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Construction of holistic Fuzzy Cognitive Maps using ontology matching method

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ABSTRACT

Fuzzy Cognitive Map (FCM) is a powerful approach to model the dynamics of complex systems, and has been applied in various fields, such as psychology, education, engineering, and management. The construction of FCMs has great importance for its application. The literature, however, takes it for granted that Fuzzy Cognitive Maps allow for a simple aggregation of domain knowledge from several experts without much considering holistic approaches with semantic comparison of concepts.

This paper describes the method for constructing Fuzzy Cognitive Maps based on the ontology matching approach in a holistic way. The ontology matching technology through a series of proposed operations is used to find the alignment between semantically related concepts and solves the semantic ambiguity problem, thereby improving the experts-based FCM construction method. This approach enhances the effective collaboration in the heterogeneous environment of today's internet-based world, and the proposed holistic FCMs also allows the user to draw additional observations concerning the underlying system, which are not available through the individual FCMs.

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1. Introduction

Fuzzy Cognitive Maps (FCMs), introduced by Kosko (1986a), are powerful tools for modeling dynamic systems. FCMs describe expert knowledge of complex systems with high dimensions and a variety of factors. An increased interest about the theory and application of FCMs in complex systems has been also noted, and their validity and usefulness has been proved in the various fields (Eden & Ackermann, 1989; Eden, Jones, & Sims, 1979; Kwahk & Kim, 1999; Lee & Kwon, 2006; Lee & Kwon, 2008; Liu & Satur, 1999; Nelson, Nadkarni, Narayanan, & Ghods, 2000; Satur & Liu, 1999; Zhang, Chen, & Bezdek, 1989; Zhang, Wang, & King, 1994). On the other hand, the usefulness of FCMs inspires many researchers and practitioners in various fields to construct their own FCM, and it is common that they have created myriads of similar cognitive maps again and again despite of the existence of similar FCMs.

Concepts in FCMs represent the variables that describe the belief systems of a person. Meanwhile, today's Internet-based society has created a collaborative environment, where marketers, managers, engineers, designers, and manufacturers from small and large organizations are collaborating through the Internet to participate in various problem solving activities: collaborative strategy, collaborative planning, collaborative development, and so on. This collaborative environment often involves different domain terminologies, domain-specific knowledge, and diverse systems. Sometimes the vocabulary in two disparate environments is completely different, but the intrinsic functions can be remarkably similar. Likewise, the FCMs in different fields look completely different, but the intrinsic mechanism, having superficially different concepts, can be similar. Therefore, the major barrier to effective collaboration in such a heterogeneous environment is the lack of explicit semantics in the concepts used within FCMs.

To the best of the authors' knowledge, the dominant emphasis in the literature is on building methodologies and tools for the development, simulation, and analysis of the FCMs, rather than on securing their semantic interoperability. The authors insist that since the semantic interoperability issue in FCMs is a relatively new initiative, little research has been carried out on its use, though it apparently has positive effects on collaboration in the Internet era. Therefore, the principal question in this paper is how to find the correspondence between semantically related concepts of different FCMs and gain insights into underlying systems. The first goal of our research is to improve the experts-based FCM construction model by solving the semantic ambiguity problem faced by experts. The second goal is to apply the semantic ambiguity problem-solving method to the reuse and merge of existing FCMs for the purpose of specifying and formally producing the holistic FCMs. The ontology matching technology through the

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series of proposed operations is used to find the alignment between semantically related concepts.

The outline of the paper is as follows: Section 2 provides the basic theory of FCMs and an ontology matching. Section 3 proposes a novel approach on developing FCMs using ontology matching method. Section 4 shows an example and concluding remarks are given in Section 5.

2. Theoretical background

2.1. Fuzzy Cognitive Maps

FCMs are directed graphs that can model interrelationships or causalities among concepts. An FCM consists of n concepts, C_i, $i = 1, \ldots, n$, a directed edge E_{ij} from concept C_i to concept C_j. A directed edges E_{ij} measures how much C_i causes C_j. In general, the edges E_{ij} can take values in the fuzzy causal interval $[-1, 1]$ allowing degrees of causality such as: C_i causally increases C_j if $E_{ij} > 0$, decreases C_j if $E_{ij} < 0$, and has no causal effect on C_j if $E_{ij} = 0$. The sign of edges indicates whether the relationship between two concepts is positive or negative, while the value of edges indicates how strongly C_i influences C_j.

An FCM construction relies entirely on human expertise and domain knowledge. Simply a single expert can draw the graph that corresponds to FCM, following three steps: (1) concept identification, (2) identification of causal relationships among these concepts, and (3) estimation of the strength of the causal relationships (Kahn & Quaddus, 2004; Kosko, 1986a). Among these steps, the main challenge of FCM construction has been considered to estimate accurately the strength of the causal relationships. The widely-used approach is to determine first the sign of each relationship, and then to describe each relationship by a linguistic term such as *weak*, *medium*, *strong* and *very strong*, and next to transform these terms into numerical values (Kahn & Quaddus, 2004; Kosko, 1986a).

