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Modeling and performance analysis of product development process network

Leijie Fu, Pingyu Jiang*, Wei Cao

State Key Laboratory for Manufacturing Systems Engineering, Xi'an Jiaotong University, 710049 Xi'an, PR China

A R T I C L E I N F O

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A B S T R A C T

Product development process (PDP) is a complex system, in which design activities and design resources are connected to each other according to specific rules. Considering the elements of PDP (complex forms of design activities, interdisciplinary collaboration and multiform resources) and relationships between them, a product development process network (PDPN) is proposed and its performance is further analyzed and optimized. In order to establish the PDPN, design activities and resources used in the PDP are mapped into the nodes of the network. And the relationships among the nodes are mapped into the edges. Then, a level-based evaluation model is proposed to illustrate the forming procedure of establishing the PDPN. Then, some typical topological and physical characteristics of the PDPN are defined and analyzed based on the complex network theory. In order to balance the resource load, the PDPN is divided into different communities, wherein a Girvan–Newman (GN) algorithm together with improved measure criterion is applied. Finally, the design process of a steam turbine rotor is chosen as an example to illustrate the feasibility and availability of the proposed method.

1. Introduction

Product development process (PDP) is considered to be a specific process of converting customers' need into a technical and commercial solution (Whitney, 1990). Each PDP is unique, but they may share some common features or elements. Therefore, it is important to model and simulate PDP with the purpose of guiding the management of future product development process (Smith and Morrow, 1999). Accordingly, an increasing amount of attentions has been paid to the construction of PDP models. Many different types of models have been found in literature, such as PERT/CPM, SADT/IDEF0, Petri net, signal flow graph, design roadmap, DSM, etc. Based on these models, PDP performances such as iteration, time, efficiency, etc., have been discussed from different perspectives in order to analyze PDP and improve its efficiency. Actually, all this research has made a great contribution to the further study of PDP.

PDP can be divided into several phases, and each phase can be decomposed into a large number of design activities. Therefore, PDP can be considered as a large, complicated and unstructured network. Actually, not only the design activities but also other elements such as human resource, hardware resource, software resource, knowledge resource, etc., are involved in PDP which are neglected in the traditional research and models. As a result, these models cannot reflect the real situation of PDP and their solution turn out to be incomplete. For example, only design activities or human resources are mentioned in the Petri net. This weakness results in an information loss of PDP, which means only partial information can be obtained in this process. Performance analysis and optimization is another important aspect of PDP research. Traditional research is incomplete in this aspect because of the neglect of resources and the relationships among them. In fact, the resources and relationships play important roles in PDP from the management viewpoint. Taking resources and relationships into consideration, PDP can be described as a more complex network than the conventional ones mentioned above. The complexity of the network structure makes it is hard to analyze and optimize its performance by using the traditional models. Therefore, some new methodologies dealing with this problem from the complex system viewpoint are needed, such as the complex network theory.

To this end, a new model for PDP called the product development process network (PDPN) is proposed in this paper, which is constructed based on the complex network theory. First, resources involved in the PDPN are investigated from previous studies and experience, which can be classified into three groups, namely human resource, tool resource and knowledge resource. According to the classification, design activities and resources are

* Corresponding author. Tel.: +86 29 82663681.
E-mail address: pjiang@mail.xjtu.edu.cn (P. Jiang).

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abstracted as the nodes of the network. Different relationships among the design activities and resources are abstracted as the edges. The generation rule and formation description of the PDPN are defined based on relation algebra. Then, several typical topological and physical characteristic indicators are defined in order to present the PDPN performance. Furthermore, with the purpose of optimizing the performance of the PDPN, the PDPN is divided into communities by using the original GN (Girvan–Newman) algorithm with the physical-characteristic-based criterion. Finally, on the basis of a case study, we discuss how the proposed method simulates the product development process, analyze and optimize the performance of the PDPN.

The rest of this paper is organized as follows. After a brief review about the related fields of PDP and its applications to indicate the background and motivation of this research in Section 2, the construction process of PDPN, such as the elements, formation description and generation rules are put forward in Section 3. And then, Section 4 shows the topological and physical characteristics of PDPN which are used to describe the performance of the network. In Section 5, an improved GN algorithm is proposed for the community detecting with the purpose of PDPN performance optimization. In Section 6, the design process of a steam turbine rotor is chosen as an example to illustrate the feasibility and availability of the proposed method. Finally, some analysis and discussions are drawn in Section 7 and the conclusions and future works are summarized in Section 8.

