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Fuzzy evidential influence diagram and its evaluation algorithm

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ABSTRACT

Fuzzy influence diagrams (FIDs) are graphical models that combine qualitative and quantitative analyses to solve decision-making problems though some shortcomings that need to be corrected still remain. One is to guarantee the exactness as node evaluation in high-complexity influence diagrams (IDs) need to be combined with a number of expert evaluations. However, traditional FIDs can only process a single expert's evaluation. The other is that they use incomprehensive evaluation criteria to score nodes in complex systems with many different relationships receiving the same score, which does not reflect their differences.

Based on the fuzzy sets theory (FST) and Dempster–Shafer evidence theory (DST), this paper proposes for the fuzzy evidential influence diagram (FEID) to construct a new ID evaluation system and modify a corresponding algorithm. FEID allows multiple experts to evaluate nodes in IDs and can describe the differences between different nodes more exactly. Besides, two different fusion methods are used in the modified FEID evaluation algorithm. One approach uses the belief function and plausibility function to cover all possible outcomes while the other approach only provides the probability function in the convenience of human judgment. These two fusion methods can both be applied to the FEID evaluation algorithm in theory but they are suited for different application areas. Numerical examples expound the calculation process of the FEID evaluation algorithm and real applications in a supply chain financial (SCF) system and a tunnel construction (TC) system are used to compare the different fusion methods. The results given by the two fusion methods demonstrate which is better for analyzing this FEID. Anyway, compared to traditional FIDs, FEIDs can more accurately reflect the true situation and achieve more useful results.

1. Introduction

Influence diagrams (IDs), which are directed acyclic graphs (DAG) composed of nodes and directed arcs, are effective tools for analyzing and evaluating risk [1,2]. The nodes represent the variables in the studied problem while the directed arcs represent the interrelations among variables. Decision-making problems processed by an ID can not only be handled by computers, but are also easily understood by technicians in different fields. Even though IDs were introduced by Howard [3] in 1984, it has matured gradually over decades of development [4,5].

However, many problems in decision-making still exist when using IDs. One is the difficulty in qualitatively quantifying the dependencies between nodes [6,7]. Many experts have proposed using non-precision variables to represent the dependencies between nodes and introduced the fuzzy set theory (FST) into IDs, which are named fuzzy influence diagrams (FIDs) accordingly. Rodriguez-Muniz et al. [8] discussed the fuzziness of chance and value nodes, and formalized new statistical rules on node removal. Kao [9] proposed an FID with possibility functions and developed a simulation algorithm for diagnosis and optimal decision. Lin et al. [10] employed IDs and FST to estimate accident probability of diaphragm wall collapse. Compare to IDs, FIDs can better deal with uncertainty in risk analysis.

But there still some shortcomings remaining that need to be corrected in FIDs. Firstly, all node relationships are represented by state vectors with one-to-one correspondence. In reality, the

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relationships among nodes should be varied. One-to-one, one-to-many, and many-to-one correspondences should be allowed to apply in evaluating node relationships. Only using one-to-one correspondence to evaluate node relationships does not reflect the actual situation. Secondly, the relationships among nodes in high-complexity IDs are uncertain and incomplete. Therefore, multiple evaluations from different experts are needed to reduce the uncertainty of IDs. However, existing IDs can only deal with an evaluation given by a single expert. Multiple evaluations cannot be fused with existing ID evaluation algorithms. Therefore, this paper introduces the Dempster–Shafer evidence theory (DST) in the description of non-precise variables and the use of information fusion to make up for these gaps.

DST was firstly proposed by Dempster [11] and Shafer [12]. When compared to FST, not only can it deal with uncertain information, but it also provides Dempster's rule to combine uncertain information from different sources. Several methods based on DST were applied to many real applications such as decision-making under uncertain environments [13–16], pattern recognition [17–19], failure analysis [20–22] and sensor data fusion [23–25]. Evidence theory, however, also has some open issues, such as conflicting management [26], generating basic probability assignment (BPA) [27–29] and dependence evidence combination [30–33].

Based on FIDs and DST, a new ID model, called fuzzy evidential influence diagrams (FEIDs), is proposed. Firstly, the basic probability assignment (BPA) is introduced in order to describe node states. Each node in the IDs can be described with multiples states rather than one state. The membership degree of each state can be expressed with an interval [0,1] rather than with binary state of 0 and 1. Secondly, FEIDs allow multiple experts to evaluate states frequency and node relationships. Expert evaluations with inconsistency can be accepted by FEID. BPA should be assigned to different evaluations of node relationships.

