Chaos and Complexity Models in Sustainable Building Simulation

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Abstract: This paper intends to provide suggestions of how sustainable building simulation might profit from mathematical models derived from chaos and complexity approaches. It notes that with the increasing complexity of building systems which are capable of intelligently adjusting buildings' performance from the environment and occupant behaviour and adapting to environmental extremes, building performance simulation is becoming more crucial and heading towards new challenges, dimensions, concepts, and theories beyond the traditional ones. The paper then goes on to describe how chaos and complexity theory has been applied in modelling building systems and behaviour, and to identify the scarcity of literature and the need for a suitable methodology of linking chaos and complexity approaches to mathematical models in building sustainable studies. Chaotic models are proposed thereafter for modelling energy consumption, nonlinear moisture diffusion, and building material properties in building simulation. This paper provides an update on the current simulation models for sustainable buildings.

Keywords: Chaos and complexity theory, Sustainable building simulation, Energy consumption, Moisture diffusion and Material properties.

1. Introduction

Buildings represent a large share of the world's end-use energy consumption. Due to rapid worldwide increases in energy consumption, climate change driven by global warming, and rising energy shortages, there is no doubt that renewable energy and sustainable buildings will play a major role in the future. Today, sustainable buildings are seen as a vital element of a much larger concept of sustainable development that aims to meet human needs while preserving the environment so that the needs can be met not only in the present, but in the indefinite future [1]. Moreover, the concept itself keeps on evolving

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and resulting in iterations of sustainability [2]. Technically, sustainable buildings require integration of a variety of computer-based complex systems which are capable of intelligently adjusting their performance based on the environment and occupant behaviour and intelligently adapting to environmental extremes [2].

With the increasing complexity of building systems, simulation based design and predictive control of building performances are becoming more and more important for a sustainable energy future. Consequently, this makes building performance models more complex and crucial and they are heading towards new challenges, dimensions, concepts, and theoretical framework beyond the traditional building simulation theories. It has been suggested that as a basis chaos and complexity theory is valid and can handle the increasing complexity of building systems that have dynamic interactions among the building systems on the one hand, and the environment and occupant behaviour on the other. In this paper we do not distinguish between chaos and complexity theories even though there has been a debate about their differences [3].

The chaos models have already been applied to some problems in building simulation applications. Chow et al. investigated chaos phenomena of the dynamic behaviour of mixed convection and air-conditioning systems for buildings with thermal control [4]. Weng et al. applied chaos theory to the study of backdraft phenomenon in room fires [5]. Morimoto et al. studied an intelligent control technique for keeping better quality of fruit during the storage process [6]. For humidity control purpose, the sampled relative humidity data in storage house were measured and analysed. Chaos phenomenon was identified in such measured relative humidity data during daytime hours.

In spite of the studies discussed above, the application of chaos theory to building performance simulation, especially to sustainable buildings, is still in its infancy. Building performance simulation models can be roughly classified into either the physical model or the black-box approach. Some may be difficult to categorise in this way. As far as the physical model is concerned, there is a voluminous literature on the models ranging from detailed to local thermal analysis of energy demand, passive design, environmental comfort and the response of control [7,8]. These physical models often require sufficient information on systems, control and environmental parameters for buildings. The output of the model is only as accurate as the input data.

Presently input data for buildings are often poorly defined, which creates ambiguity or uncertainty in interpreting the output. This is the general drawback of these models. Therefore, for many practical applications, a black-box approach, a model without internal mechanisms or physical structure, is often adopted. For example, neutral networks, fuzzy logic, and time series models [9,10] are generally better suited for prediction. However, these models have several limitations. Take neural networks as an example. Firstly, large experimental input and output data are needed in order to build neural networks which can be difficult and expensive to obtain in practice. Secondly, they are susceptible to over-training. Above all, the models have been criticised as 'black box' models with no explanation of the underlying mechanisms that drive the study systems [11].

