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Aggregating linguistic expert knowledge in type-2 fuzzy ontologies

József Mezei [a,c,*], Robin Wikström [a,b], Christer Carlsson [a]

[a] Department of Information Technologies, IAMSR, Åbo Akademi University, Joukahaisenkatu 3-5B, FIN-20520 Turku, Finland
[b] Industrial Management, Åbo Akademi University, Piispankatu 8, FIN-20500 Turku, Finland
[c] RiskLab Finland at Arcada University of Applied Sciences, Jan-Magnus Janssons Plats, 00560, Helsinki, Finland

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ABSTRACT

In many industrial contexts, knowledge and data provided by experts are imprecise as there seems to be an understanding that "experts do not need precise details as they understand anyway what is meant". The imprecision inherent in the knowledge that experts acquire in their practice require decision support tools that can be tailored to the specific application contexts to aid complex decisions. As a specific example, expert knowledge expressed in linguistic terms is not precisely structured and concepts are not defined specifically enough in order to be easy to use and process. If we want to represent and use expert knowledge for knowledge-based systems on a general level, that is easily adaptable, we need to find ways to represent and process knowledge elements; our approach is to use interval-valued fuzzy sets, fuzzy ontology and aggregation operators. We show that these instruments will offer us a novel approach for aggregation of imprecise data to obtain actionable knowledge to aid complex decisions. The framework is described and the approach is shown through the context of a fuzzy wine ontology; the problem formulation resembles many features of important and complex decision making problems found in different industries. We describe the potential application of the framework in the case of paper machine maintenance. A web-based application is introduced to better demonstrate the benefits decision-makers can receive from the proposed framework. Additionally, we present an approach to utilize the framework in finding consensual solutions in situations involving several experts.

1. Introduction

Representing expert knowledge expressed in linguistic terms and making use of this representation in an efficient way are important problems in decision making. Experts in the same field perform their work and communicate their problems with each other using a commonly shared understanding of their profession. The precise meaning of the expressions used by experts usually depends on the problem context and relies on the tacit knowledge that co-workers have co-created when interpreting these expressions. Recently, the combination of ontology and fuzzy logic has been proposed as a potential tool to capture this tacit knowledge in a systematic way and at the same time to incorporate the imprecision stemming from the specific problem context (e.g. fuzzy ontology for diet recommendation [1] or medical document retrieval [2]).

The motivation for our research originates from production process problems that can occur in a paper machine. The objective is to build a decision support system that can retrieve relevant documents describing various past events taking place in the contexts of paper machines, mainly referring to problems or failures in different processes; these documents are very useful when there is a problem with the production process as they contain information and knowledge on how to deal with and solve the problems (or at least similar problems). The support system is created by building on a fuzzy ontology and the main goal is to find and retrieve documents that are classified with imprecise information, as in most of the cases the experts specify the details of incidents in the reports using their own expressions.

1.1. Expert knowledge in the paper industry

Operational decision making in process industries is a typical case where experts rely on their life-long experience with different machines and the knowledge acquired through working with other experts [3]. Because of this reason, training new engineers is a critical problem in process industries [4]. A typical problem rooted in this setting emerges when companies try to create decision support systems to carry out the tasks previously performed by experts or to create a system that can aid newcomers replacing experts when they retire. As the knowledge-base of these systems, companies usually consider internally created problem reports, models, recommendations, etc. about problems solved, insight gained and experience collected [5]. These documents are created by expert authors, and to provide an effective way to handle the documents and to easily retrieve them, they are annotated with keywords that describe the content of the document. Keywords and documents are stored in information systems and can be accessed with standard routines of standard software. In practice, the problem becomes clear when we realize that the keywords assigned to documents were not precisely correct – not precise nor always proper. This practice of not being careful with keyword annotation turns out to be common among experts – "real experts know what the keywords mean". Keywords in this process industry context are representations of real-world events, process parts, technology elements, etc. that can overlap and show different types of relations.

