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MODELING THE BUILDING ENERGY MANAGEMENT SYSTEM OF A BUILDING USING A REVISED APPROACH OF FUZZY COGNITIVE MAPS

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Abstract. Fuzzy Cognitive Maps (FCMs) are a very simple, useful and powerful tool for modeling and analyzing dynamic complex systems. FCMs can structure virtual worlds that dynamically change with time. Mathematical models of FCMs are reviewed and a number of problems which emerged with them are briefly analyzed. In order to address some of these drawbacks a revised approach is proposed. This approach is being used to analyze the behavior and control the Building Energy Management System of a building. Simulation results of the new method are presented and discussed.

Keywords: Building energy management system; energy efficiency; fuzzy cognitive maps.

INTRODUCTION

The energy consumed by buildings represents a large part of the world's total energy consumption with a total share of 40%. This is the reason that energy efficiency of buildings becomes an issue of utmost importance. Many scientists have turned their attention to the development of new methods of taking advantage of renewable energy sources, as well as control the existing technologies, to achieve the aforementioned goal. These efforts have led to the appearance of a new research field; that of the Intelligent Buildings (IBs). Many definitions have been given to describe what an IB really is, in our research the more suitable definition is the one given by the European Intelligent Building Group (EIGB) which states that "intelligent is a building which offers its users the most effective environment and on the same time uses and manages its resources in a manner that ensures the reduction of the cost due to the use of equipment and facilities"[1]. Various methods have been used to control the operation of a building in our research we focus on the methods of Fuzzy Logic and Fuzzy Cognitive Maps (FCMs). Fuzzy Cognitive Maps (FCMs) is a methodology for modeling complex systems which exploits the knowledge and experience of an experienced user. They are the evolution of the Cognitive

Maps which were introduced by R. Axelrod in 1976 [2].

Fuzzy Cognitive Maps were a computing methodology which gives users the ability to encounter problems in the same way the human mind does; using a conceptual procedure which can include ambiguous or fuzzy descriptions [3].

They therefore offer an economical, flexible, fast and versatile approach to a variety of problems (social, political, economic, environmental and mechanical) which are extremely complex and a purely mathematical approach would be time consuming, laborious and require wasting many resources. Kosko introduced FCMs as a method to represent the causal relationship between concepts-nodes. Their goal is to represent knowledge in a symbolic way and model the behavior of systems containing elements with complex relationships, which sometimes can be hidden or illegible. Fuzzy Cognitive Maps are a very promising modeling method that as stated above has been used in a large variety of systems with very good results. However, several problems concerning the extension of this method have emerged. For this reason, a revised approach of the method in modeling FCMS is needed. The aim of this paper is to propose a revised this approach and it is outlined as follows. In

section 2 the Fuzzy Cognitive Method is being presented and the problems of the method are being analyzed. In section three a revised mathematical approach to solve these problems is being proposed. In section 4 the proposed methodology is being tested in an experiment which attempts to control the building energy management system of a building. Finally, in the fifth section conclusions are being presented and future research topics are being proposed.

EXISTING FUZZY COGNITIVE MAPS MODEL

Fuzzy cognitive maps theory

Fuzzy Cognitive Maps (FCMs) came as a combination of the methods of Fuzzy Logic and Neural Networks. They constitute a computational method that can examine situations during which the human thinking process involves fuzzy or uncertain descriptions. An FCM presents a graphical representation used to describe the cause and effect relations between nodes, thus giving us the opportunity to describe the behavior of a system in a simple and symbolic way. To ensure the operation of the system, FCMs embody the accumulated knowledge and experience from experts who know how the system behaves in different circumstances. In other words, they recommend a modeling process consisting of an array of interconnected and interdependent nodes C_i (variables), as well as the relationships between them W (weights). Concepts take values in the interval $[0, 1]$ and weights belong in the interval $[-1, 1]$. Fig.1 shows a representative diagram of a FCM [4].

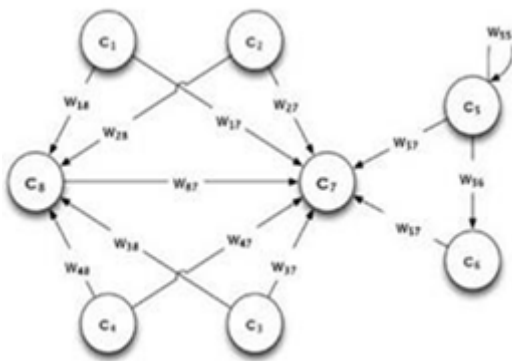


Fig. 1: Fuzzy Cognitive Map

The sign of each weight represents the type of influence between concepts. There are three types of interconnections between two concepts C_i and C_j :

$w_{ij} > 0$, an increase or decrease in C_i causes the same result in concept C_j .

