ENSEMBLE MODELLING OF HYGROTHERMAL SYSTEM FOR MULTI-OBJECTIVES MODEL PREDICTIVE CONTROLLERS

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DEDICATION

This thesis is dedicated to my father, who taught me that the best kind of knowledge to have is that which is learned for its own sake. It is also dedicated to my mother, who taught me that even the largest task can be accomplished if it is done one step at a time.

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ABSTRACT

An air conditioner maintains occupants' thermal comfort; however, it is also power-hungry in which leads to high electricity consumption. Maintaining thermal comfort while minimising electrical power consumption is difficult, especially when the weather-related inputs are not predictable. This leads to overcooling due to undershoot and undercooling due to overshoot. Undercooling causes discomfort, while overcooling causes discomfort and high-power usage. To minimise this problem, the implementation of model-based predictive controllers can be developed to produce necessary pre-emptive control decisions based on the output of the embedded simulation model in the controller. However, the simulation model must be accurate for the best result. This project develops accuracy-improved mathematical models that represent the dynamic hygrothermal behaviour of a laboratory in aiding future potential energy-efficient predictive controllers. This is to maintain the thermal comfort level in the laboratory while minimising power consumption. Two thermal comfort variables were modelled to maintain two different desired setpoints simultaneously in the future. First, the empirical modelling was developed to capture the dynamics of the temperature and humidity behaviours of the laboratory using three existing standard methods, which were: (1) autoregressive–moving-average (ARMA) model; (2) transfer function (TF) model; and (3) nonlinear autoregressive exogenous model (NARX) model. Second, the ensemble methods were implemented to increase the simulation accuracy of the developed modelling by summing up the output values from all three developed models – prior to summation, the output of each of the models was multiplied by the weight value assigned for each of the models. The values of these weights were determined using the following three ensemble methods: (1) weighted average; (2) least square technique (LST) / least square method (LSM); and (3) genetic algorithm (GA). All models' simulation outputs were compared with the actual data for accuracy benchmarking. Results showed that the most accurate ensemble models have better accuracies than the most accurate individual models developed in this research while being simulated with the testing data set in each simulation case. The improvements in the air temperature simulation models are by 3.40%, 7.38%, and 8.69% each for one-, five-, and ten-minute(s) simulation ahead, while the improvements in the relative humidity simulation models are by 0.96%, 1.35%, and 2.38% each for one-, five-, and ten-minute(s) simulation ahead. The accuracy-improved models can then be utilised in model-based predictive controllers for maintaining occupants' thermal comfort in a building while minimising the air conditioners' power consumption for energy saving and environmental conservation.

