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An expert system using rough sets theory and self-organizing maps to design space exploration of complex products

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ABSTRACT

In complex product design, product performance driving design is a new and innovative research in the engineering field. For realizing the product performance driving design, an elaborated expert system, Expert Systems for Assisting Mapping from Performance Space to Design Space (ESMPD) is proposed, which have two main modules for mapping from product performance space to interesting design space by two layers mapping method. In Rough Sets Theory Analysis Module, Rough Sets Theory (RST) is used to calculate configuration rules in incomplete configuration information system to assist product designers in mapping performance space to configuration space. In self-organizing maps Analysis Module, SOM is employed to analyze design variables and objective function based on preliminary optimization, to mapping from the fixed configuration space to smaller interesting regions in design space. The contribution of this research is utilizing the product design knowledge to guide engineer to partition and reduce the design space, which can save product design time and promote the design efficiency. Finally, a new bulk carrier design is taken as a case study to prove the validity and necessity of this expert system. The detailed analysis testifies ESMPD can effectively facilitate rapid and intelligent design, and reduce the cost of complex product design.

1. Introduction

In practical engineering field, complex products/systems such as automobiles, aircrafts and ships are usually quite difficult to be configured and designed, because a large amount of multidisciplinary knowledge and expertise must be mastered by designers, and huge design space must be exploited entirely to get appropriate design solutions. During the two decades, many methodologies and methods have been developed and innovated in complex product design. Multidisciplinary design optimization (MDO) is an effective approach to design and optimize complex products or systems with coupled design functions and variables in a large design space from different disciplines (Haftka & Watson, 2005; Weck et al., 2007), Pareto Frontier is utilized for solving multi-objective optimization problems in MDO (Baykasoglu, Oztas, & Ozbay, 2009; Kim & Weck, 2006), and approximation models are employed in complex product design to reduce expensive computation of the extremely complicated design problems (Kleijnen, 2007; Li, Li, & Azarm, 2008; Wang & Shan, 2007). In substance, these methodologies belong to optimization processes in which mathematical methods are used to search the best result of object function within a model.

However, traditional design optimization processes are usually blind to engineers, and optimization results are only given to engineers directly. In addition, ordinarily, these results are unacceptable, for the limitation of the engineering practice. Thus, designers prefer to know the whole optimization process in detail. In other words, design optimization is urgently needed to be transparent and adjustable, in which expert experience is extracted to achieve the goal of intelligent design.

Furthermore, in traditional optimization, a sampled point is randomly selected to start searching process, and then performance of this solution is evaluated (Shan & Wang, 2004). It starts from design space (design variables and their values) to performance space of complex products. We call it "forward design". With this "forward design", engineers will face a problem, how to use the successful constructed products' data and design experience? The design knowledge reused maybe hard to be pushed forward under the random sample situation. Generally, products' performance is vital for product companies, as a result, a method, which maps from performance space to design space and helps engineers to focus on smaller interesting design regions, absorbs many researchers' attention. It will save much development time and cost. Consequently, designers urgently expect that an expert

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system that can help engineers to map from performance space (evaluation of the products' performance) to design space (design variables and their values) is researched, in which with the past design knowledge, engineers can focus on interesting regions rapidly in the whole design space at the beginning of product optimization, it reduces the searching scope of design space, largely. In this paper, we named it "backward design".

