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A concept reduction approach for fuzzy cognitive map models in decision making and management

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ABSTRACT

Policy making, strategic planning and management in general are complex decision making tasks, where the formulation of a quantitative mathematical model may be difficult or impossible due to lack of numerical data and dependence on imprecise verbal expressions. For such systems, knowledge representation graphs and cognitive maps are most familiar and often used for modelling complexity and aiding decision making. Fuzzy Cognitive Maps (FCM), as graph-based cognitive models, have been successfully used for knowledge representation and reasoning. In modelling complex systems usually a large number of concepts need to be considered. However, it is often difficult in real applications to find the appropriate number of concepts. Using only a few concepts is not enough to represent the modelled system with the required precision, and increasing the number of concepts increases the complexity of the model quadratically; it is burdensome to work with for the experts. The contribution of this paper is two-fold: (i) to propose a new concept reduction approach for FCM and (ii) to apply it on developing less complex FCM for management and decision making. The behaviour of reduced models is analysed through a number of scenarios with respect to the original complex system. The main idea of the reduction is a clustering based on fuzzy tolerance relations. The new approach is focused on reducing complexity in the modelling process, which provides a more transparent and easy to use model for policy makers. The applicability of the proposed method is demonstrated via literature examples and a solid waste management case study that initiated this research. The results clearly show the advantageous characteristics of the proposed concept reduction method for FCM and its aid in policy making.

1. Introduction

Decision support issues are important in most strategic decision-making activities, where a large number of factors interrelated in a complex way need to be considered [1]. Different interpretations of information gathered from different sources often cause difficulties in the decision-making process.

Multiple decision making models are available, but tackling the complexity of the systems with quantitative mathematical models may be very difficult, especially when there is lack of numerical data. Many decision making techniques employ knowledge representation, cognitive and fuzzy models [2]. In this research study, Fuzzy Cognitive Maps (FCM, signed fuzzy directed graphs with feedbacks) are employed for modelling complexity and management procedures. They can successfully represent knowledge and human experience, introducing concepts and cause and effect relationships. Concepts represent states or variables which may be physical quantities that can be measured, such as the amount of waste. Cause and effect relationships are defined among these concepts modelling the behaviour of an arbitrary system. A cognitive map can be described as a qualitative model of the operation of a system [3,4] and can be used for helping decision makers for policy making tasks [5,2,6,7]. FCM offers a number of advantages over conventional fuzzy approaches in reasoning. It is an efficient, transparent and easy to use tool for modelling complex systems and decision support tasks [8,5,9].

A large number of approaches, methodologies, algorithms, and mathematical tools have been proposed and used for modelling complex systems and decision making in waste management [10–13]. A review of current waste management models shows that most of them fit into one of three categories – cost benefit analysis, life cycle analysis and multi-criteria techniques. A brief description of each of these models is given in [14].

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The efforts of developing these approaches [15] make apparent the need for a flexible, accurate and adaptive modelling tool. FCM is based on an abstract cognitive model that can integrate the knowledge of experts from different disciplines, simulate different policy options and give an insight into the consequences of possible decisions [6,16].

There are some known efforts in Integrated Waste Management Systems (IWMS) using FCM for modelling and decision making [17–19]. However the first, small FCM model obviously suffered from inaccuracy, thus a more detailed model was created. Unfortunately the number of relationships in FCM models is a quadratic function of the number of concepts, and the usage of the detailed model seemed very cumbersome in practice.

Modelling problems related to sustainability are a challenge due to their complexity, and especially to the involvement of various parties and human factors. A waste management system needs to be environmentally effective, economically affordable and socially acceptable [20,21] to be sustainable. It is not easy to provide a proper mathematical model able to solve such a complex decision making task [17].

This problem motivated the authors to develop a novel method to decrease the complexity of a model by reducing the number of concepts while keeping the accuracy of the model above a reasonable level. This research work investigates the decision making capabilities of less complex cognitive models which are produced after a concept reduction approach. Reduced models were compared with the original complex FCM models where a large number of concepts need to be considered as in the case of sustainable waste management systems. This domain is a challenging area where new methodologies and efforts can open entirely new research directions.

