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A Dissertation

titled

Development of Integrated Building Control Systems for Energy and Comfort Management in Intelligent Buildings

by

Rui Yang

Submitted to the Graduate Faculty as partial fulfillment of the requirements for the Doctor of Philosophy Degree in Engineering

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December 2013
An Abstract of
Development of Integrated Building Control Systems for Energy and Comfort Management in Intelligent Buildings

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An intelligent building is able to manage its indoor environment via computer technologies to optimize energy efficiency, occupants’ wellbeing, safety and productivity. The main objective in intelligent building design is to satisfy occupants’ need with high energy efficiency. As the primary task for a building control system, energy and comfort management aims to solve the conflict between improving users’ satisfaction and reducing building energy consumption. In this dissertation, a multi-agent control system is developed to integrate building control systems and to coordinate operations in building subsystems. The developed multi-agent system facilitates the building to interact with its occupants to realize user-centered control.

Based on the framework of the developed multi-agent system, control strategies are proposed to improve energy efficiency through the intelligent control of the building subsystems. Intelligent controllers are developed for the decision-making process in building energy and comfort management. The developed controllers control the building subsystems that include heating, ventilation and air conditioning system, lighting system, geothermal heat pump system, and water loop heat pump system. The proposed control
strategies improve the energy efficiency in subsystem operations while maintaining comfortable indoor environment. This dissertation also discusses the implementation of cloud computing to solve computationally intensive problems with less time and less cost in intelligent buildings. The cloud features certain limitations and vulnerabilities that may impact the performance of control system. The performance of the cloud based control system is evaluated.
To my beloved parents

Ling Peng

Mingzhou Yang

Thanks for your endless love and support

In grateful and blessed memory of my dear grandparents

Changzen Ai

Lianggen Wen

You will always live in my memory
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## Contents

Abstract ................................................................................................................................. iii

Acknowledgements ............................................................................................................. vi

Contents .............................................................................................................................. vii

List of Tables ....................................................................................................................... xi

List of Figures ..................................................................................................................... xii

1 Introduction ......................................................................................................................... 1

1.1 Intelligent Building ........................................................................................................ 1

1.2 Research Objectives ...................................................................................................... 4

1.3 Organization of Dissertation ........................................................................................ 5

2 Energy and Comfort Management in Intelligent Buildings ............................................. 7

2.1 Occupants’ Comfort ...................................................................................................... 7

2.2 Energy Management ..................................................................................................... 9

3 Development of a Multi-agent System for Building Automation Considering the Behavior of Occupants ......................................................................................................................... 12

3.1 Introduction ..................................................................................................................... 12

3.1.1 Problem Statement .................................................................................................. 12

3.1.2 Agent Technology .................................................................................................. 13

3.1.3 Multi-agent Technology for Building Automation .................................................. 14

3.2 An Overview of the Proposed Multi-agent System Framework for Intelligent Buildings ................................................................................................................................. 16
3.3 System Architecture and the Functionality of Agents ...........................................18
  3.3.1 Personal Agent .................................................................................................20
  3.3.2 Local Agent .....................................................................................................24
  3.3.3 Central Agent ..................................................................................................27

4 Multi-Objective Particle Swarm Optimization for Decision-Making in Building
Energy and Comfort Management ................................................................................30
  4.1 Multi-Objective Particle Swarm Optimization .......................................................30
     4.1.1 Basic Concept of a Multi-objective Problem .................................................31
     4.1.2 General Algorithm for PSO ..........................................................................32
     4.1.3 Weighted Aggregation Approach for MOPSO ...........................................34
     4.1.4 Pareto-based Approach for MOPSO ............................................................35
  4.2 System Configuration for Energy and Comfort Management ............................37
     4.2.1 System Configuration ....................................................................................37
     4.2.2 Local Agents ................................................................................................39
  4.3 Problem Formulation for the Multi-objective Particle Swarm Optimizer .....43
     4.3.1 Problem Formulation ....................................................................................43
     4.3.2 Experimental Results ...................................................................................45
  4.4 Conclusion ............................................................................................................48

