7th International Building Physics Conference

IBPC2018

Proceedings

SYRACUSE, NY, USA

September 23 - 26, 2018

Healthy, Intelligent and Resilient
Buildings and Urban Environments

ibpc2018.org | #ibpc2018

Modeling and model calibration for model predictive occupants comfort control in buildings

Shiyu Yang[1, 2], Man Pun Wan[1*], Bing Feng Ng[1], Zhe Zhang[2], Adrian S. Lamano[2], Wanyu Chen[2].

[1]School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore

[2]Energy Research Institute at NTU (ERI@N), Nanyang Technological University, Singapore

[*]*Corresponding email: mpwan@ntu.edu.sg*

ABSTRACT
Mathematical models are essential in Model-Predictive Control (MPC) for building automation and control (BAC) application, which must be precise and computationally efficient for real-time optimization and control. However, building models are of high complexity because of the nonlinearities of heat and mass transfer processes in buildings and their air-conditioning and mechanical ventilation (ACMV) systems. This paper proposes a method to develop an integrated linear model for indoor air temperature, humidity and Predicted Mean Vote (PMV) index suitable for fast real-time multiple objectives optimization. A linear dynamic model is developed using SIMSCAPE language based on the BCA SkyLab test bed facility in Singapore as a case study. Experimental data is used to calibrate the model using trust-region-reflective least squares optimization method. The results show that the mean absolute percentage errors (MAPE) of predicted room temperature and humidity ratio are 1.25% and 4.98%, compared to measurement, respectively.

KEYWORDS
Model predictive control; modeling; model calibration; linearization.

INTRODUCTION

Developing an appropriate building mathematical model has been a major challenge of MPC implementation for building automation and control (BAC) application (Cigler et al., 2013). Henze (2013) pointed out that about 70% of project costs were consumed by model development and calibration for MPC in buildings. Cigler et al. (2013) also found more than 55% of project time spent on modeling work for implementing MPC in different two buildings. The mathematical model of the building must be sufficiently accurate in predicting building dynamics and computationally efficient for real-time control and optimization in MPC. A viable solution is to develop linear models of buildings that are of medium to high fidelity and is computationally more efficient (Cigler et al., 2013). Currently, two modeling methods, thermal resistance-capacitance (RC) model (Sturzenegger et al., 2012) and system identification (Cole et al., 2014) have been adopted to develop linear building models for control purpose. However, most of the previous studies focus on the prediction of indoor temperature whereas the indoor humidity and human thermal comfort are seldom covered (Kramer et al., 2012). To improve indoor thermal comfort and building energy performance with MPC further, it is necessary to include humidity and thermal comfort index in the prediction model of MPC.

This work aims to develop a general methodology for constructing a linear model for indoor thermal comfort and energy optimization with MPC. A building model is developed based on the BCA SkyLab test bed facility in Singapore, as a case study, to predict indoor temperature, humidity, and thermal comfort. The thermal and humidity dynamic models are created using the RC network. A linear approximation method is proposed to linearize the nonlinearities in the ACMV cooling coil model and PMV calculation model. A model calibration procedure is also adopted to refine the proposed linear model.

METHODS

Room space model

For air-conditioned room spaces, the heat and moisture balance could be modeled by equations (1) and (2),

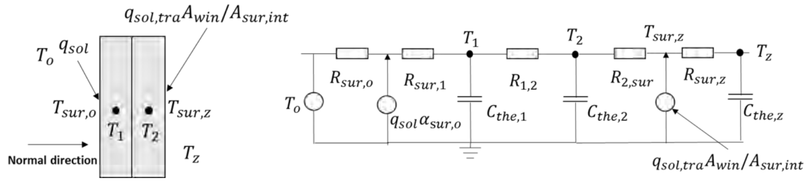
$$m_{air,z}\frac{d\psi_z}{dt} = \dot{m}_{occ} + \dot{m}_{ACMV}, \tag{1}$$

$$m_{air,z}C_{air}\frac{dT_Z}{dt} = Q_{inte} + Q_{env} + Q_{ACMV}, \tag{2}$$

where Q is heat flow rate (W), $\dot{m}$ is mass flow rate (kg/s), m is mass (kg), T is temperature (K) and ψ is humidity ratio (kg/kg). The subscript *inte* refers to internal, *z* refers to thermal zone, and *env* refers to envelope.

