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A Fuzzy Grey Cognitive Maps-based Decision Support System for radiotherapy treatment planning

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ABSTRACT

Recently, Fuzzy Grey Cognitive Map (FGCM) has been proposed as a FCM extension. It is based on Grey System Theory, that it is focused on solving problems with high uncertainty, under discrete incomplete and small data sets. The FGCM nodes are variables, representing grey concepts. The relationships between nodes are represented by directed edges. An edge linking two nodes models the grey causal influence of the causal variable on the effect variable. Since FGCMs are hybrid methods mixing Grey Systems and Fuzzy Cognitive Maps, each cause is measured by its grey intensity. An improved construction process of FGCMs is presented in this study, proposing an intensity value to assign the vibration of the grey causal influence, thus to handle the trust of the causal influence on the effect variable initially prescribed by experts' suggestions. The explored methodology is implemented in a well-known medical decision making problem pertaining to the problem of radiotherapy treatment planning selection, where the FCMs have previously proved their usefulness in decision support. Through the examined medical problem, the FGCMs demonstrate their functioning and dynamic capabilities to approximate better human decision making.

1. Introduction

Cognitive Maps [1] are signed digraphs designed to capture the causal assertions of a person with respect to a certain domain and then use them to analyze the effects of alternatives, e.g.: policies or business decisions in respect to achieving certain goals.

A Fuzzy Cognitive Map (FCM) is a graphical representation consisting of nodes indicating the most relevant factors of a decisional environment; and links between these nodes model the relationships between those ones [11].

FCM is a modeling methodology for complex decision systems [7,17,27], which has originated from the combination of fuzzy logic and neural networks. A FCM describes the behavior of a system in terms of concepts; each concept representing an entity, a state, a variable, or a characteristic of the system [5,23,26,30,32].

FCMs constitute neuro-fuzzy systems, which are able to incorporate experts' knowledge [10,11,13,16,20,24].

Recently, a FCM extension, called Fuzzy Grey Cognitive Map (FGCM), has been proposed by Salmeron [25]. FGCM is based on Grey System Theory (GST).

The improved results obtained with the FGCM in comparison with the conventional FCM approach on an Information Technology application [25] motivated us to investigate an enhanced FGCM model for decision support.

The model presented in this paper co-evaluates human hesitancy through greyness not only in the definition of the causal relations between the concepts, but also in the definition of the concept values.

The proposed methodology of FGCMs is applied to a two-level integrated decision support tool, constructed to handle the complex problem of making decisions in radiation therapy treatment. The tool consists of a clinical treatment simulation tool and a supervisor decision making tool based both on FGCMs, using the construction process.

Fuzzy Grey Cognitive Map-based Decision Support System (FGCM-DSS) results are meaningful as weight and concepts values are measured by their grey intensity to describe more reliable than the causal influences among concepts as well as the concepts steady states and encourage our research towards this type of Decision Support Systems in medicine.

The outline of this paper is as follow. Section 2 presents briefly the Grey System Theory. Section 3 describes the Fuzzy Grey Cognitive Map technique and its advantages over classical Fuzzy Cognitive Map. Section 4 shows the medical problems and their experimental analysis. In Section 5, the results with the discussion

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follow, and Section 6 concludes the paper and discusses the usefulness of the new methodology for FGCMs. Finally, an appendix shows several tables with all the relevant problem's data.

2. Grey Systems Theory

2.1. Grey uncertainty

Grey System Theory has been designed for solving high uncertainty problems with discrete small and incomplete data sets [6]. GST have been widely applied in domains as hydrology science, agriculture, energy, medicine, industry, military science, business, transportation, meteorology, geology, and so on.

GST avoid the drawbacks of conventional statistic methods and just need a small amount of data to estimate the unknown systems' behavior. GST split systems in three kinds according to the known information's degree. If the internal structures and features of a system are fully known (whole understanding), the system is called a white one, while the system's internal structures and features is completely unknown is called a black system. A system with partial information known and partial information unknown is a grey system.

GST include fuzziness, because it can flexibly handles it [14,15,31]. Moreover, fuzzy mathematics need some previous information (usually based on cognitive experiences); while GST handle objective data, it does not require any previous information other than the data to be disposed [29].

In addition, intension and extension of the analyzed objects are the critical difference between fuzzy and GST concepts. GST deal with objects with ambiguous intension and clear extension, fuzzy theory mostly handles objects with ambiguous extension and clear intension. For instance, a grey concept with a clear extension could be "*People attending to the meeting are around 10 to 20*". A fuzzy concept with a clear intension and ambiguous extension could be "*Old men*". All of us know what "*old*" is, but the specific range where men are old is not clear [29]. Moreover, fuzzy theory has its strength in the study of environments with cognitive uncertainties.

One stronger point of GST over fuzzy approach is that GST fits better with multiple meanings or grey environments [2,33]. Grey uncertainty emerges due to the lack of accurate values. For instance, as the sentence "*The expected costs for a project are between 2.0 and 3.0 millions dollars*", the uncertainty of which is produced by the multiple meanings of the sentence. The costs (multiple meaning or grey variable) could be 2.0 or 2.1 or any value between up to 3.0 millions. That is, we can only know about the costs is its range [2.0, 3.0], but we do not know the accurate costs.