Systems .........................................................................................................................49
  5.1 Introduction ..........................................................................................................49
  5.2 Agent-based System for Multi-zone Building Control .........................................50
5.3 Mathematical Model and Algorithm for the Proposed Multi-agent Control Architecture

5.3.1 Central Agent .................................

5.3.2 Zone Agent and Local Controller-agents ..........

5.3.3 Collaboration of Agents ............................

5.4 Case Study and Simulation Results .............................

6 Development of an Optimal Control Strategy for HVAC System in Building Energy Management

6.1 Introduction ..................................................

6.2 HVAC System Modeling ........................................

6.2.1 Thermal and Ventilation Models for Building Environment ......

6.2.2 Energy Models for HVAC Units ............................

6.3 HVAC Control System Design .................................

6.3.1 Primary controller ........................................

6.3.2 Secondary Controller ....................................

6.4 Case Study ..................................................

6.5 Conclusion ..................................................

7 Efficient Control of a Solar Assisted Geothermal Heat Pump System Based on Evaluation of Building Thermal Load Demand

7.1 Introduction ..................................................

7.2 Components and System Description ..........................

7.2.1 Evaluation of Building Thermal Load Demand ..............

7.2.2 Fan Coil Unit Characteristics .............................
List of Tables

3.1 Degree of occupants’ satisfaction towards thermal comfort…………………………23
4.1 Fuzzy control rules for local temperature controller……………………………………40
4.2 Fuzzy control rules for local ventilation controller……………………………………42
4.3 Fuzzy control rules for local illumination controller…………………………………43
4.4 Selected sample solutions from the MOPSO optimizer……………………………47
5.1 Best solutions and overall comfort……………………………………………………61
6.1 Suggested temperature range…………………………………………………………77
6.2 Comparison of different set points…………………………………………………..84
7.1 The operation characteristics of each mode in heating period……………………99
8.1 Experimental results on the parallel PSO performance……………………………116
List of Figures

1-1 System integrations for intelligent building .......................................................... 3
3-1 Overview of multi-agent system framework for intelligent buildings .................. 17
3-2 Architecture of the proposed multi-agent system .................................................. 19
3-3 The characteristic curve for a Gaussian function .................................................. 22
3-4 The relationship between overall thermal comfort and indoor temperature .......... 26
4-1 The Pareto front and dominance relation in a two-objective space .................... 32
4-2 The pseudo code of a general PSO algorithm ....................................................... 33
4-3 The pseudo code of MOPSO algorithm ............................................................... 35
4-4 A defined niche for each particle ......................................................................... 36
4-5 Multi-agent system with detailed structure of the local agent ............................. 38
4-6 Membership functions of local temperature controller ....................................... 40
4-7 Membership functions of local ventilation controller ......................................... 41
4-8 Membership functions of local illumination controller ....................................... 43
4-9 Pareto-optimal front of energy consumption versus overall comfort ............... 46
4-10 Pareto-optimal front with a temperature constraint ........................................... 48
5-1 Multi-agent system architecture for multi-zone building control ...................... 51
5-2 The pseudo-code of the constraint PSO algorithm .............................................. 54
5-3 Floor plan of four zones in a building ................................................................. 57
5-4 Environmental parameters for zone 1 ................................................................. 58
5-5 Environmental parameters for zone 2 ................................................................. 58
5-6 Environmental parameters for zone 3 .........................................................59
5-7 Environmental parameters for zone 4 .........................................................59
5-8 Overall comfort ..........................................................................................60
5-9 Available power and demanded power .....................................................61
5-10 Environmental parameters in zone 1 after optimization .........................62
5-11 Environmental parameters in zone 2 after optimization .........................63
5-12 Environmental parameters in zone 3 after optimization .........................64
5-13 Environmental parameters in zone 4 after optimization .........................65
5-14 Overall comfort after optimization .........................................................66
6-1 A typical HVAC system model ................................................................70
6-2 Control system structure for HVAC system ............................................76
6-3 Occupancy variation in a day ..................................................................82
6-4 Outdoor temperature variation in a day ....................................................82
6-5 Indoor temperature variation in a day .......................................................83
6-6 Indoor CO₂ concentration variation in a day ...........................................83
6-7 Energy consumption in a day ..................................................................84
7-1 Schematic diagram of the solar assisted GHP system ...............................88
7-2 Operation mode conversion flow chart ....................................................95
7-3 Outdoor temperature variation .................................................................96
7-4 Building thermal load demand .................................................................97
7-5 Useful solar energy gain ...........................................................................97
7-6 Extracted energy from ground .................................................................98
7-7 System performance factor .....................................................................99
8-1 Hydraulic loop of a water loop heat pump system……………………………………103
8-2 Water-to-air heat pump………………………………………………………………..104
8-3 Parallel asynchronous particle swarm optimization……………………………………108
8-4 Cloud based control system architecture………………………………………………110
8-5 Work flow chart of the central controller in one sampling time……………………111
8-6 Ambient air temperature………………………………………………………………..112
8-7 Thermal load in each zone ………………………………………………………………113
8-8 Indoor temperature variation in zone 1 and zone 2……………………………………..114
8-9 Optimized supply water temperature…………………………………………………..115
8-10 Total power consumption of the water loop heat pump system…………………..115
8-11 Indoor temperature variation in zone 1 when suffering time out…………………117
8-12 Indoor temperature variation in zone 3 when the data is maliciously modified in the cloud…………………………………………………………………………………118
Chapter 1

