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An interval-valued hesitant fuzzy multigranulation rough set over two universes model for steam turbine fault diagnosis

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ABSTRACT

In the field of mechanical engineering, steam turbine fault diagnosis is a difficult task for mechanical engineers who are confronted with challenges in dealing with copious amounts of uncertain information. Different mechanical engineers may have their own opinions about the system fault knowledge base that differs slightly from other mechanical engineers. Thus, to solve the problems presented by uncertain data analysis and group decision-making in steam turbine fault diagnosis, we propose a new rough set model that combines interval-valued hesitant fuzzy sets with multigranulation rough sets over two universes, called an interval-valued hesitant fuzzy multigranulation rough set over two universes. In the multigranulation framework, both basic definitions and some important properties of the proposed model are presented. Then, we develop a general approach to steam turbine fault diagnosis by using the proposed model. Lastly, an illustrative example is provided to verify the established approach and demonstrate its validity and applicability.

1. Introduction

Fault diagnosis technology has grown in importance in multiple areas of engineering, and issues with fault diagnosis technology have attracted much attention from researchers and practitioners. Until now, there are various data-based fault diagnosis techniques that have been developed, including expert systems [1], neural networks [2], and fuzzy approaches [3–5]. Taking advantages of human expertise and experiential knowledge, the expert system has been successfully utilized in steam turbine fault diagnosis. However, the limitations of acquiring expert knowledge and maintaining the rules database for steam turbines are revealed in expert system-based fault diagnosis. An additional potential weakness of this approach is that the rules database may include conflicting expert knowledge that may vary from case to case. This variation may preclude a general mathematical formulation that can be utilized for fault diagnosis in different fields. Another typical fault diagnosis technique, neural networks, addresses the shortcomings of expert systems by direct acquisition of fault knowledge from a set of training samples and exhibition of highly nonlinear input-output relationships. However, neural network-based fault diagnosis requires sufficient and compatible training samples to ensure proper training of the model.

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Free from the limitations of these models, the fuzzy approach can be used to sufficiently model the complicated relationship between faults and their features in steam turbine fault diagnosis. Additionally, many kinds of inherent uncertainties, such as inaccuracy, incompleteness, and inconsistency, are rampant in expressions of fault information available to engineers. Based on fuzzy set theory [6] and fuzzy logic [7], fuzzy approaches have been widely applied to fault diagnosis processes. The classical fuzzy set is limited by imperfect and uncertain information induced by several sources of vagueness, so several modifications and extensions have been introduced, including interval-valued fuzzy sets [8], type-2 fuzzy sets [9], intuitionistic fuzzy sets [10], and Pythagorean fuzzy sets [11]. These extensions overcome the limitations of classical fuzzy sets in different ways but are based on similar rationales.

Recently, considering that decision-makers are usually hesitant and irresolute for one thing or another when establishing a common membership degree, Torra and Narukawa [12] and Torra [13] introduced the concept of hesitant fuzzy sets, opening a new door for research on decision-making under hesitant environments. However, for real-life decision-making problems, the available information may not be sufficient for experts to provide their preferences with crisp values. Thus, a possible solution is to represent such preferences by interval values. As an extension form of hesitant fuzzy sets, Chen et al. [14] presented the concept of interval-valued hesitant fuzzy sets, which permits the membership degrees of an element to a given set are defined by several possible interval values. It is evident that interval-valued hesitant fuzzy sets can reflect individual's hesitancy more objectively than other widely developed fuzzy set approaches. Thereafter, many scholars have studied interval-valued hesitant fuzzy sets from different points of view and obtained many meaningful results [15–19]. Compared to classical fuzzy sets, since interval-valued hesitant fuzzy sets can better model insufficiency and hesitancy in available information, this approach can better handle the more uncertain information in fault diagnosis well, and provide mechanical engineers with an improved way to include their understanding about the system fault knowledge base.

Considering the above facts, as one of the commonly used multi-attribute decision-making methods, rough set theory [20] is an effective tool to acquire knowledge with its core concepts of lower and upper approximations. Moreover, rough set theory has demonstrated advantages in selecting significant attributes and explaining decisions according to attribute reductions and distinguishable relations. Over the past few years, two kinds of important generalizations of rough set theory, fuzzy rough sets [21] and multigranulation rough sets over two universes [22], have been developed in different application contexts. To effectively solve the problems of interval-valued hesitant fuzzy data analysis in fault diagnosis technology, we intend to integrate rough set theory with interval-valued hesitant fuzzy data analysis. We next itemize the necessities of combining those two theories with interval-valued hesitant fuzzy sets in detail.

(1) Rough sets and fuzzy sets, as two primary theories utilized for handling uncertain information in various information systems, are commonly viewed as correlative, but distinct and complementary. Determination of the best approach to generalize a rough set model to the fuzzy case is required for the development of rough set theory. In order to deal with various fuzzy information systems by utilizing rough set theory, Dubois and Prade [21] first constructed the concept of fuzzy rough sets. This work has been expanded by many recent studies of the fusion of hesitant fuzzy set theory with rough sets [23–26].

(2) In realistic rough set-based decision-making problems, when considering concept approximations and rules acquisitions in the background of multi-source information systems, in order to acquire knowledge efficiently, a reasonable way is to analyze these multi-source information systems directly rather than gathering each information systems as an entire information system. In this situation, the single-granulation rough set model exposes limitations that the computational times of knowledge discovery are long. Therefore, it is useful to describe a target concept through multiple binary relations according to a user's different requirements. From the perspective of granular computing [27], Qian et al. [28,29] introduced multigranulation rough sets in optimistic and pessimistic styles. Based on multigranulation rough sets model, Sun and Ma [22] further pointed out many kinds of decision-making information, such as the relationship between faults and their features in steam turbine fault diagnosis, involves two different types of objects, each of which belongs to a different universe of discourse, and the utilization of two universes and their interrelations may invalidate multigranulation rough sets model. Thus, by utilizing rough sets over two universes model [30–34], they proposed multigranulation rough sets over two universes. In light of the above, multigranulation rough sets over two universes could not only describe the decision-making information in different universes, but also synthesize multi-group expert preferences to form a final decision result by aggregating multiple binary relations. Thus, multigranulation rough sets over two universes can be seen as a relatively superior information fusion strategy under conditions of several different granulation levels.

On the basis of the above analysis, it is meaningful to utilize multigranulation rough sets over two universes model for multi-source information systems analysis. However, multigranulation rough sets over two universes can only handle crisp information systems and have limitations in processing various fuzzy information systems. Considering that interval-valued hesitant fuzzy sets can model insufficiency and hesitancy in decision-making information effectively, we aim to develop a new data analysis model in fault diagnosis techniques under the environment of interval-valued hesitant fuzzy information. Thus, to expand the application domain of multigranulation rough sets over two universes, through combining interval-valued hesitant fuzzy sets with multigranulation rough sets over two universes, it is necessary to construct an interval-valued hesitant fuzzy multigranulation rough set over two universes model and further explore its application in steam turbine fault diagnosis.

The paper is organized as follows. In Section 2, we briefly introduce interval-valued hesitant fuzzy sets, interval-valued hesitant fuzzy rough sets over two universes, and multigranulation rough sets over two universes. In Section 3, we present interval-valued hesitant fuzzy multigranulation rough sets over two universes and discuss relevant properties. Section 4 presents an analysis of the decision-making problems in steam turbine fault diagnosis. In Section 5, we give the