More specifically, as for sustainable buildings, the current models often lack the long-term economics factors, evolving factors, and flexibility necessary for dynamic predictions. These weaknesses and the current status of sustainable building simulation models have encouraged us to focus instead on a chaos-based model incorporating physical model to enhance our understanding and prediction of building physical behaviour. Chaos theory is characterised by the so-called 'butterfly effect' [12]. It is the propensity of a system to be sensitive to initial conditions so that the system becomes unpredictable over time. Yet, a chaotic process is not totally random and has broadened existing deterministic patterns with some kind of structure and order [12]. This paper extends the literature by proposing potential chaotic models in sustainable building simulation. Below we describe three such models. The first is a building energy consumption model. The second deals with a nonlinear moisture diffusion model. The third is related to building material properties.

2. Building Energy Consumption Model

Swan provided an up-to-date review of various simulation models used for modelling residential sector energy consumption and sustainability [13]. Most models rely on input data whose levels of details can vary dramatically. Li presented an overview of literature regarding long-term energy demand and CO_2 emission forecast scenarios [14]. These reviews reflect general modelling approaches currently in existence for sustainable buildings. Two approaches are generally adopted: top-down and bottom-up. The top-down approach utilises historic aggregate energy values and regresses the energy consumption of the housing stock as a function of top-level variables such as macroeconomic indicators. While the generally employed techniques account for future technology penetration based on historic rates of change, they lack of evolving factors. Hence an inherent drawback of the generally employed approaches is that there is no guarantee that values derived from the past will remain valid in the future, especially given the fact that the levels of details of input data vary significantly [13].

The bottom-up approach extrapolates the estimated energy consumption of a representative set of individual houses to regional and national levels, and consists of two distinct methodologies: the statistical method and the engineering method [13]. Methodologically, extrapolation has been questioned for many good reasons. It is therefore noted that the statistical technique is hampered by multicollinearity resulting in poor prediction of certain end-uses while the engineering technique requires more inputs and has difficulty estimating the unspecified loads [13, 15].

The major disadvantage of these models is their lack of flexibility due to the fact that there is no deterministic structure provided to characterise the data. In this context, chaos theory offers a solid theoretical and methodological foundation for interpreting the fundamental deterministic structure of the data which present the increasingly complexity of building systems. Karatasou applied chaos theory in analysing time series data on building energy consumption [16]. The correlation dimension 3.47 and largest Lyapunov exponent 0.047 were estimated for the data, which indicates that chaotic characteristics exist in the energy consumption data. Therefore, chaos theory techniques can be used to model and predict buildings energy consumption.

3. Strong Nonlinear Moisture Diffusion Model

Building envelopes can be susceptible to moisture accumulation which may cause mould growth and the deterioration of both occupant health and building materials. A certain duration of exposure conditions, such as humidity, temperature, and exposure time, is required for the growth of organisms and the start of the deterioration process. Critical exposure duration depends on the particular exposure and material. Take a critical moisture level as an example. If the moisture content in the material exceeds the critical level, there is a risk of damage [17] and mould growth [18]. Trechsel summarised that the critical moisture level can be presented as critical factors such as 'the critical moisture content' and 'the critical accumulative exposure time' [19]. He emphasised that with qualitative criteria it is not possible to assess the risk. Qualitative criteria can be used only if performance limit states are known which need statistical data. Evidence has shown the existence of inherent randomness and nonlinearity in mould growth and the data [18]. Therefore, the moisture transfer process manifestly has chaos.

From a physical modelling point of view, heat and moisture transfer phenomena in a medium are governed by heat or diffusion equations which are partial differential equations. For a homogeneous and isotropic medium, the diffusivity coefficient is often assumed to be constant in the entire domain under study. In inhomogeneous media, it depends on the coordinates [20]. Until now, there is no model has considered time-dependent diffusivity. However, time-dependent diffusivity, which might be due to the time-dependent perturbation of environment such as sudden structural change, is an optional explanation for the critical moisture level.

Yao studied one-dimensional Kuramoto–Sivashinsky (KS) equation, a nonlinear partial differential equation, in the hope of clarify the role of the time-dependent governing parameter and the sensitivity of the long-time solution to initial conditions [21]:

$$u_t + 4u_{xxxx} + \lambda(u_{xx} + uu_x) = 0 \qquad (1)$$

Nonlinear stability analysis was investigated with respect to time-dependent λ. After a certain time (t =4), chaotic behavior was observed.