As discussed above, an expert system that aids mapping from performance space to design space directly, handles and manages uncertainties, and helps designers to make design decisions in reducing design space, is imperative. Thus, in product design and optimization field, this research is going to study an effective expert system to help designers to exploit the global design space for presenting a relative transparent and smaller design space to accomplish intelligent product design. A promising expert system, Expert Systems for Assisting Mapping from Performance Space to Design Space (ESMPD), is designed based on Rough Sets Theory (RST) (Pawlak, 1982) and self-organizing maps (SOM) (Ritter, Martinetz, & Schulten, 1992), which belong to data mining (DM) technology, providing a relative transparent and optional optimization process for engineers and helping with mapping from performance space to design space. RST was first proposed by Pawlak (1982), which has been researched and applied in many fields (Leung, Wu, & Zhang, 2006; Pawlak & Skowron, 2007). The merit of RST is that, it only uses analyzed data to deduce the hidden rules, without correcting the missing or incomplete data of attributes in the whole information system. Shan and Wang (2004) first introduced RST to the mechanical area for mapping from performance to design space, and our research is the further and extended study. Shan and Wang provided an intuitive method to establish the mapping from the performance space to the design space directly. However, in practical engineering product design, especially in conceptual design, product configuration is usually included, and then design variables and their variation ranges should be confirmed. In accordance with this process of the conceptual product design, in this paper, the proposed expert system has two main modules for mapping from product performance space to interesting design space by two layer mapping method, at the first layer, RST is used to calculate configuration rules in incomplete configuration information system to assist product designers in mapping performance space to configuration space, and at the second layer, SOM is employed to analyze design variables and objective function based on preliminary optimization, to mapping from the fixed configuration space to smaller interesting regions in design space. In this study, product configuration space is considered a bridge to connect performance space and design space. The two layers methods for mapping from performance space to design space adapt to the product design more effectively. SOM (Kohonen, 2001) is an unsupervised neural network algorithm that projects high-dimensional data onto a two-dimensional map. The projection preserves the topology of the data so that similar data items will be mapped to nearby locations on the map. SOM has already been applied in engineering product design and optimization, most of researchers have gained much progress in multi-objective optimization (Budayan, Dikmen, & Birgonul, 2009; Parashar, Pediroda, & Poloni, 2008; Tanaka, Watanabe, Furukawa, & Tanino, 1995), where SOM is studied to analyze and make a trade-off of Pareto Sets solutions. To our knowledge, in this study, SOM is first used to accomplish the mentioned "backward design".

In this proposed expert system, two layers mapping are developed. At the first layer, RST is adopted to map from performance space to preliminary configuration space (subsystems or equipments and their variables of configurations), at the same time, the general design space (design variables and their intervals) can be fixed roughly. At the second layer, SOM is developed to map from preliminary configuration space to design space, analyzing the multi-dimensional design variables and their relationships that are based on the constructed kriging approximation model. To achieve the goal of focusing on interesting regions in design space, non-significant design variables are eliminated, and variable intervals are cut down. Consequently, this elaborated expert system using RST and SOM at two layers, respectively, to accomplish the "backward design", which helps designers to reduce complex design space and save much product design time.

The remainder of this paper is organized as follows. Mapping from performance space to design space and its characters are discussed in Section 2. Section 3 introduces the architecture and main functions of the innovative ESMPD. In Section 4, Configuration and Design Space Build Modules, Rough Sets Theory Analysis Module and the detailed application of RST are presented. Self-organizing maps Analysis Module and its application steps are given in Section 5. A new 50,000 DWT Handymax bulk carrier is described as a case study to prove the validity of the expert system in Section 6, and conclusions are finally made in Section 7.

2. Mapping from performance space to design space

In complex product design, mapping from performance space to design space can guide engineers to quickly locate interesting regions and effectively provide relative transparent optimization process, the architecture of which is shown in Fig. 1. In design space, the horizontal ordinate is defined as: design variables, which denotes the set of multi-dimensional design variables, $\{X_1, X_2, \ldots, X_n\}$, while the vertical ordinate is defined as: disciplines, which denotes the set of multidiscipline in product development $\{\text{structure}, \text{power}, \ldots, \text{fluid}\}$. The horizontal ordinate and vertical ordinate divide design space into small grids. Each of the grids represents an interval of design variable in the given discipline. And that, the grid with shadow shows that it is the interesting regions in design space, which is located by mapping from the specific performance of the complex product. The interesting regions in the design space are usually the expected values or intervals of the design variables in the product design. In general, they lead product to have a high performance, and they have to be confirmed at the initial design stage. The black grid in design space means the missing or incomplete information. There are lots of reasons for incomplete information existing, such as, new equipment fixed in the new product, whose performance information and using experience are not stored in the product data warehouse, except for the manufacture technical parameters that are offered by the provider, consequently, some attributes of design schemes are hard to be estimated in practice. Also, some product running environment cannot be forecasted, and the expected values and intervals of design variables are hard to be estimated at the initial design stage. The two reasons result in the incomplete data in product design. Considering the missing information, it is presumed that all the past product design data and information are stored in the data warehouse, due to the physical destroyed or the peoples' mistakes, there must be some data are lost. Accordingly, the missing or incomplete information are inevitable in product design, and they are denoted as black grids in design space in Fig. 1.

In general, there are some inherent characters of mapping from performance space to design space in complex product design, which are summarized as follows:

- *Coupled design variables*: Design variables shared in two or more than two disciplines have different change trends following the different discipline specifications and requirements, respectively.