A review on Zero Energy Buildings and Intelligent Systems

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***Abstract*—In recent years the concept of Zero Energy Building (ZEB) has attracted international interest and has led to the beginning of a new generation of buildings. There is a worldwide attempt to define the concept of ZEB and specify a methodology of modeling its operation. Defining the parameters that should be taken into consideration and classifying ZEBs helps that attempt. Energy management and intelligent control are playing a key role in the successful operation of a ZEB, improving its performance and reducing its consumption. The method of Fuzzy Cognitive Maps (FCMs) is appropriate for problems with many parameters, where mathematical modeling and calculations have difficult or, in some cases, impossible solution. ZEB is a complex system and therefore it should be as "intelligent" as possible and the use of FCMs in ZEB operation modeling is a very promising field.**

Keywords— Intelligent Systems; Intelligent Control; Zero Energy Building; Fuzzy Cognitive Maps (FCMs);

I. INTRODUCTION

According to the European Commission nowadays buildings consume about 30-40% of all primary energy produced worldwide and are responsible for the 36% of CO_2 emissions. A building's construction, operation and demolition need large amount of energy, land, water and raw materials [1], [26]. Also the amounts of greenhouse gas emissions and construction and demolition wastes cannot be neglected. For all the above reasons, scientists and engineers began to use passive techniques, mainly during the design, and active techniques, during construction and operation, taking into consideration the human need to ensure comfortable living conditions while saving energy and reducing environmental pollution.

In addition, apart from scientists and researchers, the EU "Energy Performance of Buildings" Directive (EPBD), released in 2010, and the "Energy Efficiency Directive", released in 2012, lead the member nations of EU to adjust their legislation, taking into consideration the energy performance of buildings. Specifically, from 2019 all new buildings occupied and owned by public authorities will have to be nearly Zero Energy Buildings, and by the end of 2020 all new buildings will have to be nearly Zero Energy Buildings. That attempt also appeared in USA, where US Department Of Energy (DOE) with the Building Technologies Program set the goal of "marketable zero energy homes in 2020 and commercial zero energy buildings in 2015" [6], [32]-[35]. It is a fact that different countries have different climates and as a consequence the energy demand of their buildings varies. In addition, due to different evolutionary rates, there is a remarkable difference among materials, designs, age and construction of buildings in different countries. For that reasons there cannot be a single regulation which will satisfy all countries' requirements, but there has to be an adjustment to the needs of each country [37]-[39].

Since a building is a rather complex system with many individual parts, its operation should be "intelligent". High performance control methods are necessary in order to achieve the goals mentioned above.

This paper is a review of ZEBs and intelligent systems. In the second and third section the concepts of zero energy building and intelligent systems are analyzed. In the fourth section the control method of FCM is shortly presented. In the fifth section intelligent ZEBs are discussed and in the sixth section there is a simple example of how an intelligent FCM could be applied on a ZEB. In the last part there are the conclusions, which are ground for further research and development of the subject of intelligent ZEBs.

II. ZERO ENERGY BUILDING

A. Definition and Classification

Zero Energy Building (ZEB) is based on the concept of a building which, within its boundaries, produces as much energy as it consumes, usually on an annual basis. The produced energy mainly comes from renewable energy sources which are located near the building, do not pollute the environment and their cost is reasonable. Since a specific way to achieve the desirable energy balance has not yet been defined and established, the aspect of ZEBs is rather challenging. The absence of specific characteristics and equipment requirements is the reason why an accurate definition has not yet been expressed [1]-[9].

In order to be appropriate for use, buildings should provide specific comfort conditions for people who are inside. Those conditions are achieved by consuming energy for heating, cooling, lighting and other services. Buildings mainly consume electrical energy, other types of energy which are consumed, such as thermal, are usually produced either by converting electrical energy or by passive techniques, such as solar heating or geothermal energy.

The energy requirements of each building depend on its utility. There are three categories of buildings according to their use. Those are 1) commercial, 2) public and 3) residential buildings, as it is mentioned in [10],[11]. Another important factor related to the required energy is the geographical position of each building. Usually in regions with lower temperature a larger amount of energy is consumed in space heating whereas in warmer regions more energy is consumed in air-conditioning and cooling.