$w_{ij} < 0$, an increase or decrease in C_i causes the opposite result in C_j .

$w_{ij} = 0$, there is no interaction between concepts C_i and C_j .

The degree of influence between the two concepts is indicated by the absolute value of w_{ij} .

During the simulation, the value of each concept is calculated using the following rule:

$$A_i(k) = f \left(A_i(k-1) + \sum_{j=1, j \neq i}^n A_j(k-1) w_{ji} \right) \quad (1)$$

Where k represents the iteration step, n is the number of concepts and f is the sigmoid function given by the following equation:

$$f = \frac{1}{1 + e^{-\lambda x}} \quad (2)$$

Where λ determines the steepness of function f .

The FCMs' concepts are given some initial values which are then changed depending on the weights; the way the concepts affect each other. The calculations stop when a steady state is achieved; the concepts' values become stable [1], [5-8].

As causal patterns change and experts update the causal relationships between concepts, the use of Non-Linear Hebbian Learning (NHL) procedure helps the FCM to modify its fuzzy causal web [9][10].

Due to the non-linear structure of the FCM the NHL can contribute to its training and consequently to the prediction and control of the Building Energy Management System function.

In this algorithm, the learning rule for FCMs integrates a learning rate parameter η , weight decay parameter γ , and the input/output concepts. The value of each concept changes through Eq. (1) whereas weight value is calculated using Eq. (3).

$$W_{ji}^{(k+1)} = \gamma W_{ji}^k + \eta A_i^k [A_j^k - \text{sign}(w_{ji}^k)] W_{ji}^k A_i^k \quad (3)$$

Through the NHL algorithm, the only weights that change are the non-zero ones,

all the other weights of the weight matrix W_{ji} keep their initial zero value [11].

Inefficiencies of fuzzy cognitive maps model

As stated in the introduction the FCMs is a modeling methodology which is very promising when we need to model complex systems which are highly non-linear and involve fuzzy or uncertain situations. However, with the current modeling of the method various problems emerge. These drawbacks dictate the need to use a different approach concerning the FCMs method; while on the same time keeping the core of the method intact. These problems concern various steps of the method. In this subsection, we are going to list and analyze each one and on the next section we are going to propose a revised approach to solve them. But before we begin, we should state that even if they appear separate its one is connected to the other. The first drawback concerns the calculation method of the values of the concepts; (Eq.1). The calculation equation takes into consideration the change that each concept causes separately instead of the total change which is caused to the concept C_i . This results in a significant increase to the value of the concept that goes far beyond the interval [0,1].

This is the reason why the sigmoid function (Eq.2) is needed; to suppress the result to the interval [0,1]. But due to the shape of the curve any concept value beyond 3 leads the sigmoid function to correspond it to the value 1 which is greatly problematic as the final output is corresponded to the linguistic variable "high" even if this is not always the expected or correct result. Secondly continuing the subject of the sigmoid function there is another drawback that leads to high output values. This is the fact that the center of the curve instead of being on the (0,0) point on the xy axis it is on the (0.5,0) point. This means that each concept's lowest value can be the 0.5. This problem combined with the first one makes it difficult to interpret the result even with the use on the experts' interpretation criterion (Eq.4).

$$R(x) = \begin{cases} 0, & x < 0,5 \\ \frac{x - 0,5}{0,5}, & x > 0,5 \end{cases} \quad (4)$$

Continuing with the NHL learning method (Eq.3), while running several simulations we have observed that due to the way weights are being calculated if the number of iterations of the algorithm is increased; to reach a steady state, the causality reverses and all the W_{ij} become positive. This is a very serious drawback as it changes the causality between concepts and in several occasions instead of having a lower we are going to have a larger result which can cause serious stability issues to several systems.

Finally, the last problem that demands our attention is the fact that some concepts are not being affected by others thus they should stay static through the whole iteration process. However due to the current sigmoid function and Eq.1 their value changes after the first iteration.

These problems dictated the need to have a revised approach concerning the modeling of Fuzzy Cognitive Maps.

A REVISED APPROACH

In this section of the paper a revised approach is being proposed to partly solve the above-mentioned problems. The changes that are being proposed try to address each problem separately but also in connection to the others.