Concerning the model reduction methods, several studies can be found in the literature. Alizadeh et al. [22] proposed a technique to create FCM by using historical data and then create clusters of concepts. The latter step of their algorithm is based on the DEMATEL method [23]. This method places the concepts in a two-dimensional space. The vertical axis separates the concepts according to their role, and thus evolves two groups of concepts: the cause concepts are placed on the positive side, while the effects on the negative side. The position along the horizontal axis expresses the importance of concepts. The two different ways of clustering presented in the study [23] are based on this planar rearrangement. The first approach takes only the cause/effect behaviour of concepts into account and uses the well-known *K*-means method. The centres of clusters are considered as new concepts in the reduced model. The second approach is called Two Step Clustering and uses the importance of concepts in addition. Both versions have some common properties, e.g. experts of the investigated field have to define the number of clusters, and the clusters are disjoint ones.

Nápoles et al. [24] used FCM for prediction and knowledge discovery of the HIV-1 drug resistance. They represented the protease protein with a FCM, and estimated the causality among sequence positions using Particle Swarm Optimization. In the next step, they looked for the sequence positions strongest related to the resistance target by applying Ant Colony Optimization. The applied discrete learning method simply ignores some amino acids in order to reduce the complexity of the model while keeping the quality of the map inference above an acceptable level. They used an ω parameter to control the simplification process.

Homenda et al. [25] investigated the effect of a posteriori removal of weak connections or concepts. The concepts were removed together with their connections. The weak connections were deleted by zeroing their weights. After these modifications, the simplified models were tested with well-known time series to check whether they are still able to predict future states with an acceptable low error or not.

The above-mentioned methods simply remove some concepts or connections of models [24,25] or create distinct clusters of concepts [22]. Several other clustering methods could also be applied, e.g. DBSCAN [26]. The main advantage of this method is that the a priori definition of the number of clusters is not necessary (in contrast to e.g. Fuzzy C-Means [27] or Median Fuzzy *C*-Means [28]), but it also creates hard clusters. In spite of this, the proposed new method uses fuzzy clustering which makes possible to create overlapping clusters. Instead of dropping more or less information, it tries to save as much information as possible in a cumulative form. The overlapping clusters are not a problem like in the case of hypercubes [29], moreover, according to our hypothesis, they can help clusters to imitate the behaviour of concepts of the original cognitive map. Also, some other methods are reported in the literature concerning the task of allowing overlapping clusters, but none of them have been designed keeping the objectives of the model simplification in mind. Gossen et al. [30] provided a good overview of these methods and the evaluation of them.

Two are the main contributions of this study: (i) a concept reduction approach for FCM by concept clustering based on fuzzy tolerance relations and (ii) the modelling of waste management systems using FCM and analysing the decision making capabilities of the less complex FCM produced after the proposed approach. The problem devoted to Hungarian waste management was selected to show the applicability of the proposed approach as it is a really complex decision making problem.

The suggested method, along with its validation and application, is presented in this paper. To provide further evidences of the usefulness of the suggested method three other models already published in the literature were also investigated and the results underpin our hypothesis: careful model reductions make models easier to be used and provide similar decisions keeping at the same time their original dynamic behaviour.

So, the focus is on using the newly suggested model simplification method with respect to the original FCM, to reduce the model complexity, and further to compare the results of the original and simplified models for exploiting their inference capabilities in policy making and strategic planning.

The outline of this paper is as follows. In Section 2, a description of the motivating problem of IWMS is presented, including the methods of collecting substantial information (e.g. workshop organization, text mining) to create the model. Section 3 expounds the methods applied in this paper: the basic description of FCM and the proposed model reduction technique. A basic example is provided in order to help with understanding of operation of the algorithm. Section 4 contains the details of experiments made with the original and produced model of the motivating problem after concept reduction. The description of the clusters created by the suggested model reduction technique is also provided. The results given by these two models are compared, and some observations about the practical aspects of applying the model reduction technique are provided as well. Three further FCM models were also selected from the literature. The inference capabilities of simpler models were compared against their corresponding original ones. Section 5 concludes the results and contains general remarks, including the possible directions of further research. The appendix provides some details of the performed simulations.

2. Description of the motivating problem

The IWMS development process involves social analysis, utilization of technical features, legal and institutional issues based on personal experiences, expert judgement, synthesis of conflicting opinions, etc. The subjective sources are vital to the completeness of waste management system design [31,32,15]. The development process is based on the active contribution of the proper stakeholders and assumes the communication among multidisciplinary research teams. Furthermore, participatory management schemes must be encompassed to success-