The FEID, which has been evaluated completely, is then processed by its evaluation algorithm. The equation to obtain the frequency matrix is different from the traditional FID evaluation algorithm because of the change in node state. In this paper, two different fusion methods are applied in order to obtain the frequency matrix. One approach uses the belief function and plausibility function with the results being expressed by the belief frequency matrix and plausibility frequency matrix. The other approach fuses different information into a single value while it is expressed by the probability matrix. Method 1 tends to cover for all possible outcomes while Method 2 facilitates human judgment and its subsequent treatment. These two fusion methods can both be applied to the FEID evaluation algorithm in theory but they are also suited for different application areas.

To check the practicability of the two fusion methods, FEIDs are applied to two different application areas. One is risk evaluation of supply chain finance (SCF) while the other is security risk assessment of tunnel construction (TC).

SCF is the operation process of banks for the logistics industry [34,35]. While surrounding the core enterprises, it controls the capital flow and logistics, translates the risk from an uncontrolled risk of a single enterprise to a manageable risk of the whole supply chain (SC) of enterprises to minimize the financial risk. As an effective way to solve the financing problems of small and medium-sized enterprises (SMEs), SCF has been utilized frequently by banks, SMEs, logistics enterprises, etc. [36].

Many scholars have studied the SCF risk evaluation based on casual networks using fuzzy logic. Kao and Huang [37] developed fuzzy dynamic Bayesian networks (FDBNs) and applied them to SC modeling and reasoning. The proposed FDBN algorithms are able to deal with various diagnostic queries from SCs. Kao et al. [38] presented Bayesian networks (BNs) with fuzzy parameters for SC diagnosis systems. Rodger [39] structured a Bayesian network with fuzzy logic for a real-world SC data set and determined the data set distribution using a stochastic simulation based on Markov blankets. FIDs are also used in SC risk analysis. Ferreira and Borenstein [40] presented a novel FID model to rank and evaluate suppliers in the SC. This FID model can not only assess ratings and weights of criteria using linguistic variables but also can deal with the dynamic characteristics of a long-term relationship with suppliers [41]. This FID model is also used in the SC to illustrate the above advantages.

TC is a reasonable construction method that is proposed in the long run based on rock mechanics. It is a new construction method that is combined with the use of spray anchor technology, monitoring and measurement, rock mechanics theory, and TC risk analysis, etc. As a branch of tunnel engineering, risk analysis can effectively prevent accidents occurring under construction, thereby reducing unnecessary losses. With the maturity of TC technology, engineers tend to pay more attention to construction efficiency as well as risk control. The risk analysis of tunnel engineering has also gradually become theoretical.

Einstein is one of the earlier representatives who did risk analysis of tunnel engineering as risk analysis was applied in real tunneling projects in his research efforts [42]. Reily and Brown [43] applied the Cost Estimate Validation Process (CEVP) to a real application, the Washington State Department of Transportation (WSDOT). This approach provides a method for potential risk identification and risk evaluation. For the WSDOT, they also summarized risk control strategies. Fouladgar et al. [44] combined fuzzy logic with the TOPSIS method to analyze the risk of TC. Li et al. [45] applied two attribute recognition models (ARM-C and ARM-D) to assess the risk of water inrush in karst tunnels.

In addition, causal network [46,47] models are gradually being concerned with and applied to risk analysis of TC in recent times. Based on event tree analysis, Nyv́lt et al. [48] proposed a cost evaluation model for TC within the controllable risks. Sousa and Einstein [49] used BNs to achieve risk decision. This decision model was applied in the risk analysis of the Porto Metro tunnel and provided strategies for TC. Wang et al. [50] used the techniques of BNs and Relevance Vector Machines to complete probabilistic risk assessment. A fuzzy BNs model, with detailed step-by-step procedures, was proposed by Zhang et al. [51] and applied to the risk analysis of the Yangtze River Tunnel.

The proposed FEID model is applied in both SCF and TC to analyze risks. Besides, due to the difference between structures of IDs, application in SCF is more suitable to use the first fusion method. The second fusion method suits TC more. The detailed analysis, including the reason for better method and the selection strategy of two methods, is provided in the end. The following content is organized as follows: In Section 2, some preliminaries are briefly introduced, including FIDs and DST. In Section 3, the proposed ID model is described in detail. In Section 4, two numerical examples are used to illustrate the calculation steps of proposed FEID model, and comparison between traditional and proposed method. In Sections 5 and 6, the proposed ID model is applied in credit risk evaluation of a SCF system and security risk assessment of Baihuashan TC separately. The conclusion and future work are provided in Section 7.

2. Preliminary

Some basic concepts and methods are introduced in this section. In the part of FIDs, the structure of FIDs and an FID evaluation algorithm are elaborated. In DST, some concepts (including the frame of discernment, BPA, belief and plausibility function) as well as three fusion methods are introduced. The above contents will be used in the proposed FEID model.