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Integration of chaos theory and mathematical models in building simulation Part II: Conceptual frameworks

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ABSTRACT

Current mathematical models in building research have been limited in most studies to linear dynamics systems. A literature review of past studies investigating chaos theory approaches in building simulation models suggests that as a basis chaos model is valid and can handle the increasing complexity of building systems that have dynamic interactions among all the distributed and hierarchical systems on the one hand, and the environment and occupants on the other. The review also identifies the paucity of literature and the need for a suitable methodology of linking chaos theory to mathematical models in building design and management studies. This study is broadly divided into two parts and presented in two companion papers. Part (I), published in the previous issue, reviews the current state of the chaos theory models as a starting point for establishing theories that can be effectively applied to building simulation models. Part (II) develop conceptual frameworks that approach current model methodologies from the theoretical perspective provided by chaos theory, with a focus on the key concepts and their potential to help to better understand the nonlinear dynamic nature of built environment systems. Case studies are also presented which demonstrate the potential usefulness of chaos theory driven models in a wide variety of leading areas of building research. This study distills the fundamental properties and the most relevant characteristics of chaos theory essential to (1) building simulation scientists and designers (2) initiating a dialogue between scientists and engineers, and (3) stimulating future research on a wide range of issues involved in designing and managing building environmental systems.

1. Introduction

Chaos theory offers a solid theoretical and methodological foundation for interpreting a wide class of nonlinearity, instability and uncertainty which characterise the increasingly complexity of building systems. In this context, crisis is positioned as a natural stage of any system development, but ultimately will lead to a deeper level of understanding. Chaos theory represents a significant paradigm shift from a linear world view, modelled on an old mechanistic and deterministic Cartesian/Newtonian vision, to a post-Cartesian/Newtonian nonlinear world [1]. In the companion paper, starting from the fundamental properties of chaos theory essential to building simulation scientists, the current state and future direction of chaos theory based models in simulating complex building systems, as well as scientific evidence of chaos in building behaviour, are reviewed [2]. The results suggest that chaos theory poses a promising and valid alternative for modelling complex, unsteady and unpredictable dynamics associated with many aspects of building systems. However, applications of chaotic models remained few in the literature. One reason supporting this statement is that to date no fundamental conceptual framework with sufficient explanatory power has effectively integrated the theory and practical simulation models. The aim of this paper is to develop conceptual frameworks that approach the current model methodologies and applications from the theoretical perspective provided by chaos theory, with a focus on the key concepts and the most relevant characteristics of chaos theory which have the potential to help to better understand the nonlinear dynamic nature of built environment systems.

We therefore envisage potential applications of chaos theory driven models to several leading areas of building research. The first is dealing with the life cycle analysis (LCA), and the second is related to occupants' activity and their interactions with buildings. Ways of expressing control of building engineering systems in systems modelling language are also presented. Case studies provide illustrations of complexity, turbulence, chaos and unpredictability, suggesting that contributions of chaos theory may reflect real situations and deepen our understanding and also make predictions more realistic, highlighting a need for the

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chaos theory to guide building research studies and stimulating future research on a wide range of issues of building environmental systems.

Furthermore, being aware that most building simulation scientists still view chaos theory as an abstract concept which is foreign to them and so have not yet considered it as a practical tool and a useful model approach which is reflected in its few applications [2]. We also demonstrate the power of the proposed frameworks using hypothetical and illustrative time series data which exemplifies an occupant–environment response system where we present a set of diagnostic tests and identify chaos in the data. Results are displayed graphically.

Visualisation techniques are now being developed which can spark imaginative thoughts and so help in understanding systems and their consequences. Hidalgo at Harvard is using network visualisation to study how the components of systems interact and give rise to emergent properties and behaviour [3]. He has patterned diseases and also developed a product space from which conclusions about economic aspects of viable product markets have been derived. Such techniques can serve to detect chaotic dynamics in a variety of systems. Taken together, chaos model based analysis and visualisation of complex systems may open potential practical ways of identifying, forecasting, controlling, and providing insight into complex behaviours in building systems, which would not be possible by other means of the traditional models.

This paper is structured as follows. The next section gives a brief introduction to the proposed conceptual frameworks which aims to understand the use of chaos theory driven models in aforementioned application areas, namely cases studies of life cycle analysis, occupant–environment interaction, and building systems control. Mathematical applications of chaos theory in these case study applications are presented in parallel in Sections 3 to 5. Section 6 contains an illustration which exemplifies an occupant–environment response system using hypothetical time series data. Section 7 summarizes the main conclusions.