The task is to find a way to retrieve documents from a large database of documents imprecisely annotated with keywords; the search and retrieval processes

* Corresponding author. Tel.: +358 401842180.
E-mail addresses: jmezei@abo.fi (J. Mezei), rowikstr@abo.fi (R. Wikström), christer.carlsson@abo.fi (C. Carlsson).

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need to be fast as the objective is to solve problems in almost real time - the production process should not be idle for any significant period of time. The practical and quick way to support the process operators is to identify similar problem situations, extract the documents that describe them and then use them as guidance for handling the actual problems. In the minds of process experts the various functions of a paper machine are related and interdependent [6]; these features should be used for the search and retrieval processes. The keywords classifying the documents are defined based on a set of general concepts describing the features and the processes related to paper machines. As most of the details necessary to present the application in its full extent are confidential, we will use the case of a wine ontology with the task of selecting a wine for a given context based on a set of specific wine characteristics (which resembles the original problem of identifying documents containing specific keywords) to describe the most important features of our approach.

Keywords consisting of concepts in the ontology representation are used for queries; this should be possible by building keyword combinations without following the predefined structure of the classification but using the relations – this is now a deviation from the classical building and use of ontology and there is a need to find out how to manage it.

As it was pointed out, the application for paper machines cannot be presented in full details as parts of the description are confidential; for this reason we will use the case of a fuzzy wine ontology to describe the main features of our proposed framework. The case of wine selection resembles several key features of our original task of finding documents in a database describing events similar to present problems. First, a proper description and identification of wines relies on a complex hierarchy of concepts similarly to paper machines (e.g. price, alcohol level, country of origin, color, acidity level, sugar level). Secondly, every wine is classified with these concepts using imprecise linguistic expressions (e.g. deep red, fine bouquet, long after-taste, fruity, dry) as the result of evaluation by wine experts. Third, we try to identify wines that fit a given context or a specific food from a given database of wines (in the same way as we identify documents describing similar events to present problems related to a paper machine), and this selection depends largely on the personal preferences of the person looking for a wine (as with an expert looking for supporting knowledge).

In many practical situations, there are several experts providing opinions on a given problem using linguistic terms by considering several criteria [7]. In this situation the choice of a suitable aggregation function is essential to obtain reasonable recommendations for assessing the problem. We will use aggregation operators for interval-valued fuzzy sets to aggregate linguistic opinion of experts as part of the fuzzy ontology approach. Additionally, in the presence of multiple experts an important issue is to define a procedure that can help in achieving consensus [8,9]. We will propose an optimization model relying on the fuzzy ontology to guide a group of heterogeneous experts toward consensus [10].

The main contributions of the paper are the following: (i) showing a framework of combining expert knowledge expressed in linguistic variables represented by interval-valued fuzzy sets and fuzzy ontology; (ii) introducing aggregation operators for interval-valued fuzzy sets into the framework to improve the search for the cases that are the best fit to a given context (most similar to a set of predefined requirements); and (iii) showing that (i) and (ii) can be built as a working prototype.

The next steps are outlined as follows: Section 2 introduces fuzzy sets, interval type-2 fuzzy ontology, aggregation, and provides the necessary definitions of interval-valued fuzzy numbers and Ordered Weighted Averaging (*OWA*) operators that we are going to need for the type-2 fuzzy ontology. Section 3 describes aggregation operators with illustrative examples that are used later in utilizing fuzzy ontologies for decision support in operational decision making problems in the paper industry using expert knowledge. Section 4 provides our framework for constructing and using the ontology for decision support and for finding a consensual solution. Section 5 summarizes the paper and provides some conclusions.

2. Literature review and preliminaries

In this section we discuss concepts and definitions necessary for the presentation of our approach: (interval-valued) fuzzy sets, fuzzy ontologies and aggregation with *OWA* operators.

2.1. Fuzzy sets

Zadeh [11] introduced fuzzy set theory and fuzzy logic for handling the dilemma that objects in the real world seldom have clearly-defined memberships to groups. This makes it possible for elements to belong to sets to some degree between 0 and 1. A fuzzy subset A of a set X is characterized by its membership function $\mu_A : X \to [0, 1]$ where $\mu_A(x)$ is interpreted as the degree of membership of element x in fuzzy set A for each $x \in X$.