Introduction

1.1 Intelligent Building

Intelligent buildings are becoming a trend of the next-generation’s buildings, which facilitate intelligent control of the building to satisfy the changing needs effectively. Since people spend 80% of their lifetime in buildings, a healthy and comfortable environment is important for occupants’ well-being and productivity [1]. Intelligent buildings promote occupants’ wellbeing, safety, productivity, and building’s sustainability through intelligent technologies [2].

So far, the concept of intelligent building has been discussed and defined differently in a number of academic and technical literatures. The Intelligent Building Institute of the United States focuses on technologies and defines an intelligent building as a building that provides a productive and cost-effective environment through optimization of its four basic elements including structures, systems, services and management and the interrelationships between them [3]. While the UK-based European Intelligent Building Group focuses more on users’ satisfaction and defines an intelligent building as a building that creates an environment which maximizes the effectiveness of the building's occupants and enables efficient management of resources with minimum life-time costs of hardware and facilities [3]. By summarizing different definitions in Asia, So et al. redefined an intelligent building as one that designed and constructed on an appropriate
selection of quality environment modules to meet the user's requirements by mapping to the appropriate building facilities to achieve long-term building value [4]. Even though there is no standard and accordant definition existing for intelligent building, most attempts have several features in common [5] [6]. Intelligent Buildings:

- Provide well indoor environment to promote users’ living comfort, work efficiency, healthy well-beings, safety, and security.
- Maximize building performance and efficiency in building construction, operation and maintenance.
- Have long-term and sustainable values that are environmentally friendly.

Intelligent buildings use advanced computer technologies to effectively control the building facilities and provide a productive indoor environment in a cost-effective manner [7]. Designing an intelligent building demands a careful consideration of environmental factors that may affect occupants’ comfort, well-being and productivity [8]. Many efforts have been made in developing advanced and innovative technologies for intelligent buildings. Previous efforts in this area include advanced development of system integration [6] [9], network protocol [10], and building subsystem control, which include heating, ventilation and air conditioning (HVAC) system [11][12], lighting system [13][14], fire protection system[6], security system[15]. The research and technologies in intelligent buildings are characterized by a hierarchical level of system integration [5][16]. System integration is the process of integrating systems, devices and programs in a common architecture so as to share data and perform control. Intelligent buildings usually comprise three levels of system integration, as shown schematically in Figure 1-1.
Figure 1-1: System integrations for intelligent building.

The top level is the structure and function management level which deals with the provision of various features of building operation and management. This level makes proper operation and management regulations for different functional buildings. Different functional buildings, such as commercial buildings, residential buildings, educational buildings, and industrial buildings, require different operation and management regulations.

