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Predicting building's corners hygrothermal behavior by using a Fuzzy inference system combined with clustering and Kalman filter

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ABSTRACT

The hygroscopic characteristics of building materials can affect thermal gain or losses that are directly associated to energy consumption due to the latent heat transport. Moreover, some specific regions can accumulate humidity on building structures, and some of this regions, known as building corners, are still barely explored due to modelling complexity, high computer run time, numerical divergence, and highly moisture-dependent properties. This article presents an alternative to predict temperature, vapor pressure, and moisture content profiles in specific points where moisture can be easily accumulated, increasing mould growth risks and/or causing structural damage to the building. In order to avoid time-consuming numerical models, this article uses a Takagi–Sugeno fuzzy inference system with a multiple-input, single-output (MISO) structure to predict building corners hygrothermal behavior. Due to the ability of nonlinearity detection, associated with a small number of "if–then" rules with fuzzy antecedents and crisp mathematical functions or linear functions in the resultant part, the fuzzy system was combined with subtractive clustering method and Kalman filter to enhance its performance. The results suggested that the developed Takagi–Sugeno fuzzy model has achieved good accuracy in terms of precision when the results were compared to the analytical model. Moreover, in terms of simulation time, after the tuning and optimization procedures, the prediction of temperature, relative humidity, and vapor pressure on specific nodes are faster than the numerical model.

1. Introduction

Over the last century, considerable amounts of carbon dioxide and other greenhouse gases were released into the atmosphere due to human activities. The largest portion of these gases comes from burning fossil fuels to produce energy, which demand has alarmingly increased in the last forty years. In terms of buildings, commercial and residential buildings are responsible for about 40% of the energy consumption in the United States of America and this percentage increases in countries on economic growth [1,2]. Even considering the governments' efforts to reduce gases emissions, and the direct relation between gases that are harmful to the environment and global warming, the prediction to decrease the use of fossil fuels by the United States of America is about 4% in the next thirty years.

By taking this statistical information into account, it can be noticed that the independence of fossil fuels to produce energy decreases slowly. In this way, many countries are implementing actions to reduce the energy demand and consequently reduce gases emissions. Based on successful energy efficiency policies applied by many governments all around the world, the Brazilian government has created an energy certification program for buildings to avoid energy waste. By reducing the energy demand of both new and retrofitting buildings, the Brazilian certification program has been justified considering almost two main factors: (*i*) buildings from residential, commercial, and public sectors are responsible for at least 45% of the total energy demand in Brazil [2,3], and (*ii*) even holding a consistent hydroelectric energy resource and passing through an economic crisis, according to recent statistical studies from the Brazilian government [2], the energy demand in 2050 will be increased by a factor of three.

Building certification in Brazil can be performed by using two distinct methods: (*i*) the prescriptive method—which uses a set of equations based on the building project parameters to determine the efficiency of the envelope, lighting, and air-conditioning systems, and (*ii*) the simulation method—which adopts a software capable to simulate building's thermal and energy behaviors. In this second approach, the main idea is to compare the simulation results in terms of energy

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Nomenclature

w	moisture content (kg/m^3)
P_v	partial vapor pressure (Pa)
T	temperature (K)
K	liquid water permeability (s)
P_{suc}	suction pressure (Pa)
g	gravity (m/s^2)
t	time (s)
k_p	absolute permeability (m^2)
k_{rg}	gas relative permeability (−)
P_g	gas pressure − dry air pressure plus vapor pressure (Pa)
c_m	specific heat capacity of the structure (J/kg K)
c_{pl}	specific heat capacity of the water liquid (J/kg K)
c_{pa}	specific heat capacity at constant pressure of the dry air (J/kg K)
c_{pv}	specific heat capacity at constant pressure of the vapor (J/kg K)
L	vaporization latent heat (J/kg)
J	density of moisture flow rate (kg/m^2/s)
q	heat flowing into the structure (W/m^2)
h	convective heat transfer coefficient (W/m^2 K)
p	premise (−)
z	input vector of the premise (−)
i	dimensionality of the premise space (−)
j	rule number (−)
A	linguistic label of the fuzzy set (−)
f	rule output, which is the function that implies the value of y when $z_1, \ldots, z_m$ satisfies the premise (−)
u	input vector to the consequent part (−)
R	Fuzzy rule or implication (−)
s	partial terms of f, where s and r compose the consequent parameter set (−)
r	polynomial coefficient vector (−)
n	center of the Gaussian function (−)
M	number of rules (−)
y	variable of the consequence whose value is inferred (−)
v	normalized firing strength (−)
k	number of membership functions of the Takagi–Sugeno fuzzy model
$u_1(k)$	outdoor temperature (K)
$u_2(k)$	outdoor relative humidity (−)
$y_1(k)$	estimated temperature of the node (K)
$y_2(k)$	estimated partial vapor pressure of the node (Pa)
$y_3(k)$	estimated relative humidity of the node (−)

