A System Dynamics Approach to Modeling Climate Change Impact: A Case Study of Wood Materials for Buildings

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Abstract. This paper presents a new system dynamics approach to modeling climate change impact. The approach we proposed is a physically based stochastic dynamic method. To illustrate the applicability of the model, a case study of wooden church building is conducted to simulate the impacts of climate change scenarios and the adaptive capacity of buildings’ wooden materials. Model predictions and forecasts are in good agreement to the measurements. Results show that wooden building materials offer an effective and resilient response to anticipated future climate changes. The developed model provides a sound basis for studying climate change impacts.

Introduction

An important methodology in exploring climate change, energy and environmental systems is system dynamics. It is a method of analyzing, managing, and finally controlling complex systems that time is an important factor [1]. Literature constitutes a large body of such dynamic models on climate change, however, in general, circulation methods present the majority. According to the IPCC report [2], warming of the climate is unequivocal, however, the impacts will be diverse and vary regionally. The detailed and short time scale problems for regional areas cannot be easily described using the scaled down results from the coarse resolutions of circulation methods. The identification of the system’s dynamics is a key issue for improving the understanding of the system. It is desirable that the model parameters have physically meaningful interpretations. This paper proposed an improved system dynamics approach to modeling the impact of climate change on wooden building and environment dynamics. We chose wooden buildings as a case study because of the following reasons.

Firstly, buildings consume 40% of primary energy and 40% of greenhouse gas emissions in developed countries [3]. To address global warming, efficiently using sustainable and resource-efficient building materials has become today’s central research theme. As a renewable and most abundant resource, wooden-structured buildings are very common in Europe, Northern America and other parts of the world. It
is therefore important to investigate the performance of wooden-structured buildings under climate change impacts.

Secondly, we carefully designed and gathered full-scale measured time series data from a wooden church that are especially useful for testing the developed model. Because strong scientific evidence links climate change with increasing temperatures and precipitations in Nordic climate, assessing if and how wooden buildings can be influenced under higher temperature and humidity scenarios is vital to understanding global warming effect. The purpose of this paper is to address these issues. The developed model is a general model capable of being applied to any research area.

Material and Methods

The Model

The developed model is a time series stochastic model derived from the physical model of combined heat and moisture transfer of whole building whose conceptually simple configuration is schematically shown in Figure 1 [4]. Briefly, the whole building’s thermal and moisture transfer is modeled using first principles. Stochastic terms are added to account the modeling errors. The model is then parametrised as time series model. The final dynamic model is

\[
\begin{align*}
T^+ &= a_1 T^+_{t-1} + a_2 T^- + a_3 \rho^+ + a_4 \rho^- + a_5 I + \varepsilon_1 \\
\rho^+ &= b_1 \rho^+_{t-1} + b_2 \rho^- + b_3 T^+ + b_4 T^- + b_5 I + \varepsilon_2 
\end{align*}
\]

\(T^+\) and \(T^-\) = indoor and outdoor temperatures at time \(t\) [°C]

\(\rho^+\) and \(\rho^-\) = indoor and outdoor moisture contents at time \(t\) [g/m\(^3\)]

\(I\) = solar radiation at time \(t\) [W/m\(^2\)]

\(\varepsilon\) = the error term

Figure 1. Schematic representation of the building system modeled in this paper.

Measurement Data

The time series data used in this study were measured in a relatively new wooden church equipped with high-resolution measurement systems. Measurement was monitored for two periods including follow-up data over the course of seven years. The first period began shortly after the church was completed in 2005-2006 and the second period started in 2011-2012, which, ideally, provided independent datasets for model calibration and verification. Wood is the major structural material of the church. Figure 2 displays the layout of the church and material properties.
Results

Using the outdoor temperature, humidity and solar radiation obtained from the Finnish Meteorological Institute, model validation is shown in Figure 3 and climate change impact scenarios are displayed in Figure 4. Because the positive effects on moisture-buffering of wooden materials are well documented and widely acknowledged, Figure 4 implies that wooden material will help to reduce the indoor humidity and the impacts of climate changes.

Figure 2. Layout and wooden structure in the measured church.

Figure 3. Indoor temperature and humidity comparison between measurement and model; Different datasets were used for calibration and validation (there was measurement gap between them).
Conclusions

This paper presents a simple and efficient dynamic approach for modelling indoor environment. The developed model has been successfully applied to a test church building and then used to make projections about future climate change impact based on the projected changes in indoor conditions. The results show that climate change leads to rises in humidity levels in indoor air, which increases moisture damage risks. Simulation shows that wooden building materials provide a positive way of reducing the increased humidity and the potential moisture damage risks. The model comparison with measurement shows high accuracy of the developed model. The model is general enough to be applicable to wide research areas.

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