A ZEB is characterized by its connection to the grid according to the following reasoning. Usually in regions where a connection to the grid is not accessible buildings are not connected to the grid. Those ZEBs are characterized as autonomous or stand-alone ZEBs.

On the other hand ZEBs which are connected to the grid are separated in three categories [40] :

- **Nearly Zero Energy Building (nZEB)** is a ZEB connected to the grid which has nearly zero energy balance. This means that the consumed energy is slightly higher than the produced energy.
- **Net Zero Energy Building (NZEB)** is a ZEB connected to the grid which has zero energy balance. In that occasion the consumed energy is equal to the produced energy.
- **Net plus or Positive Energy Building** is a building with positive energy balance. The positive energy building consumes less energy than it produces and the excess energy is supplied to the grid.

In all the above cases the energy balance is calculated on annual basis.

The design of each building is made taking into consideration the energy requirements and the applications which are used to satisfy those requirements. The required energy is mainly produced by renewable energy sources, but when those sources are not enough to satisfy the load, conventional energy sources might be used as well. The energy sources may be on the building, on its site or at a distance.

It was mentioned above that in cases of positive energy buildings excess energy is usually provided to the grid. Alternatively, that energy might be saved for later use in energy storage devices. Those devices can also be used in autonomous buildings in order to save energy for later use. However those devices have the disadvantages of 1) limited technology and 2) the need of regular maintenance and replacement [11], [12].

S.D.Pless and P.A.Torcellini make a classification of ZEBs according to their energy supply [12]. They refer to four different definitions regarding the energy source, the site of energy production, the energy costs and the emissions. Those parameters are determined by the designer and the owner of the building and they affect the construction materials and the energy sources that will be placed on the building and on its site. Regarding if the energy sources are on-site or off-site, there is also another type of classification in four categories, NZEB-A, NZEB-B, NZEB-C and NZEB-D [12]. In addition, various calculation methods have been used, some of them and their parameters are mentioned in [1], [12].

B. Comfort Conditions

Apart from the consumed energy, their energy source and their energy management, all buildings should provide specific comfort conditions for people who live, work or are hosted inside.

Fig.1 is a graphic presentation of comfort zones as a function of temperature and humidity. Thermal comfort is the condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation (ANSI/ASHRAE Standard 55), [13]. This means that two people who are in the same inner environment might not feel the same comfort, and it depends on various reasons, both environmental and personal. Environmental factors are: air temperature, air velocity, radiant temperature and relative humidity. Personal factors are: clothing, metabolic heat, sickness and well-being generally [14]. Furthermore, thermal comfort conditions can be predicted and controlled inside a building and there are regulations that define those conditions such as ISO 7730 [15].

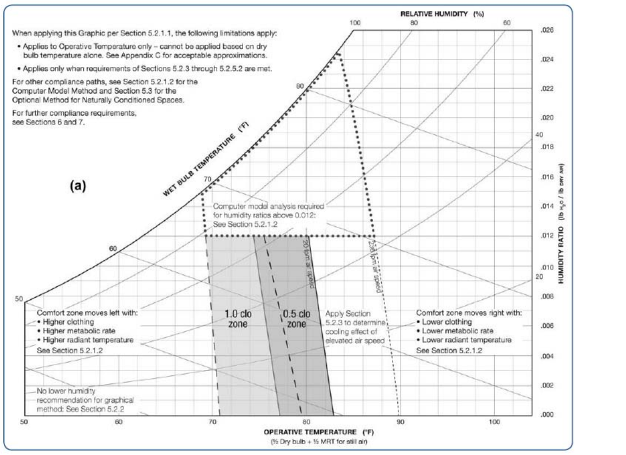

Fig.1 The Graphic Comfort Zone Method, Standard 55-2010. Source ASHRAE

C. Modeling and Control

In order to create a model of a ZEB, someone should consider several parameters. The most important of them are:

- *The size and construction materials*. Buildings made of different size and different materials do not react in the same way even if they are exposed at the same climate.
- *The utility.* As it was mentioned above, buildings which are

used for different activities, have different energy requirements. The amount, the quality and the time period of energy consumption are different in each case. For example an industrial building is has different needs comparing to a school, or a hospital, or a typical house.

