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Product element sensitivity measurement under multiple exogenous uncertainties considering change propagation behavior

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Abstract

In the flexible design for a complex product, it's necessary to identify the product element's sensitivity to multiple exogenous uncertainties at initial design stage. In the traditional method, relation transitivity is a basic assumption in the change propagation network. This assumption is not always a realistic situation in the product system design. In order to make the sensitivity parameter better reflect the change propagation behavior, this paper provides a sensitivity identification method based on the Multi-Domain Matrix (MDM). A change attenuation parameter is introduced, and the combined influence matrix of the MDM is obtained using the powers of the MDM. Based on the combined influence matrix, the sensitivity value of a product element to all exogenous factors is obtained. A case study on the design of a High Speed Rail (HSR) system is used to illustrate the application of this approach. Results show that the proposed approach can identify the sensitivity of a product element more reasonably.

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Keywords: sensitivity; exogenous uncertainty; change propagation ; multi-domain matrix(MDM)

1. Introduction

Complex products inevitably face various exogenous uncertainties during their long lifecycles. These uncertainties come from user context, market as well as political and cultural context [1,2]. In order to deal with these exogenous uncertainties, flexibility has become an increasing important design criterion in the system initial design process. Flexibility in system enables a product to change easily in the face of uncertainty [1,3]. In fact, flexible designs are widely in many real world applications, such as flexible product platforms [4,5].

Flexible systems can be obtained by incorporating flexibilities within the physical components of system. These physical components are called flexible design opportunities [6-8]. A vital aspect in the flexible design is to identify these flexible design opportunities. It means that designers should identify the most sensitive product elements under uncertainties and limit their resources in the selected system elements in the subsequent design phase.

There are several Design System Matrix (DSM) -based methods to identify flexible design opportunities [6-8]. These include Change Propagation Analysis (CPA) [5], sensitivity Design Structure Matrix [9], and Engineering System Matrix (ESM) [10]. Although these works have attempted to address the issue of identifying flexible design opportunities, they do have some limitations [7,8]. First of all, these methods don't take into consideration the indirect influence relationships. Second, these methods only consider one main uncertainty source. Further research is needed to understand how to identify flexible design opportunities when multiple uncertainties are considered simultaneously.

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Hu and Cardin use the Bayesian Network (BN) to model complex change propagation and capture flexible design opportunities effectively [11]. This method can analyze indirect influences of changes, and can analyze multiple exogenous uncertainties at the same time. However, this method cannot deal with loops in change propagation due to the limitation of the BN. Also, this method needs exact influence relationship values available.

Hu and Poh [7] develop a sensitivity-based method for the identification of flexible design opportunities. In this method, the design variables, external factors and relationships between them are represented by a directed network. The arcs in the network represent binary relationships. This method identifies flexible design opportunities based on whether a design variable of the system is sensitive to external uncertainties or not. In other words, if the design variable is reachable by exogenous factors, it will be considered as a potential flexible design opportunity in design process. A Depth-First-Search (DFS) based algorithm is presented to quantitatively measure the sensitivity of each design variable for engineering system design. This method is applicable for the case in which exact weighted change propagation relationships are not available. However, this method is based on an assumption that the network or graph is transitive. This assumption leads to some limitations. First, in the definition of sensitivity of the design variable, change propagation decay is not considered. In fact, change propagation decay phenomena are common in complex engineering domains, because many products are designed to include certain tolerance margins which can absorb some degree of changes [12]. Second, this method doesn't consider the fact that if there are more propagation chains from a node *j* to node *i*, the sensitivity of node *i* to node *j* tends to be stronger. As a result of these limitations, too many product elements maybe have the highest sensitivity value, and too many product elements maybe have the same sensitivity value. These limitations make this method ineffective in some cases.

In order to make the sensitivity parameter better reflect the change propagation behavior, this paper improves the sensitivity identification method by Hu and Poh [7]. Inspired by the Katz's centrality measure [13], this paper introduces the concept of attenuation in change propagation. Katz's centrality is often used in social network to identify important nodes. In the deduction of Katz's centrality, the matrix powers and attenuation parameter are used. In this paper, the matrix powers and attenuation parameter are used to obtain the sensitivity strength of a node to another. Just like Hu and Poh's work, this method only deals with unweighted networks, so it cannot model the change propagation behavior exactly. However, it can reflect the change propagation behavior to a degree. It's intuitive and helpful to identify sensitive product elements in the initial design process.

The remainder of the paper is structured as follows. In section 1, the change propagation network and sensitivity are introduced. The proposed method is presented in Section 2. In Section 3, a High Speed Rail (HSR) case is used to illustrate this method and results are discussed. Finally, Section 4 concludes the paper.

2. Change propagation network and sensitivity

In order to explain sensitivity, the digraph is used to model the dependency relationships between system elements and exogenous factors. As for a product, a system element means parts, sub-assemblies, sub-systems or other design variables. Fig. 1 shows a digraph representation of a generic product. Nodes c_1 , c_2 ,…, c_n represent the elements in the product system, while nodes ef_1 to ef_m stand for exogenous uncertainties.

The arcs in the digraph represent the direct influence relationships. For example, the arc between ef_m and c_3 represents that the element c_3 need to be changed due to the effect of changing the exogenous factor ef_m; the arc between c_2 and c_3 represents their direct influence relationship in the product system boundary.

In fact, a node in the graph can be influenced by another node through indirect connections. For example, In Fig. 1, c_3 is influenced by ef_3 through c_2. Thus, a system element may be sensitive to exogenous factors through direct or indirect connections.

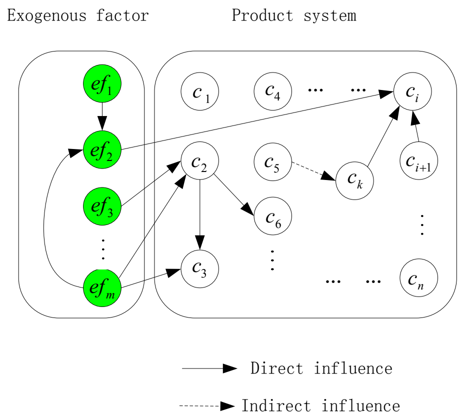

Fig. 1. Digraph about product system and exogenous factors (adapt from [7])

Suppose that a product consists of n elements, $C=\{c_1, c_2 ,…, c_n\}$. Meanwhile, m exogenous factors are analyzed, $EF=\{ef_1, ef_2 ,…, ef_m\}$. Let G be a digraph, $G = (V,E)$ representing the system, where $V = C \bigcup EF$. If $(v_i,v_j) \in E$, where $1 \le i \le (n+m)$, $1 \le j \le (n+m)$, $i \ne j$, there is an arc from v_i to v_j. This arc means that if a unit change Δv_i occurs, the element v_j will need to change to facilitate this perturbation in v_i.

Definition 1 [7] : If ($\Delta v_i \neq 0$), then ($\Delta v_j \neq 0$). The node v_j is sensitive to the node v_i in this situation.

The sensitivity value is related to 2 factors: the number of change propagation chains and the step numbers or lengths of these change propagation chains. Here "chains" equal to