ABSTRAK

Pendingin hawa mengekalkan keselesaan haba penghuni-penghuni dalam bangunan; walau bagaimanapun, pendingin hawa menggunakan kuasa elektrik yang tinggi dan mengakibatkan bil elektrik yang tinggi. Mengekalkan keselesaan haba sambil meminimumkan penggunaan kuasa elektrik adalah sukar, lebih-lebih lagi apabila gangguan daripada input-input yang berkaitan dengan cuaca tidak dapat diramal. Ini mengakibatkan penyejukan berlebihan akibat kurang lajakan dan kekurangan penyejukan akibat lebih lajakan. Kekurangan penyejukan mengakibatkan ketidakselesaan manakala penyejukan berlebihan mengakibatkan kedua-dua ketidakselesaan dan penggunaan kuasa yang tinggi. Untuk meminimumkan masalah ini, perlaksanaan pengawal ramalan berasaskan model boleh dibangunkan bagi menghasilkan keputusan kawalan pendahuluan yang perlu berdasarkan output model penyelakuan yang terbenam kalam pengawal. Walaubagaimanapun, model penyelakuan mestilah tepat untuk keputusan yang terbaik. Projek ini membangunkan model-model matematik yang ditambahbaik ketepatan bagi mewakili perlakuan dinamik higrotermal untuk sebuah makmal bagi membantu perlaksanaan pengawal peramal cekap tenaga yang berpotensi pada masa akan datang. Ini dilakukan untuk mengekalkan tahap keselesaan haba dalam makmal sambil meminimumkan penggunaan kuasa. Dua pemboleh ubah keselesaan haba telah dimodelkan bagi mengekalkan dua titik tolak berbeza yang dikehendaki serentak pada masa akan datang. Mula-mula, pemodelan empirikal telah dibangunkan bagi merakam dinamik kelakuan-kelakuan suhu udara dan kelembapan relatif dalam makmal menggunakan tiga kaedah standard yang sedia ada, iaitu: (1) model autoregresif–purata-bergerak (*autoregressive–moving-average (ARMA) model*); (2) model rangkap pindah (*transfer function (TF) model*); dan (3) model eksogen autoregresif tak linear (*nonlinear autoregressive exogenous (NARX) model*). Kemudian, kaedah-kaedah *ensemble* dilaksanakan bagi meningkatkan ketepatan pemodelan dengan menjumlahkan nilai output daripada ketiga-tiga model yang telah dibangunkan – sebelum dijumlahkan, output bagi setiap model didarabkan dengan nilai pemberat yang telah ditentukan bagi setiap model. Nilai pemberat-pemberat ini telah ditentukan menggunakan tiga kaedah *ensemble* berikut: (1) berpemberat purata (*weighted average*); (2) teknik kuasa dua terkecil (*least square technique (LST)*) / kaedah kuasa dua terkecil (*least square method (LSM)*); dan (3) algoritma genetik (*genetic algorithm (GA)*). Output penyelaku daripada kesemua model dibandingkan dengan data sebenar bagi tujuan penandaan aras. Keputusan-keputusan menunjukkan bahawa model-model *ensemble* yang paling tepat mempunyai ketepatan yang lebih baik berbanding model-model individu yang paling tepat yang dibangunkan dalam penyelidikan ini ketika diselakukan dengan set data ujian dalam setiap kes penyelakuan. Penambahbaikan model penyelakuan suhu udara adalah sebanyak 3.40%, 7.38%, dan 8.69% masing-masing untuk penyelakuan satu, lima, dan sepuluh minit ke hadapan manakala penambahbaikan model penyelakuan kelembapan relatif adalah sebanyak 0.96%, 1.35%, dan 2.38% masing-masing untuk penyelakuan satu, lima, dan sepuluh minit ke hadapan. Model-model penyelakuan yang telah ditambahbaik ketepatan kemudiannya boleh dimanfaatkan dalam pengawal ramalan berasaskan model bagi mengekalkan keselesaan haba penghuni-penghuni dalam bangunan sambil meminimumkan penggunaan kuasa pendingin hawa demi penjimatan tenaga dan pemuliharaan alam sekitar.

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LIST OF ABBREVIATIONS

ARMA	-	Autoregressive–moving-average
LTI TF	-	Linear time-invariant transfer function
NARX	-	Nonlinear Autoregressive Exogenous
ARX	-	Autoregressive Exogenous
GA	-	Genetic Algorithm

CHAPTER 1

INTRODUCTION

1.1 Background of Study

The air conditioner is one of the typical thermal comfort equipment used to maintain the occupants' thermal comfort in a building. Even though it is an effective equipment to maintain an indoor space's desired thermal setpoint, it also utilises a high amount of electricity. This high-power consumption is economically bad to the consumer due to the high electricity bill and also environmentally harmful to the nature if the electricity used to power the air conditioner is generated from the non-renewable fossil fuel sources such as natural gas, coal, and diesel. As cooling demands increase because of these developments, the energy sector is being greatly disrupted because the energy sector is thought to be a key contributor to climate change [1], [2]. According to the International Energy Agency (IEA) in the year 2021, 606.490 exajoule of energy is produced worldwide each year [3]. In 2015, it is reported that nearly 40% of the generated energy is utilised by buildings, which also accounts for an equivalent amount of greenhouse gas emissions [4]. Meanwhile, buildings are the world's third most total final energy consumption in 2017, trailing only the industry and transportation sectors [5], [6]. Over 70% of greenhouse gas emissions originate from metropolitan areas, primarily because of continuous use of heating, ventilation, and air conditioning (HVAC) systems. Thus, it is highly desirable to ensure that the air conditioner can be operated at its highest efficiency without sacrificing the users' thermal comfort [1], [7], [8].

The air conditioner system's disturbance is the unpredictable weather-related inputs, such as the outdoor temperature, solar radiation, and rainfall. These disturbances will lead to overshoot and undershoot while maintaining the indoor space's thermal conditions at the desired setpoints – both the overshoot and undershoot will cause discomfort to the occupants in the thermally controlled occupied area. In contrast, the undershoot will cause unnecessary power usage during the extra cooling. Predictive controllers can be implemented to produce necessary control outputs that can minimise the overshoot and undershoot while maintaining the desired setpoints. However, an accurate simulation model representing the plant's dynamic behaviour is required for the predictive controller to function effectively.

Some of the air conditioning systems today are capable of maintaining the desired indoor air temperature and the desired indoor relative humidity. Besides, there is also the requirement for the air conditioner in the large non-residential spaces to mix a certain percentage of fresh outdoor air into the existing air circulated in the area. The mixing of outdoor and existing air was done to reduce the content of unpleasant odours, harmful microorganisms, and carbon dioxide to an acceptable level to minimise the negative effect on the occupants' health and productivity. These new criteria lead to additional desired setpoints, which then lead to multi-objective setpoints.