- *The geographical position.* Buildings in different latitudes and longitudes have different energy requirements as well as different prospects of energy production.
- *The "regional climate levels or microclimate".* Buildings which are at high altitudes, those which are by the sea and those in the middle of a plain, practically have different climates, different temperatures and humidity, and as a consequence they have different energy requirements.
- *The available renewable energy sources*. All types of renewable energy sources cannot be placed on all buildings, some of them cannot be placed even on their site.
- *Unpredicted parameters*. Those can be of two kinds. First, people who are hosted in the building and their activities cannot always be predicted, the reason is the subjective factor, mentioned in part B. And second, renewable energy sources are highly depended on whether conditions and there is always a percentage of uncertainty on whether predictions.

Modeling a building, considering all those parameters is a rather complex problem and it requires detailed and careful steps. The designer, the engineer and the owner should cooperate and adjust the building to achieve the desired performance.

Furthermore, using traditional control methods on such a complex system is only achieved by separating different tasks and controlling one application at a time. Usually there is one control system for lighting, one for heating/cooling, one for ventilation, etc. In order to control groups of applications and consider the interaction between them, for example ventilation affects not only the inside air quality but the temperature as well, more "intelligent systems" are essential.

III. Intelligence and Intelligent Systems

It is appropriate at this point to briefly comment on the meaning of the word intelligence as generic term. The precise definition of "intelligence" has been eluding mankind for thousands of years. However the true nature of intelligence has been debated more intensely than ever over the last century. As the science of psychology has developed one of the biggest questions it had to answer concerned the nature of Intelligence. Some of the definitions that have been given for intelligence have been the ability to adjust to one's environment. Of course by such a definition even a person who is generally considered to be dull can be regarded as being intelligent if he can take care of himself. Other definition is such as having the tendency to analyze things around yourself. However it can be argued that such behavior can lead to over-analyzing things and not reacting to one's environment and dealing with it in an "intelligent manner".

One of the most definitive things ever said regarding the nature of intelligence was that intelligence is whatever IQ tests measure. The IQ test has been in use throughout the 20th century and serves as an accepted measure of a person's intelligence. It is used by institutions such as schools and the army to screen people's level of intelligence and decisions are made based on that. The IQ test consists of a series of questions regarding certain skills such as vocabulary, mathematics, spatial relations. The scores that a person gets on these tests depend on the amount of questions that a person answers correctly.

All these have lead scientists and engineers to develop a challenging scientific area that of Intelligent Systems (IS). The area of broadly perceived as IS has emerged, in its present form, just after World War II, and was initially limited to some theoretical attempts to emulate human reasoning, notably by using tool from formal logic. The advent of digital computers has clearly played a decisive role by making it possible to solve difficult problems. In the mid-1950 the term artificial intelligence was coined. The early research efforts in this area, heavily based on symbolic computations alone, though have had some successes, have not been able to solve many problems in which numerical calculations have been needed, and new, more constructive approaches have emerged, notably computational intelligence which have been based on various tools and techniques, both related to symbolic and numerical calculations. This modern direction has produced many relevant theoretical results and practical applications in what may be termed intelligent systems.

It is quite natural that a field, like that of intelligent systems, which is both scientifically challenging and has such tremendous impact on so many areas of human activity at the level of an individual, small social groups and entire societies, has triggered attempts to discuss basic topics and challenges involved at scientific gatherings of various kinds, from small and informal seminars, through specialized workshops and conferences to large world congresses.

More recently, this issue has been addressed by disciplines such as psychology, philosophy, biology and of by artificial intelligence (AI); note that AI is defined to be the study of mental faculties through the use of computational models. Again no consensus has emerged as yet of what constitutes intelligence. Intelligence is also considered as a very general mental capability that, among other things, involves the ability to reason, plan, solve problems, think abstractly, comprehend complex ideas, learn quickly and learn from experience. It is not merely book learning, a narrow academic skill, or test-taking smarts. Rather, it reflects a broader and deeper capability for comprehending our surroundings—"catching on," "making sense" of things, or "figuring out" what to do. Fuzzy Logic and Fuzzy Cognitive Maps have emerged as serious scientific developments the last 20-25 years in modeling and controlling dynamic complex. It is now time to see how FCM can be used intelligently to address challenging problems and issues for Decision Making Support Systems (DMSS). But first a short introduction to Fuzzy Cognitive Maps is needed.