RC models of walls, ceiling and floor

Figure 1 shows the lumped parameter and RC representations of a building wall model. The wall is virtually split into two aggregates and only heat conduction in the normal direction is considered. The RC model is a 5R2C model, which includes two thermal capacitances of the two aggregates, three thermal conduction resistances of aggregates and two surface thermal resistances between surface and air (outer and inner surfaces).



a) b)

Figure 1 a) lumped parameter and b) RC representations of a building wall model

In Figure 1, the symbols R, C, and q refer to thermal resistance (K-m/W), thermal capacity (J/K) and heat flux (W/m^2), respectively. Subscripts sur, o, 1, the, sol, z, tra, and int refer to surface, outside, aggregate number, thermal, solar radiation, thermal zone, transmission, and interior respectively. The same model treatment is applied to the roof and the floor.

Linearized cooling coil model

When the ACMV system is in operation, the supply air relative humidity (RH) is assumed 100% and the heat/mass transfer between the mixed air and the cooling coil can be described by,

$$Q_{cc} = \dot{m}_{ma}(C_{air} + C_{vap}\psi_{ma})(T_{ma} - T_{sa}) + \dot{m}_{ma}L_{vap}(\psi_{ma} - \psi_{sa}), \tag{3}$$

$$\psi_{sa} = 0.62198p_{vap,sat}/(p_z - p_{vap,sat}), \tag{4}$$

$$p_{vap,sat} = e^{(77.345+0.0057T_z-7235/T_z)}/T_z^{8.2}, \tag{5}$$

where the subscripts *ma*, *vap*, *sat* and *cc* refer to the mixed air in FCU, water vapor, saturation and cooling coil, respectively. *L* refers to the specific latent heat (J/kg) of water condensation.

For temperature between 283.15K – 293.15K (covering the typical range of supply air temperatures), nonlinear equations (4) and (5) can be approximated by the linear equation,

$$\psi_{sa} = 7.014 \times 10^{-4}T_{sa} - 0.1913\ . \tag{6}$$

With this assumption, the indoor moisture and sensible heat load removed by AMCV system can be calculated by,

$$\dot{m}_{ACMV} = 2.58\times10^{-4}\dot{m}_{fa}T_{fa} + 2.58\times10^{-4}\dot{m}_{ra}T_{ra} - 2.57\times10^{7}Q_{cc} + 0.633\dot{m}_{fa}\psi_{fa} - \left(\dot{m}_{fa} + 0.368\dot{m}_{ra}\right)\psi_{ra} - 0.0703\dot{m}_{fa} - 0.0703\dot{m}_{ra}, \tag{7}$$

$$Q_{ACMV} = 369.4\dot{m}_{fa}T_{fa} - \left(1005\dot{m}_{fa} + 635.6_{ra}\right)T_{ra} - 0.368Q_{cc} + 9.062\times10^{5}\left(\dot{m}_{fa}\psi_{fa} + \dot{m}_{ra}\psi_{ra}\right) + 1.734\times10^{5}\dot{m}_{fa} + 1.734\times10^{5}\dot{m}_{ra}, \tag{8}$$

where the subscripts *fa* and *ra* refer to fresh air and return air. When the supply air flow rate and fresh air flow rate are constant, the equations become linear. The equations are valid under the conditions of RH_{sa} = 100%, 283.15K < Tsa < 293.15K according to the assumptions in the modeling procedure.