Greeks

ϕ	relative humidity (−)
ρ_l	liquid water density (kg/m^3)
δ_v	vapor diffusive permeability (s)
ρ_v	water vapor density (kg/m^3)
μ_g	dynamic viscosity (Pa·s)
ρ_a	density of dry air (kg/m^3)
ρ_0	density of the dry material (kg/m^3)
λ	thermal conductivity (W/m K)
β_v	surface coefficient of water vapor transfer (s/m)
σ	spread of the Gaussian function (−)
τ	Gaussian membership function (−)

consumption to a reference case in order to classify buildings according to an energy consumption scale.

When the simulation method is considered and some simulation software is adopted, it is important to take into account that most of building simulation software available does not take into account the moisture presence in building materials [4]. Once the humidity is considered, simplifications in the models do not represent the real effect of the moisture presence. The importance of considering the moisture presence in building structures has been discussed by researchers and it is continuously in evidence since the Annex 24 presented by the International Energy Agency (IEA) in 1996 [5] and the Annex 41 in 2008 [6]. Recently, according to Santos and Mendes [7], it was presented that the moisture presence in building porous elements can imply an additional mechanism of transport absorbing or releasing latent heat of vaporization, causing mold growth and/or structural damage (Fig. 1), which can consistently affect the energy waste or gain though building materials. Moreover, mathematical simplifications considering only unidirectional heat and moisture transfer through the surfaces may provide inconsistent results when compared to a realistic multidirectional analysis.

By comparing building simulation software where simplifications, as unidirectional calculations, were considered, the problem of taking into account multidirectional and coupled heat and moisture transfer calculations is that, for performing a whole-building hygrothermal analysis, simulations become hardware- and time-consuming due to numerical divergence and highly moisture-dependent properties. In this way, this work proposes an alternative way to analyze the hygrothermal performance of buildings, by considering the coupled heat and moisture transfer.

In order to emphasize the importance of multidirectional heat and moisture transfer analysis, specific parts of the building were evaluated. Hygrothermal bridges investigation, those parts that appear when the building envelope changes its geometry and/or changes its materials were the main issues of this study (Fig. 01).

In this work, a multidimensional model proposed by Santos and Mendes [7] was adopted to calculate the coupled heat, air, and moisture transfer through a building envelope. This very time-consuming computational code was used to simulate the effects of building lower and upper hygrothermal bridges that are used to define the corners of the building envelope, where there are local increases of heat flux density and a decrease or increase of internal surface temperatures. Weather data from Curitiba (a Brazilian city located in the South of the country) were used as input to generate temperature, vapor pressure, and relative humidity profiles of specific positions on the internal building surface, those that generally present mould growth and problems due to moisture accumulation. By using data provided by the analytical algorithm, a Takagi–Sugeno (T-S) fuzzy model combined with subtractive clustering and Kalman filter, temperature, vapor pressure, and relative humidity profiles were predicted by using a multiple-input, single-output (MISO) model. By considering the capability of fuzzy models to deal with the nonlinearity, in this case caused by the moisture presence, this strategy can be used on building and energy simulation to evaluate the effects of moisture accumulation on surfaces in a faster and easier way.

The T-S fuzzy model structure, which consists of “if–then” fuzzy rules, has been widely applied to solve modeling, identification, forecasting, pattern recognition, data analysis, and control problems [10–21] related to thermal systems, especially those associated to building structures and materials' properties. Owing to its nonlinearity and simple structure, the T-S fuzzy model is capable to approximate and predict complex systems using a moderate number of rules.

The remainder of this paper is organized in the following form. Section 2 presents the complete formulation of the numerical model used to describe the building corners hygrothermal behavior. In the sequence, Section 3 addresses the system identification technique based on T-S fuzzy structure and the model evaluation criteria. Section 4 describes the simulation parameters of the numerical model that were used to collect data for the identification procedures, which was presented in Section 5. Section 6 presents the identification results by using the fuzzy model, and to finish this work, the conclusions were reported on Section 7.