The middle level is the system automation level that controls, supervises and coordinates the intelligent building subsystems. This level is usually performed by the building automation system (BAS), energy management system (EMS), and communication management system (CMS) [16]. The BAS controls subsystems such as the HVAC system, lighting system, lift/elevator system. The EMS supervises and coordinates energy-consuming units to minimize the operation cost. The CMS provides control-related communication between controllers and end-points to help coordination between automation systems [17]. To monitor and control the entire building energy
consumption continuously as well as maintain the occupant's comfort effectively, numerous sensors, actuators and control processors can be interconnected together to form actually a real-time sensor network.

The bottom level is the subsystem or field level that includes various subsystems. The HVAC system provides comfortable thermal environment to occupants. The lighting system controls the artificial lighting and utilizes the daylight properly to achieve constant lighting conditions. The security and safety system controls security access, detects dangerous instances, and alerts users on emergency situations. The power supply system manages electrical power, natural gas, and other possible renewable power supplies such as wind power, solar power, and geothermal. The communication system provides communication services including local area network, internet connection, remote control, and building control networking to users. Other subsystems include fire protection system, life/elevator system and etc. Intelligent building allows interaction and integration between subsystems to provide building services to users.

1.2 Research Objectives

This dissertation focuses on discussing the development of integrated building control systems for energy and comfort management in intelligent buildings. There are three major research objectives that are to be illustrated in this dissertation.

The first objective is the design and development of an integrated building control system to perform intelligent control over the entire building environment. The designed integrated system should be able to tackle different control tasks in building management and automation.
The second objective is the energy and comfort management to optimize occupants’ comfort and energy efficiency, which are two primary concerns for evaluating the performance of a building control system. Occupants’ satisfaction is related to both the condition of the environment and occupants’ preferences over the environment. Since maintaining high comfortable indoor environment always leads to high energy consumption, the integrated control system needs to solve the conflict between improving user’s comfort and saving the energy consumption.

The third objective is to solve various complex and nonlinear problems in different levels of building subsystems by applying effective and intelligent control techniques. In this dissertation, multiple intelligent control techniques are utilized to deal with different problems in both the development of the building automation system and the control on the subsystems. The utilized intelligent control techniques are agent technologies, swarm intelligence, neural network approaches, and fuzzy control method. This research will demonstrate how these intelligent technologies are implemented in tackling complex problems in the different levels of system automation.

1.3 Organization of Dissertation

This dissertation consists of four major parts based on the research objectives. The first part introduces the challenges and problems in energy and comfort management for intelligent building. Chapter 1 gives a brief introduction of the intelligent building and presents the research objectives. Chapter 2 discusses the major problems in building energy and comfort management.

The second part presents an integrated control system for intelligent buildings, and proposes solutions for energy and comfort management in the system automation level.
Chapter 3 proposes a multi-agent system model for intelligent buildings, which takes into consideration the behaviors of the occupants. Based on the integrated control system design, Chapter 4 presents a multi-objective particle swarm optimizer for the energy and comfort management decision-making. Chapter 5 discusses the energy and comfort management of multi-zone building in a micro-grid system that has renewable power supply.

The third part discusses the control and optimization system in the subsystem levels and their interactions with the integrated control system. Chapter 6 presents an intelligent optimal controller for the HVAC system that is an essential subsystem in most buildings. Chapter 7 discusses the efficient control approach in heat pump systems that involve solar heat and geothermal, which are renewable thermal energy supplies. Chapter 8 presents an optimal controller for water loop heat pump system, and discusses the controller’s performance when deployed on a cloud platform.

The fourth part is the summary part that concludes this dissertation and discusses future research outlook that are presented in Chapter 9.
Chapter 2

Energy and Comfort Management in Intelligent Buildings

Intelligent buildings provide a productive environment that maximizes the effectiveness of the building occupants, and enable the efficiency of building management through minimize lifecycle costs of building facilities. However, energy consumption and users’ comfort usually affect each other in an opposite way. That is, more energy is needed for a higher comfort level. Therefore, one primary goal of a building automation system is to solve this conflict between energy consumption and occupants’ comfort.

