CHAOS MODELS IN SUSTAINABLE BUILDING SIMULATION

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Summary

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

Keywords: Chaos theory, Sustainable building simulation, Energy consumption, Moisture diffusion

1 Introduction

Buildings represent a large share of world’s end-use energy consumption. Due to rapid increase of energy use, the climate change driven by global warming, and rising energy shortage, there is no doubt that renewable energy and sustainable buildings are future's direction. 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 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 from the environment and occupant behaviour and adapting to environmental extremes [2].

With the increasing complexity of building systems, building performance simulation is becoming more crucial, and it is heading towards new challenges, dimensions, and concepts and theories beyond the traditional ones. It has been suggested that as a basis chaos theory is valid and can handle the increasingly 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. Chow et al. investigated chaos phenomena of the dynamic behaviour of mixed convection and air-conditional systems for buildings with thermal control [3]. Weng et al. applied chaos theory to the study of backdraft phenomenon in room fires [4]. Chaos phenomenon has been identified in relative humidity time series i storage house [5].

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 [6]. The physical models often require sufficient information on systems, control and environmental parameters for buildings. The output of the model is only as accurate as input data. Presently there are many building input data which are poorly defined, which creates ambiguity or uncertainty in interpreting the output. Therefore, for many practical applications, a black-box approach, for example neutral networks and fuzzy logic models, is often adopted which is generally better suited for prediction. However, these models have several limitations such as over-fitting and requirements for large experimental data. Above all, the models have been criticized as 'black box' model with no explanation of the underlying dynamics that drive it [7].

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 building simulation models have encouraged us to focus instead on a chaos-based model incorporating physical model in understanding and prediction of building performance. Chaos theory is characterised by the so-called ‘butterfly effect’. 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 [8]. This paper extends the literature by proposing potential chaotic models in sustainable building simulation. Below we describe two such models. The first is building energy consumption model. The second deals with nonlinear moisture diffusion.

2 Building Energy Consumption Model

Swan and Li provided up-to-date review of simulation models regarding energy consumption and sustainability in residential sector, and forecast scenarios for long-term energy demand and CO_2 emission [9,10]. The review reflects general modelling approaches currently in existence in sustainable buildings. Two approaches are generally adopted: top-down and bottom-up. The top-down approach utilizes 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 general employed techniques may account for future technology penetration based on historic rates of change, they lack of evolving factors. Hence an inherent drawback 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 [9,10].

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 [9]. 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 engineering technique requires many more inputs and has difficulty estimating the unspecified loads [9].

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 analsying building energy consumption data [11]. They evaluated several chaos indices and found that chaotic characteristics exist in the energy consumption data set. It was concluded that chaos theory techniques based on phase space dynamics 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 growth of moulds and the deterioration of both occupants' health and building materials. Many building materials have a critical moisture level for such deterioration risk [12,13]. It has been emphasized that with qualitative criteria it is not possible to assess the risk because qualitative criteria can be used only if performance limit states are known which need statistical data [13]. Evidence has shown the existence of inherent randomness and nonlinearity in mould growth and the data [14]. Therefore, moisture transfer process manifestly has chaos.

From a data modelling point of view, diffusion equations governing diffusion under moisture and temperature gradients are used to model moisture transfer across building components. Yao studied one-dimensional nonlinear Kuramoto–Sivashinsky (KS) equation in the hope of clarify the role of nonlinear terms [15]:

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

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

It is not difficult to see that the KS equation and moisture diffusion equation do not differ significant. Until now, there is no model that considers time-dependent diffusivity. However, time-dependent diffusivity, which might be due to time-dependent perturbation of environment such as sudden structural change, is a possible explanation to the critical moisture level. 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 in related to chaos generation.

4 Conclusions

This paper aims to provide a suggestion to update the current status of simulation models for sustainable buildings. Two chaotic models were proposed. The first is the building energy consumption model as chaotic characteristics has been observed in the specific energy consumption data set. The second is dealing with investigation of nonlinearity of the moisture diffusion model. The conclusion to be drawn is that chaos theory may reflect real situations and deepen our understanding and also make predictions more realistic in sustainable building simulation.

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