2.2. Grey numbers

Let U be the universal set. Then a grey set $\mathbf{G} \in U$ is defined by its both mappings. Note that

$$\mathbf{G} = \begin{cases} \bar{\mu}_G(x) : x \to [0,1], \\ \underline{\mu}_G(x) : x \to [0,1], \end{cases} \tag{1}$$

where $\underline{\mu}_G(x)$ is the lower membership function, $\bar{\mu}_G(x)$ is the upper one and $\underline{\mu}_G(x) \leqslant \bar{\mu}_G(x)$. Also, GST extend fuzzy logic, since the grey set $\mathbf{G}$ becomes a fuzzy set when $\underline{\mu}_G(x) = \bar{\mu}_G(x)$.

A grey number is one whose accurate value is unknown, but it is known the range within its value is included. We denote a grey number as $\otimes G$, with both a lower limit ($\underline{G}$) and an upper limit, it is called an interval grey number [15], and it is denoted as $\otimes G \in [\underline{G}, \overline{G}] | \underline{G} \leqslant \overline{G}$.

Both limits are fixed numbers in first order interval grey numbers. A black number would be $\otimes G \in (-\infty, +\infty)$, and a white number is $\otimes G \in [\underline{G}, \overline{G}], \underline{G} = \overline{G}$. We have not information about black numbers and we have the complete information about white numbers. If the grey number $\otimes G$ has only lower limit is denoted as $\otimes G \in [\underline{G}, +\infty)$, and if it has only upper limit is $\otimes G \in (-\infty, \overline{G}]$.

There is another kind of grey numbers that vibrate around a base value (a) and it can be denoted as $\otimes G(a) \in [a - \delta_a, a + \delta_a]$. Note that the grey number $\otimes G$ is formed with the vibration of the base value a with an intensity δ_a.

2.3. Grey operations

We define the length of a grey number as $\ell(\otimes G) = |\underline{G} - \overline{G}|$. In that sense, if the length of the grey number is zero ($\ell(\otimes G) = 0$), it is a white number. In other sense, if $\ell(\otimes G) = \infty$ the grey number is not necessarily a black one, because the length of a grey number with only one limit (lower or upper limit) is infinite, $\otimes G \in [\underline{G}, +\infty)$ or $\otimes G \in (-\infty, \overline{G}]$, but it is not a black number.

In addition, if we have two grey numbers $\otimes G_x$ and $\otimes G_y$, then the following operations are defined.

$$\otimes G_x + \otimes G_y \in [\underline{G}_x + \underline{G}_y, \overline{G}_x + \overline{G}_y]. \tag{2}$$

Note that $-\otimes G \in [-\overline{G}, -\underline{G}]$, then

$$\otimes G_x - \otimes G_y \in \otimes G_x + (-\otimes G_y), \tag{3}$$
$$\in [\underline{G}_x, \overline{G}_x] + [-\overline{G}_y, -\underline{G}_y], \tag{4}$$
$$\in [\underline{G}_x - \overline{G}_y, \overline{G}_x - \underline{G}_y]. \tag{5}$$

The multiplication of two grey numbers is denoted as

$$\otimes G_x \cdot \otimes G_y \in [min(\underline{G}_x \cdot \underline{G}_y, \underline{G}_x \cdot \overline{G}_y, \overline{G}_x \cdot \underline{G}_y, \overline{G}_x \cdot \overline{G}_y), \tag{6}$$
$$max(\underline{G}_x \cdot \underline{G}_x, \underline{G}_x \cdot \overline{G}_y, \overline{G}_x \cdot \underline{G}_y, \overline{G}_x \cdot \overline{G}_y)]. \tag{7}$$

Note that $\otimes G^{-1} \in \left[\frac{1}{\overline{G}}, \frac{1}{\underline{G}}\right]$, then

$$\frac{\otimes G_x}{\otimes G_y} \in [\underline{G}_x, \overline{G}_x] \cdot \left[\frac{1}{\overline{G}_y}, \frac{1}{\underline{G}_y}\right], \tag{8}$$
$$\in \left[min\left(\frac{\underline{G}_x}{\overline{G}_y}, \frac{\underline{G}_x}{\underline{G}_y}, \frac{\overline{G}_x}{\overline{G}_y}, \frac{\overline{G}_x}{\underline{G}_y}\right), max\left(\frac{\underline{G}_x}{\overline{G}_y}, \frac{\underline{G}_x}{\underline{G}_y}, \frac{\overline{G}_x}{\overline{G}_b}, \frac{\overline{G}_x}{\underline{G}_y}\right)\right]. \tag{9}$$

Furthermore, the multiplication of a scalar λ and a grey number $\otimes G$ is defined as

$$\lambda \cdot \otimes G \in [\lambda \cdot \underline{G}, \lambda \cdot \overline{G}]. \tag{10}$$

Moreover, the whitenization process converts grey numbers as white ones [15]. The whitenization $\tilde{\otimes} G$ of the grey number $\otimes G \in [\underline{G}, \overline{G}]$ computes as

$$\tilde{\otimes} G = \alpha \cdot \underline{G} + (1 - \alpha) \cdot \overline{G}, \tag{11}$$

where $0.0 \leqslant \alpha \leqslant 1.0$. If $\alpha = 0.5$, then it is called equal mean whitenization.

3. Fuzzy Grey Cognitive Maps

3.1. Fundamentals

Fuzzy Grey Cognitive Map (FGCM) is an innovative soft computing technique [25]. A FGCM represents unstructured knowledge through causalities expressed in imprecise terms and grey relationships between them based on Fuzzy Cognitive Maps [11,12]. FGCM, as FCM, represents human tacit knowledge.

FGCMs are dynamical systems involving feedback, where the effect of change in a node may affect other nodes, which in turn can affect the node initiating the change.

FGCM nodes represent concepts with grey variables. The causal influence of the causal grey variable over the effect one is modeled