IV. Fuzzy Cognitive Maps

Fuzzy Cognitive Maps (FCMs) are a combination of fuzzy logic and neural networks. They are a method of modeling complex problems, based on human reasoning. A human can make a decision even if a problem is uncertain or ambiguous, using his experience and assessment ability. FCMs are based on that reasoning. They are a graphical presentation of the problem. Each parameter (variable) is presented with a node and it is called “concept”. The interaction between concepts and the way they affect each other are presented with “weights”. Concepts take values in the interval [0, 1] and weights belong in the interval [-1, 1]. Fig.2 shows a representative diagram of a FCM [16].

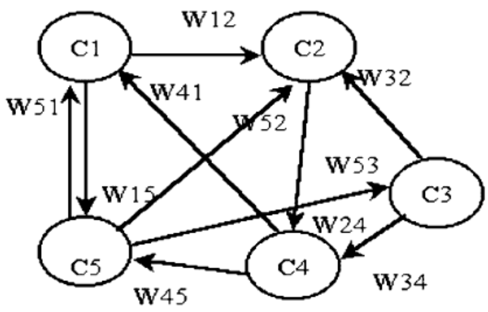

Fig.2 A simple Fuzzy Cognitive Map

The sign of each weight represents the type of influence between concepts. Between two concepts C_i and C_j there could be three cases:

- $w_{ij}>0$, an increase in C_i causes an increase in concept C_j, and a decrease in C_i causes a decrease in concept C_j.
- $w_{ij}<0$, an increase in C_i causes a decrease in C_j, and a decrease in C_i causes an increase in C_j.
- $w_{ij}=0$, there is no interaction between concepts C_i and C_j.

The amount 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:

$$A_i(t) = f\left(A_i(t-1) + \sum_{\substack{j\neq i \\ j=1}}^{n} A_j(t-1)\cdot w_{ji}\right) \tag{1}$$

Where t represents time, n is the number of concepts and f is the sigmoid function given by the following equation:

$$f = \frac{1}{1+e^{-\lambda x}} \tag{2}$$

In which $\lambda>0$ determines the steepness of function f.

Usually in problems there is a number of concepts and **A** and **w** are matrices.

The FCM concepts take initial values and then they are changed depending on the weights and the way the concepts affect each other. The calculations stop when a stable state is achieved and the values of concepts do not change furthermore [16]-[19].

V. Intelligent Zero Energy Buildings

If someone would like to see how deep in the past the concept of intelligent building begins, they should go back to ancient Greece and Rome, where houses were build oriented to the sun in order to take advantage of the solar radiation and be warm in winter. Buildings have changed radically since then, but the concept of using energy sources in the most effective way has been the same. As it was mentioned above, intelligent buildings have nowadays been part of legislations and their construction will be inevitable.

The term Intelligent Zero Energy Building (I-ZEB) is even harder to be defined, when today there are so many different approaches for a ZEB and its characteristics. Intelligence as it was discussed in section III has paramount importance and contribution in the design of future ZEBs, since many different parameters and concepts must be taken into consideration. Apart from the parameters of the buildings characteristics, the used equipment and external parameters such as weather, additional parameters should be taken into consideration. For example, what would constitute Intelligent Efficiency (IE)? If IE is considered as a simple ratio of two measured parameters, the numerator and the denominator, the parameters that should be considered must be chosen. Otherwise, a further step should be made and search for “intelligent measurements” should be considered. Therefore, in the future IZEB will be a major part of the outgoing research.

The first step of constructing an I-ZEB is its design. Several design optimization techniques have been discussed ([20]-[23]) taking into consideration various parameters, such as climate, utility, location etc.

Attia et al. in [24] have been comparing various tools of building performance optimization, considering usability, accuracy, process adaptability, interoperability and intelligence, and have reached to the conclusion that each tool has its disadvantages because the ZEB system has many parameters and each tool gives priority to some of them.

In addition, energy efficiency, use and cost optimization have been discussed in [25]-[31] emphasizing the complexity of the problem and the necessity of finding an appropriate methodology in order to overcome the arising difficulties. Some of the benefits that intelligent buildings earn through energy management are:

- Longer lifecycle of building and its equipment.
- Reduced system and equipment failures.
- Improved comfort conditions for hosted people.

- Increased productivity of stuff.
- Low energy consumption.
- Reduced cost of operation and maintenance.
- Lower impact on the environment.

