



# **Intelligent Control System Design for Energy Conservation in Commercial Buildings**

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# Abstract

This thesis focuses on the development of model predictive control (MPC) strategies for reducing energy consumption in air-conditioned buildings. It is well known that the building sector is responsible for 40 per cent of the world's energy usage and 33 per cent of all greenhouse emissions. As a result of global environmental issues and decreasing energy resources, there is strong motivation to develop more efficient control strategies for Heating, Ventilation, and Air Conditioning (HVAC) systems in buildings. The existing HVAC control strategies are not energy or cost efficient, which results in energy waste, high on-peak electricity demand and poor thermal comfort in buildings.

Previous works have shown that MPC can be utilised as a supervisory controller to achieve energy saving while maintaining the indoor thermal comfort in buildings. However, most of the past studies were focused on small residential buildings or mid-size commercial buildings. It is highly desired to improve the existing MPC strategies to make them more reliable and applicable for large commercial buildings. This thesis extends the previous works by addressing the following challenges when dealing with the large buildings. Firstly, HVAC plants and the thermal dynamics of buildings are inherently nonlinear. Accurate modelling of these components is difficult due to the limited number of sensors that are usually installed and the paucity of prior knowledge of the system. There is a need to develop models that are capable of effectively handling the nonlinearity to achieve better modelling accuracy. Secondly, in large commercial buildings with adjacent large open spaces, the effects of thermal coupling between differently

controlled spaces play a crucial role. This significance of the interaction between zones has seldom been discussed before and requires more thorough investigation. Thirdly, although load shifting function of MPC have been proven to be effective in achieving cost savings in buildings with a considerable thermal mass, it is demanding to investigate the application value of these strategies in lightweight commercial buildings. Finally, given the presence of uncertainties, these models may not be able to predict the indoor temperature accurately, which may lead to poor control performance and even instability in operation of the MPC strategy. The existing robust control approaches are generally too conservative, and may not be suitable for use in real-world buildings.

In this study, the advantages of neural networks (NNs) will be exploited to address the challenges outlined above. NNs are known as universal approximators, meaning that they can model any continuous functions with any desired degree of accuracy. In particular, the NNs will be used to conduct modelling work, generate control rule, and improve the performance of classical MPC. The major contributions of this thesis are presented in four chapters, with each based on an individual scientific paper.

*Paper-1* presents a systematic modelling method for air handling units (AHUs) and thermal zone using a recursive NN (RNN). As the major novelty, a cascade NN structure is developed, which enables the thermal dynamics modelling of both interior zones and perimeter zones within investigated building. This approach allows accurate prediction of both supply air temperature and zone temperature prediction, making it suitable for predictive control design.

Continuing with the first paper, *Paper-2* introduces a multi-input, multi-output (MIMO) model, which effectively models the convective heat exchange between open spaces within multi-zone commercial buildings. The proposed model allows closed-loop prediction for several adjacent zones simultaneously by considering their thermal interaction. A NN-based optimal start-stop control method is also developed in this paper to demonstrate the energy saving potential enabled by using the proposed predictive model.

The NN models provide accurate prediction results, but they are in general difficult to optimise under an MPC framework. *Paper-3* presents a hybrid MPC (HMPC), which combines the classic MPC with an inverse NN model. With the HMPC, the classical MPC based on linearised building model optimises the supplied cooling energy. The inverse NN model compensates the nonlinearity associated with the AHU process and generates more accurate control inputs. Simulations and experiments demonstrate the feasibility of the proposed method in achieving energy and cost reductions while maintaining good indoor thermal comfort in the investigated large commercial building.

The MPC formulation in *Paper-3* does not take the system uncertainty into account. In reality, however, the modelled building energy systems are always affected by uncertainties, so that the modelling errors become inevitable which cause control performance degradation to the MPC. *Paper-4* considers the application of a robust MPC (RMPC) to handle the system uncertainty within buildings. In particular, an uncertainty estimator is developed based on the previously presented RNN model to provide uncertainty bound to the conventional closed-loop min-max RMPC. The newly developed bound estimator reduces the conservatism of the RMPC and achieves improved control performance.

In conclusion, the research work presented in this thesis has made important contributions to the research of intelligent model predictive control for air-conditioning systems in commercial buildings. The methodologies developed in this thesis can be utilised for other buildings or for the control of other dynamic systems.

# Declarations

I certify that this work contains no material which has been accepted for the award of any other degree or diploma in my name, in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text. In addition, I certify that no part of this work will, in the future, be used in a submission in my name, for any other degree or diploma in any university or other tertiary institution without the prior approval of the University of Adelaide and where applicable, any partner institution responsible for the joint-award of this degree.

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# List of Publications

This thesis is submitted as a portfolio of publications either published or submitted for publication by peer-reviewed journals according to the ‘Academic Program Rules’ of the University of Adelaide. The papers included in this thesis are all closely related to the field of the research of this work. This thesis is based on the following papers, which are referred to by their Arabic numerals:

**Paper-1** Huang H., Chen L., Mohammadzaheri M., Hu E., “A New Zone Temperature Predictive Modeling for Energy Saving in Buildings”, In *Procedia Engineering*, vol. 49, pp. 142 - 151, 2012.

**Paper-2** Huang H., Chen L., Hu E., “A neural network-based multi-zone modelling approach for predictive control system design in commercial buildings”, In *Energy and Buildings*, vol. 97, pp. 86 - 97, 2015.

**Paper-3** Huang H., Chen L., Hu E., “A new model predictive control scheme for energy and cost savings in commercial buildings: An airport terminal building case study”, In *Building and Environment*, vol. 89, pp. 203 - 216, 2015.