In order to meet the requirement of energy efficiency and occupants’ satisfaction, work needs to be done to reduce energy consumption in building operation and to evaluate occupant’s satisfaction in response to changes of the environment. This Chapter introduces an approach to evaluate occupants’ comforts based on related parameters in building environment. The building energy supply sources and loads are also introduced in this Chapter.

2.1 Occupants’ Comfort

Occupants’ quality of living in building is mainly determined by three basic factors: thermal comfort, visual comfort, and indoor air quality comfort [1]. These three factors
are mainly controlled through HVAC system and lighting system, as well as other auxiliary control facilities such as window opening and shading system. Therefore, the proper control of the HVAC system and the lighting system is important in improving building’s energy efficiency and occupants’ comfort.

To evaluate the occupants’ comfort in the indoor environment, indoor environmental parameters are used as indices to form the function of occupant’s comfort by utilizing the actual value of the corresponding environmental parameters and occupant’s preferences of these parameters. Indoor temperature is used to indicate the thermal comfort in a building environment; and the heating and cooling system is utilized to maintain the indoor temperature in a comfortable region. Indoor carbon dioxide (CO₂) concentration is used as an index to measure the air quality in the building environment; and the building ventilation system is utilized to provide fresh air into the building environment [1]. Indoor Illumination level is used to indicate the visual comfort in a building environment, which is measured in lux [18]; and the electrical lighting system serves as actuators to control the indoor illumination level. Therefore, the indoor temperature, indoor CO₂ concentration, and indoor illumination level are utilized as environmental parameters to evaluate occupants’ thermal comfort, visual comfort, and indoor air quality comfort, respectively.

In order to quantize and scale user’s comfort, these environmental parameters are measured to illustrate occupants’ comfort based on their preferences. Equation (2.1) proposes a feasible approach to evaluate occupants’ indoor comfort under certain circumstances.

\[
Comfort = w_T \left[1 - \left(\frac{e_T}{T_{set}}\right)^2\right] + w_A \left[1 - \left(\frac{e_A}{A_{set}}\right)^2\right] + w_L \left[1 - \left(\frac{e_L}{L_{set}}\right)^2\right]
\]

(2.1)
where Comfort is occupants' comfort level inside the current indoor environment. It varies in the range of [0,1]. \( w_T, w_L, \) and \( w_A \) are weighting factors that indicates the importance of three comfort factors. \( w_T, w_L, \) and \( w_A \) varies in the range of [0,1], and \( w_T + w_A + w_L = 1 \). They are user-defined parameters that could be set by users through user interface.

\( T_{set}, L_{set}, \) and \( A_{set} \) represent for the set points of the temperature, the illumination, and the indoor air quality, respectively.

\( e_T, e_L, \) and \( e_A \) are the differences between the measured values and set points of the temperature, the illumination, and the indoor air quality, respectively. They have,

\[
e_T = T_{actual} - T_{set} \tag{2.2}
\]

\[
e_L = L_{actual} - L_{set} \tag{2.3}
\]

\[
e_A = A_{actual} - A_{set} \tag{2.4}
\]

\( T_{actual}, L_{actual}, \) and \( A_{actual} \) are the measured actual value of the indoor temperature, the indoor illumination level, and the indoor air quality, respectively.

### 2.2 Energy Management

Energy management can help organizations meet these critical objectives by improving environmental quality and saving energy in building operations. Building energy management is needed in managing both thermal and electrical energy supply sources and loads.

The utility grid is usually used as the primary power supply to building loads. Natural gas is also utilized to provide thermal energy to buildings. Micro-grid technology provides an opportunity to integrate the operation of electrical and thermal energy supply and
demand [19][20]. Besides the distribution grid, the energy supply may include renewable energy resources such as PV solar cells, wind powers, and geothermal, autonomous power generators such as fuel cells, combined heat and power system, and energy storage devices such as batteries and water tanks.