There are various methods of control and optimization which can be applied on ZEBs. In the next section there will be an example of the way a FCM could be applied and model the operation of a ZEB.

VI. Using FCM in ZEB applications

At this point the relation between all the above sections will be discussed. Kolokotsa D. et al. in [36] present the components of ZEB architecture during real-time operation. In order to make a FCM to represent the interconnection of those components and create a model of the building's operation, an expert should consider each component as a concept and determine the weights between them. In Fig.3 there is a simple FCM presenting the operation of a ZEB.

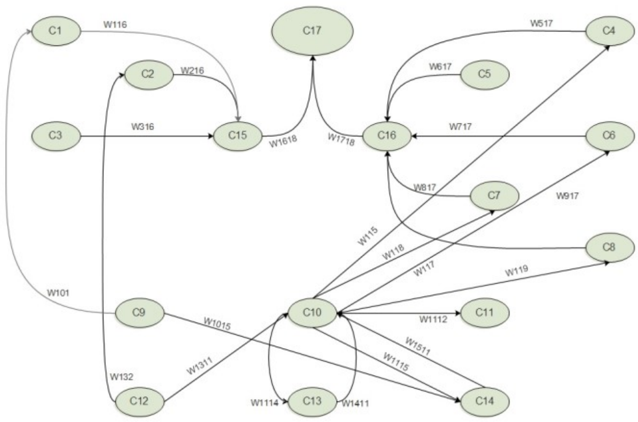

Fig.3 A FCM representing a ZEB.

In that FCM the concepts are:

- C1: PV System
- C2: Wind Turbine
- C3: Geothermal Energy
- C4: Lighting
- C5: Electrical/Electronic Devices
- C6: Heating
- C7: Cooling
- C8: Ventilation
- C9: Solar Radiation
- C10: Windows
- C11: Natural Light inside the building
- C12: Air Velocity
- C13: Shading
- C14: Inside Temperature
- C15: Total Produced Energy
- C16: Total Consumed Energy
- C17: Energy Balance

Concepts C1-C3 refer to energy production, C4-C8 refer to energy consumption and C9-C14 refer to parameters which play an important role and cannot be neglected. Concept C15 refers to the total produced energy and concept C16 to the total consumed energy. The last concept, C17, is the energy balance of the building. It is equal to the total produced energy minus the total consumed energy (C15-C16). The desired energy balance value is zero. A positive value is also accepted since the excess energy will be provided to the grid.

As it was mentioned in the introduction a ZEB should produce as much energy as it consumes within a year. Using an FCM to control and manage the produced and consumed energy is perhaps the most important tool in the achievement of the balance goal.

An expert determines the weights and the interaction between concepts. In a simulation initial values are given to all concepts. The intelligent system changes the values until a steady state is achieved. In the occasion of a ZEB some concepts cannot change value. Those are the wind velocity, and the solar radiation, because those parameters depend on weather. Also there are some concepts, such as PV system, wind turbine and geothermal energy, which can be controlled partially, for example with an MPPT tracker in a PV System. Those concepts might be changed or not by the intelligent system. And finally the rest of the concepts, grid, lighting, electrical/electronic devices, heating, cooling, ventilation, windows, natural light inside the building, shading and inside temperature, are those which are determined by the FCM and are calculated from the intelligent system in order to attain appropriate comfort conditions for people who are inside the building. Once those conditions are attained and a steady state is reached, then the intelligent system stops the calculations.

If the system has reached a steady state and a sudden change happens, for example someone opens a window, the FCM calculates new values for each concept and arrives in a new steady state. This means that the system behaves dynamically to changes, adjusting to them.

VII. Conclusions

In this paper the concepts of ZEB and IS were analyzed and a combination of them was discussed. IS are necessary in the case of ZEB, since it is a complex system with many parameters. FCMs, based on human thought and reasoning, make that complex problem seem rather simple.

The method of FCM, which was developed here with 17 concepts, gives a new approach to ZEB modeling. This method is rather promising for future research and simulations, since all the single parts of the building and their interaction are considered simultaneously and the way each one of them affects the energy balance, which is the result, can immediately be determined.

There has been some research on the aspect of mathematical modeling of ZEBs and there has been an effort to create some calculation and design methodologies. However, further research on that subject is essential since a specific methodology of energy management and balance achievement has not yet been established.

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