This research focuses on constructing the model describing the dynamic indoor hygrothermal (temperature and humidity) behaviour of the Industrial Instrumentation Laboratory at Malaysia-Japan International Institute of Technology (MJIIT), Universiti Teknologi Malaysia (UTM) Kuala Lumpur. The model will be essential for potential predictive controllers in the future to maintain the hygrothermal level at desired setpoints during unpredictable weather conditions and to reduce power wastage due to unnecessary overcooling. The laboratory's two dynamic indoor thermal behaviours, the air temperature, and the relative humidity, were selected to be modelled in this research at this moment. The models representing indoor air temperature and relative humidity can be used for the potential multi-objective predictive controllers in the future. Additional thermal comfort-related indoor dynamic behaviour of the laboratory, such as the content of dust and carbon dioxide in the air of the occupied indoor space, can be added in the future for a higher possible multi-objective predictive controller.

Most works in Malaysia related to building hygrothermal issues and investigations are done using in situ experiments and are not focused on simulation.

Examples of work done in Malaysia include Ali et al. [9], Aktas et al. [10], and Mohammad Yusoff [11].

Ali et al. in [9] focus on in situ experiments combined with hygrothermal analytical methods to assess the thermal envelope quality together with the operative conditions against condensation and mould growth risks of a building. The results show that the building is overcooled, leading to poor envelope hygrothermal performance with associated condensation and mould growth problems on the non-air-conditioned sides of the envelopes. No simulation models were used in their work.

Aktas et al. in [10] focus on tackling urban heat islands in Kuala Lumpur through actual experiments and not using any simulation. They also focus on outdoor temperatures near buildings. Mohammad Yusoff in [11] focuses on a heritage mosque's indoor thermal comfort based on in situ experiments. Again, no simulation models were used in this work.

Hence, this research aims to fill the gap in hygrothermal modelling, focusing on creating and utilising indoor hygrothermal models for simulation in Malaysia.

1.2 Research Objectives

The objectives of this research are:

1. To install relevant sensors at strategic locations to facilitate hygrothermal data collections from an actual laboratory.
2. To develop the mathematical models representing a laboratory's dynamic hygrothermal behaviour using black-box models as accurately as possible with limited knowledge and resources.
3. To improve the simulation output accuracy of the constructed black box models by implementing ensemble methods to emphasise the strength of the

output feature(s) of each of the developed black-box models and validating them with the actual values recorded at the laboratory.

1.3 Research Significance

The contributions of this research are:

1. The installation of the relevant sensors at strategic locations to facilitate hygrothermal data collections from an actual laboratory. This setup may be upgraded with newer types of sensors in the future to collect newer types of data for newer research objectives. This setup can also be converted into a smart laboratory facility for various research purposes in the future.

2. The construction of the mathematical models representing the dynamic hygrothermal behaviour of an actual laboratory using several types of black-box models. The models are developed with minimal physical knowledge related to the hygrothermal behaviour of the laboratory. The simulation outputs from these black-box models have been compared with the actual output recorded at the laboratory for accurate benchmarking. Since the models developed in this research are simple models with less parameters compared to the high-fidelity white box models, they are suitable to be implemented in model-based predictive controllers cost effectively because simple models require less computational power and can be implemented using low-cost computers, microprocessors, and microcontrollers.

3. The improvement of the simulation output accuracy of the constructed black-box models using ensemble methods to emphasise the strength of the output feature(s) of each of the developed black-box models. The output values are then combined into a single output value based on the strength of each model's output. The simulation outputs from these ensemble models have also been compared with the actual output recorded at the laboratory for benchmarking

purposes. These accuracy-improved black box models are still simple, require less computational power and can be implemented using low-cost computers, microprocessors, and microcontrollers.

1.4 Research Scopes

First, the Industrial Instrumentation Laboratory at Malaysia-Japan International Institute of Technology (MJIIT), Universiti Teknologi Malaysia (UTM) Kuala Lumpur, is selected as the plant to be modelled in this research and will be described in more detail in Subsection 3.2. The laboratory was selected since it is conveniently located in the city centre, where the climate is hot and humid, which is the focus of this research.

Second, only the weather-related inputs are used for the model developed in this research. The Industrial Instrumentation Laboratory is equipped with air conditioners and ventilation fans. However, the data available by the time this research are done is recorded when these thermal comfort equipment are not operated.