2. Literature review

A number of articles about PDP performance analyzing models have appeared in literature, which can be classified into two groups namely graph-based models and matrix based models (Jun and Suh, 2008). The graph-based models mainly include PERT/CPM (Project Evaluation and Review Techniques/Critical Path Method), SADT/IDEF0 (Structure Analysis and Design Techniques/Integration Definition for Function Modeling), signal flow graph, design roadmap, Petri net, etc. The PERT/CPM method developed in 1950s is an efficient tool for PDP modeling, in which nodes represent task completion milestones and arcs represents individual tasks. This model is useful for capturing the requiring time to reach each milestone for detecting the critical path, but regrettably with the limitation that cannot represent circuits (Wiest and Levy, 1969). SADT/IDEF0 was proposed in 1970s. Although it is widely used to document complex process, it is difficult to maintain and prone to ambiguous interpretation (Park and Cutkosky, 1999; Ross, 1977). In order to analysis the iteration characteristics of PDP, the signal flow graph model was proposed, in which the probability analysis of lead time was computed and the key divers of lead time were identified (Eppinger et al., 1997). Park reported a model named “design roadmap” to describe the large-scale PDP in which numerous tasks were involved. The key representation of this model is a graph of information-processing units with explicitly defined input and output feature units (Park and Cutkosky, 1999). These models can only reflect part characteristics of PDP. With the purpose of making an exact and full description of design process, Zu proposed an improved Petri net model called “Hierarchical Time Colored Petri Nets (HTCPN)”. Some characteristics of modern product development pattern were discussed in this model, especially temporal dependencies (Zu and Huang, 2004). DSM (Design Structure Matrix) is the most representative matrix-based model for PDP. Maria proposed a model to estimate PDP over time based on the DSM model, which captures the information between tasks by using the concept of probability of change and impact (Carrascosa et al., 1998). Steven used a matrix to capture the sequence of and the relationships among the design tasks. These relationships were analyzed to find the alternative sequences and/or definitions of the tasks to improve the development efficiency (Eppinger et al., 1994). Smith proposed the work transformation matrix (WTM) model based on DSM too. It represents the strength dependence between two activities with off-diagonal elements of a matrix as well as execution time of each activity with diagonal elements (Smith and Eppinger, 1998). There is still a kind of limitation of these models based on DSM, however, is that it is difficult for the uninitiated to understand the PDP. A conclusion can be drawn from the reviews that the traditional models have a common weakness, that each of these models emphasize emphasizes only one aspect of the PDP at the expense of neglect others. This weakness leads to the difficulties in representing the elements and relationships of PDP in analyzing and optimizing its performance.

Although Jun describes PDP as a complex network, there is still very little research treating this problem from the complex system viewpoint (Jun and Suh, 2008). Actually, PDP is constructed by complex forms of design activities, interdisciplinary collaborations and multiform resources. Due to its complexity, a new method based on the complex theory is needed for the PDP modeling, performance analyzing and optimization. As an efficient method for complex system analyzing, the complex network theory (CNT) has been widely applied in different fields in the past decades, such as social networks, information networks, biological networks, electrical transmission network, etc. (Barabasi and Albert, 1999; Boccaletti et al., 2006; Newman, 2003; Rosato et al., 2007; Watts and Strogatz, 1998). Although did not relate to PDP fields directly, some applications can be found based on CNT. Shiau proposed a distributed change control workflow model to control the continuous changes in design projects. This model is a two-layer approach derived from the principles of configuration management and routing algorithm (Shiau and Wee, 2008). A complex weighted network is proposed by Sun in order to describe and analyze mobile collaboration space. The terminals were regarded as the nodes and the relationship between them as the edges in this model; some indicators such as node strength, cluster coefficient and other parameters are defined and calculated to monitor the collaborative space (Sun and Jiang, 2006). Jiang reported a new method for system safety based on the complex network theory after analyzing the structure vulnerability of the process industry system. This model enables the operators to find the critical node and the crisp of the process industry system for design the system of the safety control and failure prevention (Jiang et al., 2007). Although some researchers have applied the complex network theory on PDP related fields, few works have been published on the PDP modeling, performance analysis and optimization by using it directly.

In conclusion, from the brief literature review of the relate aspects, two points can be made as follows:

1. PDP can be described as a complex network in which not only design activities but also other elements (human resource, toll resource, knowledge resource, etc.) are involved in. These elements and relationships among them which play important roles in PDP are ignored in traditional research. This lack results in an inaccuracy in the PDP performance analyzing and optimization.
2. The complex network theory is considered to be one of the most effective tools in complex systems analyzing. Some beneficial attempts have been made in the research of using CNT in the fields of collaborative design, mobile collaborative network, etc. However, few studies have been reported on