It is not difficult to see that the KS equation and nonlinear moisture diffusion equations do not differ significantly. Thus the KS equation example is expected to more easily expose major points and hopefully identify open questions that are related to the critical moisture level or mould phenomena as related to chaos phenomena.

4. Material Properties Model

Porous media have played a major role in building engineering applications. They are important elements of heat and mass conservation for buildings and have been extensively studied [22]. A porous material has a unique structure of complex geometry which is characterised by the presence of a solid matrix and void phases with porosity. The heat and mass transport behaviour of porous media is largely governed by the interactions among coexisting components. These interactions occur through interfaces. Theoretically, transport processes in a porous medium domain may be described by a continuum at the microscopic level based on the Navier-Stokes equations for example, as taking into account the multi-phase nature of the domain. However, for most cases this is impractical because of the inability to both describe the complex geometry and trace a large number of interfacial boundaries for the porous domain. Therefore, the porous media models are often constructed through averaging the governing equations, for example Navier-Stokes equations, in continua at the microscopic level over a length scale such as representative elementary volume [23]. During the averaging process some integrals are performed, introducing a weighted average of the relevant variables, parameters and properties which can be determined by laboratory and field measurements.

However, both laboratory and field measurements are often tedious, time consuming and expensive. This has motivated researchers toward the development of mathematical modeling approaches based on routinely measured properties. In general, three types of mathematical models are used to model material transport properties: empirical, bundle of tubes, and network models [24]. The empirical models provide a set of analytical functions to fit the measurement data for material properties. The model has the advantage of simplicity but the disadvantage of limited flexibility and adjustability and hence low reliability.

Depending on how they represent the geometry of the material, both the bundle of tubes and the network models rely on the pore structure, such as pore distribution, connectivity and tortuosity, to derive the material's transport properties. These models are also called pore-distribution models and were pioneered by Fatt [25-27]. The bundle of tubes model approximates the pore structure in a fairly simple way, for example, a set of parallel tubes [24]. Networks models approximate the pore structure by a lattice of tubes and throats of various geometrical shapes on the microscopic scale. Creating a network model is laborious and not straightforward especially for 3D models [28].

Most importantly, these models, or current state of material property modelling approaches, are case sensitive depending on the excited boundary or the environment. Therefore, variations of material properties under different conditions are large, which has been a challenge for modellers. On a longer time scale, **a** large quantity of data is often needed to build the model and this can be difficult and expensive to accomplish in practice. In addition, in a wide environment setting when different environmental phenomena overlap, material properties become complicated and difficult to predict [29]. This is due to the lack of a deterministic structure or a core mechanism which characterises the material transport properties. Chaos theory provides a tool to exploit the underlying structures that appear random or unpredictable under traditional analysis.

Stazi et al. applied chaos theory to investigate the hygrometric properties of building materials, such as adsorption and suction curves [29]. The constitute relationship of a material's water content and the environment humidity was modelled on the basis of fractal geometry using the material's pore radius as:

$$u = u(\phi, D) \tag{2}$$

where u is the hygroscopic content inside the material and ϕ the relative humidity of the material. Their relationship was determined through finding the material 's fractal dimension of water inside the pores, D, which was 2.5265 for mortar [29].

The novelty of the model lies in its ability to construct the relationship between the water content inside the material and the relative humidity of the environment based on the material's geometric property characterised by the fractal dimension. The knowledge of the fractal dimension of the pore spacing in a porous medium is enough to work out the suction and adsorption curves of the material. It is, therefore, natural for us to consider chaos theory as a source of inspiration to envisage the importance of the concerns raised in research in different fields of building material properties.

5. Conclusions

This paper suggests some new thinking about how to update the current status of simulation models for sustainable buildings. Three chaotic models are proposed. The first is the building energy consumption model because chaotic characteristics have been observed in the specific energy consumption data. The second deals with the investigation of nonlinearity of the moisture diffusion model. The third model involves the investigation of material physical properties. The conclusion to be drawn is that chaos theory may reflect real situations, deepen our understanding, and make predictions more realistic in sustainable building simulation.

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