Linearized PMV calculation model

Predicted Mean Vote index (Fanger, 1970) is calculated according to the equation,

$$PMV = \left(0.303e^{-0.036M} + 0.028\right)Q_{diff}. \tag{9}$$

The difference between the internal heat production and loss, Q_{diff}, that occurs in a human body is calculated by,

$$Q_{diff} = M - Q_{work} - Q_{res} - Q_{sens} - Q_{evap}, \tag{10}$$

$$Q_{res} = 0.0014M(307.15 - T_{air}) + 1.72 * 10^{-5}M\left(5867 - p_{vap}\right), \tag{11}$$

$$Q_{sens} = 39.6 * 10^{-9}f_{clo}\left(T_{clo}^4 - T_{mr}^4\right) + f_{clo}h_{conv}\left(T_{clo} - T_{air}\right), \tag{12}$$

$$Q_{evap} = 0.42(M - Q_{work} - 58.15) + 3 * 10^{-3}\left[5733 - 6.99(M - Q_{work}) - p_{vap}\right] \tag{13}$$

$$T_{clo} = T_{skin} - R_{clo}\left[f_{clo}h_{conv}(T_{clo} - T_{air})\right] - Ins_{clo}\left[39.6 * 10^{-9}f_{clo}\left(T_{clo}^4 - T_{mr}^4\right)\right] \tag{14}$$

In the equation (9) – (14), *M* is the metabolic rate of a human being (W), *p* is air pressure (Pa), f_{clo} is clothing factor, and Ins_{clo} is clothing insulation (1 clo = 0.155 m^2-K/W). The subscripts *clo*, *mr*, *vap*, *conv, sens*, *evap*, *res*, *skin* and *work* refer to clothing, mean radiant, water vapor, convection, sensible, evaporation from occupant skin, respiration of occupant, skin surface, and external work.

There are two nonlinear items, radiative heat transfer $39.6 * 10^{-9}f_{clo}(T_{clo}^4 - T_{mr}^4)$ and water vapour pressure, p_{vap}, in the PMV model. The radiative heat transfer term can be linearized by (Park, 2013),

$$\begin{aligned} Q_{rad} &= 39.6 * 10^{-9}f_{clo}(T_{clo} + T_{mr})(T_{clo}^2 + T_{mr}^2)(T_{clo} - T_{mr}) \\ &= h_{rad}f_{clo}(T_{clo} - T_{mr}). \end{aligned} \tag{15}$$

The water vapor pressure can also be calculated by the following equation, for air temperatures within 293.15 - 303.15 K covering the range of typical room temperatures,

$$p_{vap} = \psi_z p_z/(\psi_z + 0.622) \cong 1.598\times10^{5}\psi_z. \tag{16}$$

In a scenario that the cloth factor, metabolic rate of the occupants, external work of the occupants and room pressure can be assumed constant, likely so in a typical office environment, the PMV equation can be reduced to one linear equation,

$$PMV = \begin{bmatrix} (0.68h_{conv} + 0.0051h_{rad} + 0.06)T_{air} + 0.68h_{rad}T_{mr} + \\ (35.7h_{conv} + 35.7h_{rad} + 419)\psi_z + 7.3 - 208h_{rad} - 208h_{conv} \end{bmatrix} / (h_{conv} + h_{rad} + 11.73). \tag{17}$$

The equation is valid for a common office environment with air conditioning where room temperature is within 293.15 - 303.15 K.

MPC formulation

A MPC controller for future study of building energy and indoor thermal comfort optimization with MPC could be modeled as