2. Proposed conceptual frameworks

The research results cited above demonstrate that the hypothesis of chaos as a modelling basis is valid and reflects the increasing complexity of dynamic building systems. Despite these contributions, the review clearly identifies the paucity of literature and the need for a suitable methodology of linking chaos theory to mathematical models in building studies. We take a step forward in this direction through proposing conceptual frameworks that approach the current model methodologies and applications from the theoretical perspective enriched by chaos theory with a focus on the key concepts and their potential to help better understand the nonlinear dynamic changes in building systems.

We focus on intelligent buildings for two reasons: intelligent buildings involve more complex systems because they include consideration of not only information flow and non-deterministic human behaviour, but also the integration of various problem-solving methodologies in order that a building can learn and adjust its performance [4–6], but there have been so few applications of chaos theory. It should be noted, however, that most of the following discussions are equally applicable to conventional buildings.

In the following, basic concepts of chaos theory are explored to show their potential contributions to a more holistic understanding of complexity of building systems. The theoretical concepts are discussed with reference to case studies.

3. Life cycle analysis model

This section provides an overview discussion of Life Cycle Analysis (LCA)'s general properties and identifies its dynamics and chaotic characteristics. It then proposes the use of chaos theory outlined in the previous section in modelling LCA to capture the complex characteristics of building behaviour.

3.1. The overview of life cycle analysis model

Life Cycle Analysis (LCA) has long been used in the planning design and management over the lifetime of the building as a way of taking into account whole life costing balanced by quality factors. Evaluation should involve the process of building life cycle management so that the life cycle profits are maximised. In such a context, the future cost needs to be appropriately addressed. The most obvious starting point is to consider the dynamic characteristics of the building and the organisation it contains.

For buildings with complex systems, like intelligent buildings, uncertainty or randomness exists not only in the systems but also in every phase of the life cycle. Wong et al. reviewed current investment evaluation models for intelligent buildings and concluded that net present value, LCA analysis and cost benefit analysis are the most commonly applied approaches [5]. Within these approaches, a LCA analysis calculates the cost of a building over its entire life span and tries to offset this with the benefits accrued. These models presume considerable stability in the building's LCA process and takes linearity to be the appropriate profile for such a stable process. However, a building's lifetime is constantly in flux with outliers initiating sustained instability. The lifetime costs should not only include those outliers which include operation, maintenance, repair, natural hazards, damage but also the impacts on people hence their productivity and therefore the business.

Take the cost of damage as an example. Research on earthquakes suggests that economic losses caused by less drastic structural damages as well as functional disruptions can be much higher than the initial cost [7]. Therefore, damages due to emergent events need to be addressed. Another example is the issue of economic impact on productivity hence business. Research has revealed that the cost of employing people is several orders higher than that of not only the capital costs but also the costs of operating and maintaining a building [6,8]. It is not difficult to see that even small differences in capital costs can translate into large differences over the life time of a building hence, the issue of the longer term issues productivity gains or losses for example caused by poor physical indoor environments needs to be included in the evaluation process. These process variables are subject to various degrees of uncertainty or randomness. Although attempts have been made to address these issues through for example soft computing models [9,10], there has not been any widely acceptable method to link these complexities to whole life values, meaning whole life costs and quality. Dynamic cost models that allow for evaluating interactions between for example costs of operation and gains of productivity through a building's life cycle are rare. Cost–benefit analysis is often ignored. Chaos theory applied to LCA models of intelligent buildings can help to unravel some of the complexities and discover the extra sensitive factors which can destabilize the predictions.

3.2. Chaos theory and life cycle analysis model

In this paper, the whole life cost and quality which together constitute value, is defined as a state. As for the process, LCA presents cost behaviour over time, based on the building's initial cost, operation, maintenance, natural hazard, damage and/or failure consequences, all of which can impact on business because productivity can be affected. The evaluating process has defied prediction due to several reasons and gives rise to a chaotic state.

Firstly, healthy buildings tend to increase productivity. Initially there was a lack of data but now we have evidence from research and companies themselves [8,11]. People with good well-being work better and the physical, social and work environment all affect this. Building maintenance and operation management, now called facilities management, is important too because occupants need to feel they are cared for by the company. The study of various management styles in relation to chaos theory is active (e.g. [12,13]). Chaos theory has been used as a