Since the introduction of fuzzy logic in the context of decision making [12], fuzzy sets has evolved into a commonly used alternative to model imprecision and uncertainty. Decision support systems based on fuzzy modeling offer a useful tool to aid the decision makers, especially when decisions need to be drawn from incomplete information. As a good example, [13] offers a fuzzy multi-criteria decision-making formulation of maintenance problems. Type-2 fuzzy sets, originally introduced by Zadeh [14], make it possible to model and minimize the uncertainty, in a more effective way than type-1 fuzzy sets. As type-1 fuzzy sets are limited to a crisp value for defining the membership function, type-2 fuzzy sets have membership functions that themselves are fuzzy. The membership function is therefore not two-dimensional but three-dimensional, making type-2 fuzzy sets more complex to visualize but, at the same time, achieving more possibilities for modeling uncertainty [14,15]. In recent years, models based on type-2 fuzzy sets have become one of the most important directions in fuzzy set theory with applications in various fields [16].

Interval-valued fuzzy sets (*IVFS*) are the most used subclass of type-2 fuzzy sets, due to the fact that it solves some of the computational problems regarding type-2 fuzzy sets. *IVFS*s have proved to be useful especially for computational intelligence problems [17]. *IVFS* specifies an interval-valued degree of membership to each element, due to the notion that there is a lack of objective procedures for selecting a crisp membership degree for the elements in a fuzzy set [14]. In the following, formal definitions required in the paper are discussed.

2.1.1. Interval-valued fuzzy numbers

A *fuzzy number A* is a fuzzy set in $\mathbb{R}$ with a normal, fuzzy convex and continuous membership function of bounded support.

Definition 1 *([18])*. An interval-valued fuzzy set A defined on X is given by

$$A = \{(x, [\mu_A^L(x), \mu_A^U(x)])\}, \quad x \in X,$$

where $\mu_A^L(x), \mu_A^U(x) : X \to [0, 1]; \forall x \in X, \mu_A^L(x) \le \mu_A^U(x)$, and the ordinary fuzzy sets $\mu_A^L(x)$ and $\mu_A^U(x)$ are called lower fuzzy set and upper fuzzy set of A, respectively.

All interval-valued fuzzy sets on X are denoted by $IVFS(X)$. Since every $A \in IVF(\mathbb{R})$ is uniquely associated with the corresponding membership function, throughout the paper we will use the notation $A(x) = \mu_A(x)$ We consider a subclass of $IVFS(\mathbb{R})$: interval-valued fuzzy numbers (IVFN), which is simply the case when $A^L(x)$ and $A^U(x)$ are ordinary fuzzy numbers.

For the α-level sets of $A^L(x)$ and $A^U(x)$ we will use the notations $[A^L(x)]^\alpha = [a_1(\alpha), a_2(\alpha)]$, $[A^U(x)]^\alpha = [a^1(\alpha), a^2(\alpha)]$ and $[A]^\alpha = ([A^L(x)]^\alpha, [A^U(x)]^\alpha)$. The arithmetic operations of interval-valued fuzzy numbers can be defined using γ-cuts and the Extension Principle [14].

In the application of aggregation operators, the ordering procedure is a crucial step. There exist several methods for ranking fuzzy quantities, specifically fuzzy numbers, but the literature on ranking procedures for interval-valued fuzzy sets does not offer many different approaches. In this paper we use the mean value of $A \in$ IVFN to obtain the orderings:

Definition 2 *([19])*. The *mean* (or expected) value of $A \in$ IVFN is defined as

$$E(A) = \int_0^1 \alpha(M(U_\alpha) + M(L_\alpha))\mathrm{d}\alpha, \tag{1}$$

where U_α and L_α are uniform probability distributions defined on $[A^U]^\alpha$ and $[A^L]^\alpha$, respectively, and M stands for the probabilistic mean operator.