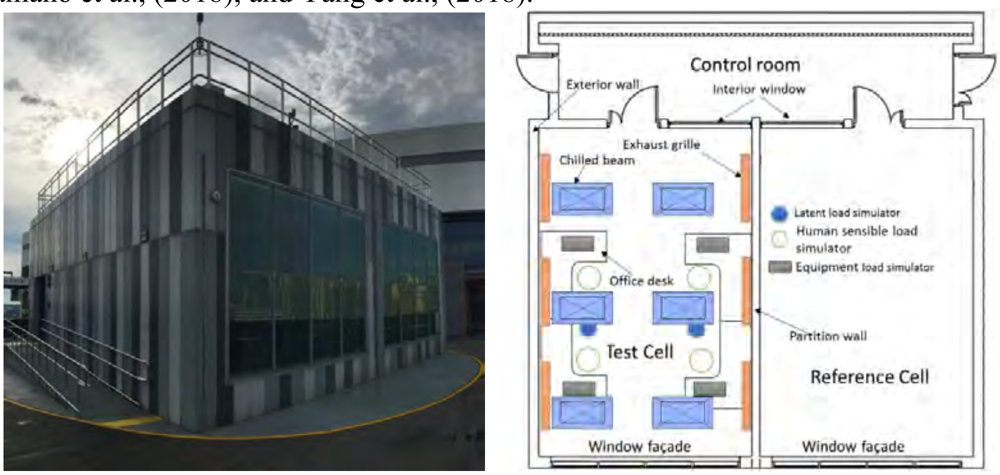
$$J = Minimize\left(\sum_{i=0}^{M}\sum_{k=0}^{N}Q_{i,t+k|t}^2 + \sum_{k=0}^{N}\left(W_{PMV}PMV_{t+k|t}\right)^2 + \sum_{k=0}^{N}W_{\epsilon}\left(\epsilon_{t+k|t}\right)^2\right), \tag{18}$$

where Q, PMV, W and ϵ refer to normalized cooling power, normalized thermal comfort, weighting factor and slack variable. M and N refer to the number of cooling system and prediction horizon.

The objective function subjects to the building dynamics modelled in this section, limits of cooling power and acceptable indoor thermal comfort zone (-0.5<PMV<0.5). In this study, the building dynamic model is linearized. This results into a convex optimization problem, which can be more efficiently solved compared to a nonlinear optimization problem with a nonlinear building model, for finding the optimal control strategies for building control (Cigler et al., 2013).

CASE STUDY AND RESULTS DISCUSSION

The physical building studied in this work is the BCA SkyLab located in the BCA Academy in Singapore. SkyLab has two side-by-side identical experimental cells with full-height window façade on one side, as shown in Figure 2. The properties of the building envelope are described by Lamano et al., (2018), and Yang et al., (2018).



a) b)

Figure 2 a) exterior view of BCA SkyLab, b) Schematic drawing of BCA SkyLab

An ACMV system that consists of one fan coil unit (FCU) and six active chilled beam (ACB) units was installed in the Test Cell of SkyLab, as shown in **Error! Reference source not found.**. The chilled water valve in FCU was controlled by a thermostat according to pre-cooled air set point temperature. The pre-cooled air from FCU was supplied into the ACB units, meanwhile, induced some room air into the ACB units. The sensible load in the induced air was removed by the cooling coils in ACB. The conditioned induced air mixed with pre-cooled air and was distributed into the room space. A heat exchanger was installed to regulate the supplied chilled water temperature of ACB higher than dew point in the room space to avoid condensation. Thus, FCU is capable of dealing with all the latent load and partial sensible load and the rest sensible is removed by the ACB.

The Test Cell operates at a design condition during office hours (9 am – 6 pm of weekday). The design occupancy density, internal plug load and internal lighting load are 0.092 person/m^2, 16 W/m^2 and 8.22 W/m^2 floor area, respectively. The ACMV system supplies constant 33 l/s fresh air and 147 l/s supply air into the room space.

Based on the modeling methods described earlier, an integrated linear model the Test Cell is developed in the MATLAB/Simulink environment. The RC models and heat/mass balance of room air model are developed using SIMSCAPE language, which is an object-oriented physical modeling method (Miller & Wendlandt, 2010). The thermal comfort in SkyLab Test Cell is modeled with Equation (17) and measured three-day average velocity (0.09 m/s) in the occupied zone during office hours. The FCU in the AMCV system is modeled with Equations (7) and (8) under design conditions. The cooling coils in ACB system are treated as negative heat sources. The developed model is calibrated and refined using measurement data obtained in SkyLab. Fourteen days (8th to 21st January 2018) of experiment was conducted to measure the room temperature and humidity responses to different conditions.