Third, only two dynamic behaviours related to the laboratory's thermal comfort control are modelled for this research due to time constraint, which are temperature and humidity. Additional hardware for recording other dynamic behaviours related to thermal comforts, such as indoor air quality (IAQ), will be developed and installed for data collection as a future work.

Fourth, only the data recorded for 11 days are used for this research for the black box models development. Due to time constraint, only the data recorded for 11 days are available by the time this research is done. Additional data could not be recorded because the plant to be modelled (the laboratory) at the campus was not accessible due to the multiple movement control orders (MCOs) during the COVID-

19 pandemic. This additional data will be recorded in the future for models' improvement.

Fifth, even though some of the wall surfaces of the plant to be modelled (the laboratory) has a few doors, windows, and ventilation fans, all these items are incorporated into the walls and assumed to be part of the walls with uniform heat conductivity rate to maintain the models simplicity – instead of having multiple mathematical terms to represent the heat conductivity characteristic through multiple types of surface (the surfaces of the walls, doors, windows, and ventilation fans), the number of the mathematical terms representing the heat conductivity through the surface are reduced when the doors, windows, and ventilation fans are incorporated into the walls and assumed to be part of the walls with uniform heat conductivity rate.

Sixth, the surface areas of the outer walls of the plant to be modelled (the laboratory) are considered to receive either no solar radiation (0% radiated area) or complete solar radiation (100% radiated area), also to maintain the simplicity during the models' development. There is a complex set of mathematical formula to calculate how much the surface of an area receives sunlight at a given time of the day based on the surface inclination, surface bearing, the sun inclination, the sun bearing, the position of nearby object(s) that can partially/fully block the direct sunlight to the surface, etc., but this calculation is not implemented in this research due to time constraint.

Seventh, only three types of black-box models and three ensemble algorithms are implemented and investigated in this research due to time constraint. The three types of black-box models are: (1) the autoregressive–moving-average (ARMA) model; (2) the linear time-invariant transfer function (LTI TF) model; and (3) the nonlinear autoregressive exogenous (NARX) model. Meanwhile, the three types of ensemble algorithms are: (1) the weighted average (WA) ensemble model; (2) the least square technique (LST) / least square method (LSM) estimated ensemble model; and (3) the genetic algorithm (GA) estimated ensemble model.

Finally, the simulation models developed in this research only simulate output at every one-minute interval and produce output for one, five, and ten minute(s) ahead due to time constraint.

1.5 Thesis Outline

This thesis is organized into five chapters. Their contents are outlined as follows:

1. Chapter 1 contains the introduction of the research, which includes brief executive summary information where the project's scope is also discussed. It also explains the objectives of the research. The research's significance has also been discussed in this chapter.

2. Chapter 2 provides a literature review and briefly discusses modelling methods of dynamic systems. In particular, the autoregressive–moving–average (ARMA) model, the linear time-invariant transfer function (LTI TF) model, the nonlinear autoregressive network with exogenous inputs (NARX) model, and the ensemble learning will be introduced. Recent works on modelling and simulating the dynamic indoor hygrothermal behaviour of a building, focusing on hot and humid environments, will be reviewed next. Finally, the issues that remain in this area will be discussed, highlighting research gaps and the possibility of improvements.

3. Chapter 3 briefly explains the methodology for the research in every research stage. This chapter briefs the construction, testing, and optimisation processes for each type of simulation model utilised in this research.

4. Chapter 4 presents the results and discussions of the research. This chapter presents the hygrothermal model's simulation results, comparing the individual black-box models, the ensemble models, and the actual values obtained from the laboratory. The focus is on how the proposed ensemble learning improved the prediction output of the lab's humidity and temperature.

5. Chapter 5 concludes the thesis by reviewing the objectives and their fulfilment, a summary of the work that has been accomplished, and the recommended future work.

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[1] **S. F. M. Hussein**, H. Nguyen, S. S. Abdullah, Y. Lim, and Y. Tan, “Black Box Modelling the Thermal Behaviour of iHouse using Auto Regressive and Moving Average (ARMA) Model,” J. Teknol., vol. 78, no. 6–13, pp. 51–58, 2016.

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[1] **S. F. M. Hussein**, M. A. Abu Bakar, Y. Makino, H. Nguyen, S. S. Abdullah, Y. Lim, and Y. Tan, “Simplifying the Auto Regressive and Moving Average (ARMA) Model Representing the Dynamic Thermal Behaviour of iHouse Based on Theoretical Knowledge,” in 17th Asia Simulation Conference, AsiaSim 2017, Melaka, Malaysia, August 27 – 29, 2017, Proceedings, Part II, vol. 752, 2017, pp. 697–711.

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