**Paper-4** Huang H., Chen L., Hu E., “Reducing energy consumption for buildings under system uncertainty through robust MPC with adaptive bound estimator”, *Submitted to Building and Environment*, 2015.

The following conference papers are of close relevance to the present work and are included in the appenices.

- 2013** Huang H., Chen L., M. Mohammadzaheri., Hu E., Chen ML., “Multi-zone temperature prediction in a commercial building using artificial neural network model”, In Control and Automation (ICCA), 2013 10th IEEE International Conference on, pp. 1896-1901, 2013.
- 2014** Huang H., Chen L., Hu E., “Model predictive control for energy-efficient buildings: An airport terminal building study”, In Control Automation (ICCA), 11th IEEE International Conference on, pp. 1025-1030, 2014.
- 2015** Huang H., Chen L., Hu E., “A hybrid model predictive control scheme for energy and cost savings in commercial buildings: Simulation and experiment”, In American Control Conference (ACC), 2015, pp. 256-261, 2015.

# Nomenclature

$C_z$  capacitance associated with the fast-dynamic masses (kJ/°C)

$C_w$  capacitance associated with the slow-dynamic masses (kJ/°C)

$C_a$  specific heat of air (kJ/kg°C)

$C_{cw}$  the overall thermal capacity of the chilled water and metal body of cooling coil (kJ/°C)

$C_{pw}$  specific heat capacity of chilled water (kJ/°C)

$CO_2$  carbon dioxide concentration (ppm)

$D_{out}$  outdoor air damper opening level (%)

$A$  area of the solid surface (m<sup>2</sup>)

$f_w$  chilled water flow rate (l/s)

$f_{cw}$  chilled water flow rate (l/s)

$H_r$  relative humidity (%)

$T$  thermal node temperature (°C)

$T_c$  chilled water temperature (°C)

$T_{sp}$  set point temperature (°C)

$T_{oc}$  temperature constraints during occupied hours ( $^{\circ}\text{C}$ )

$T_{uc}$  temperature constraints during unoccupied hours ( $^{\circ}\text{C}$ )

$T_{cwo}$  outflow water temperature ( $^{\circ}\text{C}$ )

$T_{ao}$  discharge (outflow) air temperature ( $^{\circ}\text{C}$ )

$T_{cwr}$  return chilled water temperature ( $^{\circ}\text{C}$ )

$T_{cws}$  supply chilled water temperature ( $^{\circ}\text{C}$ )

$T_{ai}$  temperature of the air going into the cooling coil ( $^{\circ}\text{C}$ )

$m_w$  water mass-flow rate of the cooling coil (kg/s)

$\dot{m}$  mass flow rate of the supplied air (kg/s)

$P_c$  power consumption of cooling energy consumed by the cooling coils (kW)

$P_f$  power consumption of supply fan (kW)

$Q_{chil}$  cooling load of the building (kW)

$Q_f$  supplied free-cooling energy (kW)

$Q_c$  supplied cooling coil energy (kW)

$Q_s$  heat gain generated by solar radiation (W)

$Q_p$  heat gain generated by occupancy (W)

$Q_{leak}$  heat gain caused by the leakage of the zone (W)

$R$  thermal resistance associated with walls, window or floor ( $^{\circ}\text{C}/\text{W}$ )

$R_c$  convective heat transfer coefficient between adjacent zones ( $^{\circ}\text{C}/\text{W}$ )

$R_w$  convective heat transfer coefficient associated with the air node and surface of the wall ( $^{\circ}\text{C}/\text{W}$ )

$R_{win}$  convective heat transfer coefficient through window ( $^{\circ}\text{C}/\text{W}$ )

$R_f$  convective heat transfer coefficient associated with the floor ( $^{\circ}\text{C}/\text{W}$ )

$S_r$  global horizontal irradiation ( $\text{W}/\text{m}^2$ )

$U$  overall heat transfer coefficient ( $\text{kJ}/\text{m}^2\text{K}$ )

$h$  convective heat transfer coefficients per unit area ( $\text{W}/\text{m}^2\text{K}$ )

$V_c$  chilled water valve opening level (%)

$V_{cw}$  chilled water valve opening level (%)

$V_z$  volume of the zone ( $\text{m}^3$ )

$\Delta t$  sampling time of the building data (s)

$n_a, n_b$  orders of the input variable

$r$  order of the system

$n_k$  time delay of the input variable

$f$  nonlinear neural network function

$\rho$  density of the air ( $\text{kg}/\text{m}^3$ )

$k$  time delay of the input variable

$w$  uncertainty

### *Subscripts*

$i$  indices for zones

sa supply air

r return air

out outdoor air

w walls and ceiling

g windows

f floor

N prediction horizon

k time step

cws supply chilled water

cwr return chilled water

### *Abbreviations*

COP Coefficient of Performance of the chiller plant

MPC Model Predictive Control

HMPC Hybrid Model Predictive Control

MIMO Multi-input, Multi-output

HVAC Heating, Ventilating, and Air Conditioning

BMS Building Management System

AHU Air Handling Units

CAV Constant Air Volume

VAV Variable Air Volume

ANN Artificial Neural Network

RNN Recurrent Neural Network

RMPC Robust MPC

ARMPC Adaptive Robust MPC

SMPC Stochastic MPC

BC Baseline Control

RC Resistance Capacitance

OSSC Optimal Start-Stop Control

TOU Time-of-Use

LTI Linear Time Invariant

PMV Predicted Mean Vote index

NARX Nonlinear Autoregressive models with exogenous input

ARMAX Autoregressive Moving Averagemodel with exogenous inputs

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