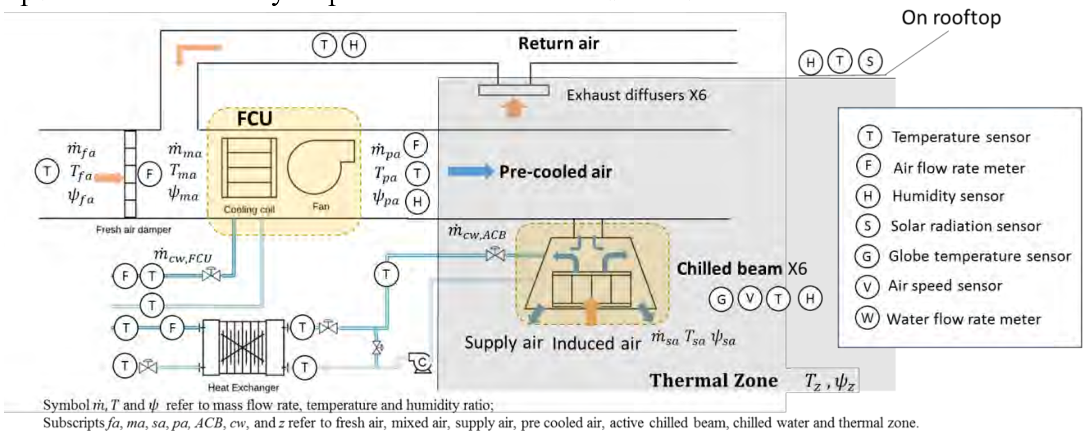
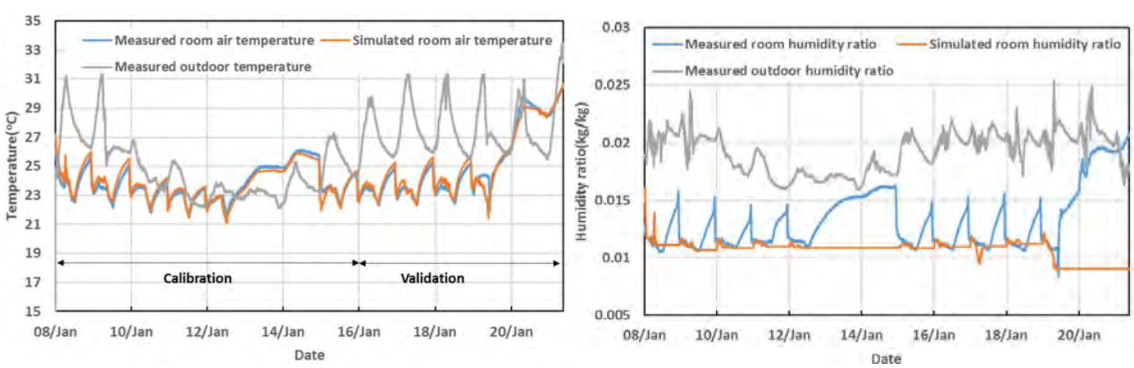


Figure 3 Schematic drawing of the ACMV system in SkyLab Test Cell

In the Test Cell, there are some thermal masses (such as ducts, furniture and steel beams) inside the ceiling space, raised floor space and room space that are not included in the RC model. Thus, the R and C parameters of roof, floor and internal thermal mass are tuned in the calibration procedure. The thermal mass in room space is represented by a 1R1C node, separately, which is only connected to room air temperature node. The Trust-Region-Reflective Least Squares optimization method (Coleman & Li, 1996) is then employed to tune the RC model parameters in MATLAB environment to minimize the sum-squared error of room temperature as. After calibration, the parameter values of the SkyLab Test Cell are listed in Table 1.