New calculation equation

The first problem that we are going to address is the one of the calculation of the value of each concept. Until now in order to calculate the new value we simply summed the weighted values of all the concepts that affected the one in question (Eq.1). What we propose is to calculate a unified value to be added to the previous value of the concept. This value is going to represent the total variation caused from all the other concepts. The new equation proposed for this reason is:

$$A_i[k + 1] = f \left(A_i[k] + \frac{\sum_{j=1, j \neq i}^n A_j[k] w_{ji}}{\sum_{j=1, j \neq i}^n w_{ji}} \right) \quad (5)$$

As a result of this calculation the new value is almost always between the interval [0,1], a fact that makes the use of the sigmoid function more accurate.

Modifying the sigmoid function

Secondly concerning the sigmoid function, we are going to propose a modified form where we can adjust the various parameters (slope, upper, lower limit, symmetry with the y axis) to fit our needs. This function is described by the following equation [12]:

$$f(x) = m + \frac{M - m}{1 + e^{-r(x-t_0)}} \quad (6)$$

Where:

- m is the lower limit of the curve
 - M is the upper limit of the curve
 - r is the slope of the curve and
 - t_0 is the symmetry to the y axis

For the purpose of this paper we are going to use the following values:

- m=-1,
- M=1,
- r=1,
- $t_0=0$

We can see the sigmoid function of the curve to the following figure (Fig. 2).

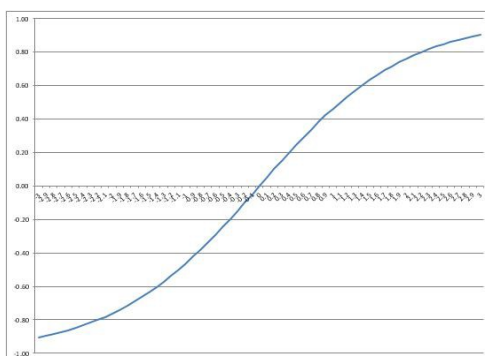


Fig. 2. Sigmoid Function

Using the aforementioned equation, we can also solve the last problem that we analyzed in the previous section of the paper; the constant concepts maintain their initial value.

The learning algorithm

In this subsection, we are going to propose an alternation of the NHL equation for the calculation of the weights. Our goal is to maintain the correct causality (as given by the experts) between the concepts regardless the number of the iterations that is needed to reach a steady state. For this purpose, we propose the following equation, which is the same as Eq.3 but slightly modified.

$$W_{ji}^{(k+1)} = \text{sign}(W_{ji}^k) [\gamma |W_{ji}^k| + \eta A_i^k [A_j^k - \text{sign}(w_{ji}^k)] W_{ji}^k A_i^k] \quad (7)$$

By separating the sign of W_{ji} and doing the calculation with the absolute value we achieve the correct causality without losing the accuracy of our results.

BUILDING ENERGY MANAGEMENT SYSTEM

The Building Management System (BEMS) is a system of utmost importance for the control of the building. As heating, cooling and domestic hot water production are three operations that consume excessive amounts of energy we designed a system to reduce it.

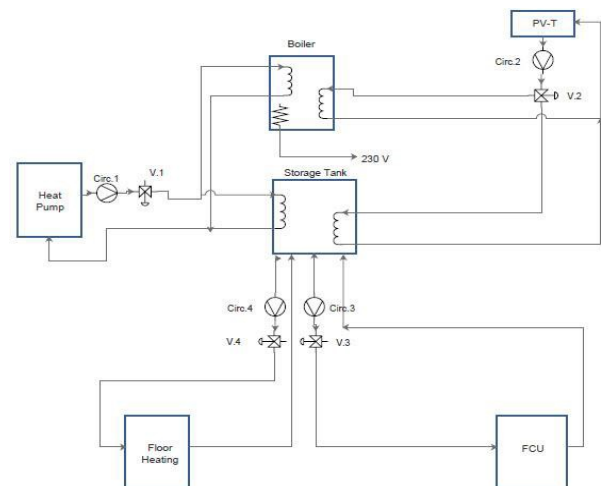


Fig. 3. Building Energy Management System

The system is shown in Fig. 3, and consists of:

- A boiler for the domestic hot water storage.
- A storage tank for the storage of water for the heating and cooling of the building.

is very promising in the field of energy efficiency of buildings.

The experiments and simulations conducted above reveal the following conclusions:

The convenience offered by FCMs when we face complex problems, such as the control of a building automation which require the consideration of many parameters. The controller which was developed gives us much faster and accurate results on how to effectively use the building automation without wasting time in the mathematical modeling of the problem.

The FCM developed simplifies the study of energy saving.

The improvements proposed in this paper lead to a more accurate results of the method and can lead to further improvements.

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METADATA

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