In order to increase the credibility of FCM, a group of experts instead of a single expert has been preferred and involved in the construction process. The popular practical approaches to construct FCMs by a group of experts are brainstorming and focus group interviews. Formal brainstorming to create FCMs is accomplished through a structured group workshop by allowing every expert to contribute his or her own ideas to the final FCMs (Hegedus & Rasmussen, 1986; Novak, 1998). In focus group interviews to construct FCMs, the qualitative and open-ended questions are posed to experts (Eden, 1988; Nelson, Nadkarni, Narayanan, & Ghod, 2000), in which the interview process follows either a deductive (Newstead, Handley, Wright, & Farrelly, 2004) or an inductive approach (Del et al., 2005).

In a group of experts-based FCM construction, the basic assumption is that each expert can draw a different size FCM with different related concepts, and there is no restriction on the number of experts or on the number of concepts. Technically any set of FCMs can be naturally combined by adding augmented adjacent matrices (Kosko, 1986b, 1986c). The first step towards combining the individual FCM of each expert is to equalize the size of FCMs. Suppose k-many experts develop each FCM and the ith expert's FCM is $n_i \times n_i$ adjacent matrix A_i. These different adjacent matrices can be augmented to include any missing concept(s) by adding extra rows and columns of all zeros: F_i. Consider a simple example as shown in Fig. 1. There are five different concept nodes and the first expert's edges $E_{ij}^{(1)}$ and second expert's edges $E_{ij}^{(2)}$ from concept C_i to concept C_j.

Since each FCM_k describes kth expert's perception about the subjective world rather than objective reality, we should consider the credibility of individual experts. The simplest method for combining FCMs is to calculate the average of each causality weight across two experts. Therefore the combined matrix F is equivalent to $(F_1 + F_2)/2$. This simple approach can be extended and modified to accommodate credibility of different experts such that the experts with higher credibility have stronger influence on the structure of collective FCM. More detailed discussions on assigning weights can be found in the literature, including probabilistic approach (Kosko, 1988), fuzzy approach to combining knowledge (Kosko, 1986c), computational methods based on Hebbian learning (Dickerson and Kosko, 1993), and evolutionary algorithms (Koulouriotis, Diakoulakis, & Emiris, 2001).

2.2. Ontology matching

An ontology, which was originally defined as an "explicit specification of a shared conceptualization", refers to a particular theory of the nature of being or existence, and is used with different meanings in different applications (Gruber, 1993; Guarino & Giaretta, 1995). In Fig. 2, the left ontology represents the set of items of bookstore and right ontology illustrates the content of personal library. Ontologies are expressed in a large variety of ontological languages, fortunately, most of which are comparable and interpretable (Staab & Studer, 2009). An ontology can be formally defined as a tuple $O = \langle Classes, Individuals, Properties, Relations \rangle$. *Classes* define the concepts and set of individuals in the domain. For example, *Book* and *Novel* in Fig. 2 are classes; *Individuals* denote the object instances of these classes. For example, the object "*Linear Algebra*" of class *Textbook* is an individual; properties refer to the attributes and the possible associations with objects or data. For example, *has Author* "*John*", called object-property, *has Price* "*100*", called data type-property; relations specifies how individuals are related to other individuals. For example, *Science is-a Book* in Fig. 2 and *is-a* is relation and creates a taxonomy. The reader is referred to Staab and Studer (2009) for more details.

In a distributed environment system, however, semantic ambiguity or heterogeneity cannot be avoided. Different experts have different interests and knowledge, use different terminology at different levels of detail and adopt different ontologies. Therefore, first barrier in the ontology design for a domain of interest may be heterogeneity. Given two ontologies O_1 and O_2, ontology matching has been a solution to the semantic heterogeneity problem and aims at finding correspondences such as equivalence and other relations between semantically related entities of different ontologies, and an alignment refers to a set of correspondences between pair of entities of O_1 and O_2 respectively (Euzenat & Shvaiko, 2010; Shvaiko & Euzenat, 2013). For example, simple alignment and correspondences in Fig. 2 are as follows:

⟨*Alignment*⟩
⟨*Correspondence1*⟩*http://URI$_1$/bookstore#Book* $=_{1.0}$ *http: // URI$_2$/library#Volume*,
⟨*Correspondence2*⟩*http://URI$_1$/bookstore#Science* $\subseteq_{0.8}$ *http:// URI$_2$/library#Essay*
⟨*/Alignment*⟩

which assert the equivalence relation between the *Book* class in left ontology and the *Volume* class in right ontology, and *Essay* subsume *Science*. The confidences in these correspondences are quantified with 1.0 and 0.8 degrees respectively.

3. Holistic FCM construction

The main challenge of FCM construction has been to estimate the strength of causal relationships among the concepts and some

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