Table 1 Tuned parameter values of liner model of SkyLab Test Cell

Envelope	**Initial U value** (W/m^{2}K)	**Initial C value** (kJ/m^{2}K)	**Tuned U value** (W/m^{2}K)	**Tuned C value** (kJ/m^{2}K)
Internal thermal mass	1.6	100	32	485
Roof	0.25	308.4	0.67	391.67
Floor	0.25	77.6	0.43	85.7



a) b)

Figure 4 Comparison of simulated a) temperature and b) humidity ratio with measured data

Figure shows that there is good agreement between the simulated and measured results after the model calibration. The mean absolute percentage error (MAPE) of room temperature is 1.25% for the entire fourteen-day period. The MAPE of room humidity is 4.98% during office hours. The deviation of the humidity ration prediction in non-office hours is because the model does not consider the moisture penetration from the ambient into room space.

CONCLUSIONS

Methods to build a linear building model, which can be used to predict indoor temperature, humidity and thermal comfort for indoor environment control with linear MPC, are proposed. The RC model is adopted to represent the heat and moisture dynamic in the building. The heat transfer and dehumidification process in the ACMV system and PMV index calculation models are linearized by linear approximation of the nonlinear items in the theoretical models. A case study is conducted based on the BCA SkyLab in Singapore. After calibration, the developed linear model has high accuracy and the MAPE of predicted room temperature and humidity ratio are 1.25% and 4.98% compared to measured data, respectively.

ACKNOWLEDGEMENT

This research is supported by the National Research Foundation (NRF) of Singapore through the Building and Construction Authority (BCA) under the Green Buildings Innovation Cluster (GBIC) grant nos. NRF2015ENC-GBICRD001-020 and GBIC-R&D/DCP02. Technical support from the Simulation Group of ERI@N and scientific inputs by Prof Gregor Henze, University of Colorado Boulder are appreciated.

REFERENCES

Cigler, J., Gyalistras, D., Široky, J., Tiet, V., & Ferkl, L. (2013, June). Beyond theory: the challenge of implementing model predictive control in buildings. In Proceedings of 11th Rehva World Congress, Clima (Vol. 250).

Cole, W. J., Powell, K. M., Hale, E. T., & Edgar, T. F. (2014). Reduced-order residential home modeling for model predictive control. Energy and Buildings, 74, 69-77.

Coleman, T. F., & Li, Y. (1996). An interior trust region approach for nonlinear minimization subject to bounds. SIAM Journal on optimization, 6(2), 418-445.

Fanger, P. O. (1970). Thermal comfort Analysis and applications in environmental engineering. Thermal comfort. Analysis and applications in environmental engineering.

Henze, G. P. (2013). Model predictive control for buildings: A quantum leap? Journal of Building Performance Simulation, 6(3), 157–158.

Lamano A.S., Yang S, Wan M.P. et al. (2018). Energy Performance of an Integrated Automated Blinds and Dimmable Lighting System with Model-Predictive Control (MPC). COBEE2018.

Miller, S., & Wendlandt, J. (2010). Real-time simulation of physical systems using Simscape. MATLAB News and Notes, 1-13.

Park, H. (2013). Dynamic thermal modeling of electrical appliances for energy management of low energy buildings (Doctoral dissertation). Université de Cergy Pontoise.

Sturzenegger, D., Gyalistras, D., Morari, M., & Smith, R. S. (2012, November). Semi-automated modular modeling of buildings for model predictive control. In Proceedings of the Fourth ACM Workshop on Embedded Sensing Systems for Energy-Efficiency in Buildings (pp. 99-106).

Yang, S., Wan, M.P., Ng, B.F., Zhang, T., Babu, S., Zhang, Z., Chen, W. and Dubey, S. (2018). A state-space thermal model incorporating humidity and thermal comfort for model predictive control in buildings. Energy and Buildings, 170, 25-39.