix. Finally, a case study is presented to illustrate the validity of the proposed method.
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1. Introduction

Complexity continues to be one of the biggest challenges faced by the modern manufacturing today. A reliable manufacturing system is a prerequisite to ensure that well-designed products can be manufactured in faultlessly [1]. With the dynamic development in customer demands and design techniques, the complexity of manufacturing systems is also increased accordingly in both physical and functional domains [2]. Decreasing complexity is an effective way to improve reliability of manufacturing systems [3,4]. Therefore, the complexity analysis of manufacturing systems has been extensively studied by many scholars.

Researchers have studied the complexity of manufacturing systems from different perspectives. Taking into account that the layout of manufacturing systems determines its structural complexity, Elmaraghy et al. [5] proposed a model which is used to evaluate the structural complexity of manufacturing systems layout in the physical domain. Samy et al. [6] developed a new system granularity complexity index, which could sum up and normalize the complexity resulting from the system layout complexity and the equipment structural complexity. Bozarth et al. [7] analyzed the impact of supply chain complexity on the performance of manufacturing systems. Hu et al. [8] defined complexity as an entropy function and proposed a unified measure of complexity to assist in designing multi-stage assembly systems with robust performances. Shannon's information theory/entropy approach provides a new way for complexity modeling and commonly used as the underlying basis for quantifying the complexity [9]. From the view of information theory, many studies have analyzed the complexity of manufacturing systems [10,11]. With all the documents mentioned above, not only is the meaning of complexity of manufacturing systems defined from multiple viewpoints, but also the complexity of manufacturing systems is described qualitatively and quantitatively by analyzing the relationships among equipment, components, and manufacturing systems. These studies make the research on the complexity analysis of manufacturing systems become scientific and systematic gradually.

Suh [12] presented the Axiomatic design (AD) theory and defined complexity as the uncertainty in achieving the functional requirements that need to be met, which provides a new theoretical basis for complexity analysis of manufacturing systems from the viewpoint of quality design.

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However, in real case problems, the relations between FRs and DPs may be unknown or uncertain, and the expert's descriptions may be fuzzy, which will lead to the uncertainty of the relations between FRs and DPs are difficult to represent rightly. Moreover, conventional qualitative evaluation of the design parameters constrains the designer to understand the complexity of manufacturing systems accurately. And then the reliability-oriented complexity analysis of manufacturing systems is prevented.

As can be seen from the above analysis, complexity breeds couplings and defects, and coupling reduces reliability. Complexity analysis of manufacturing systems can provide feedback and promote the reliability evolution of the manufacturing system. Driven by these requirements, a novel approach to reliability-oriented complexity analysis of manufacturing systems based on fuzzy axiomatic domain mapping is proposed in this paper.

2. The foundations of complexity modeling for manufacturing systems

2.1. Fundamentals of axiomatic design

The axiomatic design (AD) theory was proposed by Suh [13], which is typically used to guide designers to use all existing design tools to get a successful new design or to diagnose and improve an existing design. AD theory consists of four domains and two axioms. Four domains respectively refer to Customer Domain defined by Customer Attributes (CAs), Functional Domain for defining Functional Requirements (FRs) and constraints, Physical Domain for representing Design Parameters (DPs), and Process Domain for characterization of Process Variables (PVs).

Axioms are widely accepted principles which are fundamental to assure the mapping quality of the four domains. They are stated as follows:

Axiom 1：Independence axiom

Maintain the independence of the FRs.

Axiom 2：Information axiom

Minimize the information content of the design scheme.

Independence axiom, the first axiom of the AD principles, is about maintaining the independence between FRs. The mapping relationship between FRs and DPs can be expressed as:

$$\{FRs\} = [A]\{DPs\}, \quad A = [A_{ij}]_{m\times n} \tag{1}$$

$$A = \begin{bmatrix} A_{11} & A_{12} & \cdots & A_{1n} \\ A_{21} & A_{22} & \cdots & A_{2n} \\ \vdots & \vdots & \cdots & \vdots \\ A_{m1} & A_{m2} & \cdots & A_{mn} \end{bmatrix} \tag{2}$$

$$A_{ij} = \frac{\partial FR_i}{\partial DP_j} \tag{3}$$

where $\{FRs\}$is the collection of FR vectors, $\{DPs\}$are the collection of DP vectors, and $[A]$ is the design matrix.

Information axiom, the second axiom of the AD principles, is about minimizing the information content of the design. Since the information content is determined by probability. The axiom also shows that the design with the highest probability of success is the best [14]. The positive significance of the information axiom lies in that it has provided a criterion for evaluating the quality of design. If the probability of success for a given FR is p_i, the information content can be denoted as:

$$I_i = \log_2 \frac{1}{p_i} \tag{4}$$

If there is more than one FR, the information content can be calculated as:

$$I_{system} = \sum_{i=1}^{n} \log_2 \frac{1}{p_i} \tag{5}$$

2.2. Manufacturing systems complexity

Manufacturing system complexity is usually divided into dynamic complexity and static complexity. The dynamic complexity is mainly related to real-time operation and material flow pattern, which emphasizes the complexity of the operating state of manufacturing systems [15]. However, in the design stage of manufacturing systems, its complexity is mainly characterized by the static complexity that determined by system structure and components. The focus of this paper is on the mapping relationship between the functional domain and the physical domain in the design process, namely the static complexity.

The complexity of manufacturing systems increases with the increase of the coupling degree and uncertainty. A higher complex system often requires a larger amount of information to describe the system state. That is, an increasing complexity of a system, through increased coupling, variety, and uncertainty, will increase its information content [14]. Therefore, the complexity of manufacturing systems could be measured by the information content.

2.3. Fuzzy axiomatic domain mapping theory

The relation matrix which is used to characterize the correlation between functional requirements and design parameters consists of “0” and “1” . Those symbolize whether there are relations between FRs and DPs. However, in dealing with practical problems, there is always a potential or very small or indirect relationship or even an unknown relationship between an *FR* and a *DP*. And the descriptions of these relations are often fuzzy, such as medium, higher, lower, very high and so on. In order to clearly express and make full use of these fuzzy information, fuzzy axiomatic domain mapping theory, a better solution to the problem of fuzzy information in evaluation and decision-making is proposed, which refers to adopt the triangular fuzzy number method into the “Zig”

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