Dictated by the requirements of occupant comfort, the typical electrical demands or loads include HVAC system, lighting system, fire safety system, lift system, and etc. HVAC system and lighting system are used to provide a comfortable living environment for building occupants. According to California Commercial End-Use Survey [21], the primary electric end-uses in buildings are interior lighting, cooling, refrigeration, and ventilation; and the primary natural gas end-users are space heating and water heating, and cooking. HVAC system and lighting system together consume up to 60% of the electrical power for buildings. The rest of energy is consumed in different kinds of equipment depending on the functionality of the building. Therefore, proper energy management of the HVAC system and the lighting system can help the building save a significant amount of energy.

Moreover, building energy management system requires more than the control of building’s HVAC system and lighting system. It also needs to deal with all kinds of energy-related actuators to perform the needed functionality of the building. Building energy management is a fundamental and important issue for building automation, which needs to handle other information. For instance, it is designed to monitor electricity’s hourly market price for avoiding peak load hours or to monitor the fire alarm detectors for notifying the building occupants in case of a fire or other emergency.

Therefore, an intelligent building requires a sophisticated building automation
system to manage a large set of actuators and equipment. Operating such system effectively requires the optimized performance of almost every subsystem. As to the energy efficiency, in addition with the usage of loads, the determination of the control strategy is also important to improve energy efficiency in building operations. These can be achieved by the application of intelligent controller that aims to reduce the energy consumption without compromising the occupant’s comfort. The design of such control systems highly depends on the functionality of the target building as well as the inhabitant’s living pattern. The HVAC system in a commercial building such as an office can be designed to operate in two different modes: user-presence mode and user-absence mode. In daytime, the HVAC system is operated to provide workers with a comfortable environment to insure high productivity; while in nighttime, the HVAC system can be operated in a less-comfort mode to saving energy with the absence of occupants. As for a residential building like a house which may have residents all the day, the HVAC system needs to maintain constantly comfortable environment for the residents; and therefore, different control strategies should be developed for different types of buildings.

To sum up, the key to improve energy efficiency in building operation is to coordinate and optimize the operation of various energy sources and loads. An effective control system is needed for building energy and comfort management.
Chapter 3

Development of a Multi-agent System for Building Automation Considering the Behavior of Occupants

3.1 Introduction

3.1.1 Problem Statement

Energy efficiency and occupant’s comfort are two primary concerns for evaluating the performance of a building control system. As illustrated in Chapter 2, occupant’s quality of living in buildings is mainly determined by three basic factors: thermal comfort, visual comfort, and indoor air quality comfort. These three factors are determined by operation of the HVAC system and lighting system. For building energy management, it requires not only the control of building’s HVAC system and lighting system, but also the ability to deal with all kinds of energy-related actuators to perform the needed functionality of the building.

In addition, building management system should be designed under the guideline of user-centered control, since one primary goal of the building management system is to fulfill various needs from occupants. Intelligent buildings should be capable of interacting with occupants and the ambient environment to determine the appropriate
control strategy. Moreover, during building operations, the interactions between users and the environment always have a direct effect on the system performance. For instance, users of an electrical lighting system may turn the lights on or off, or may set the electrical lighting level to control the interior light. Users of an HVAC system may change the temperature set point in order to start the heating or air conditioning system. Hence, an intelligent control system should not only react quickly to these activities, but also communicate with users to obtain meaningful feedbacks. Researches have been done for observing and learning user’s behaviors. Multiple sensors can be embedded into the building system to observe occupant’s behaviors. With proper classification and analysis, the occupancy data can be derived through these sensors [22]. Based on the observations on real schedules of occupants, studies have also been conducted to simulate the behaviors of occupants and predict their impacts on the building [23], [24].

### 3.1.2 Agent Technology

Agent technology can be applied into the building environment to control environmental parameters and solve possible conflicts arising between energy efficiency and user’s satisfaction. Generally, an agent is defined as a software or a hardware entity that is situated in a certain environment and is able to autonomously react to changes in that environment [25]. An agent has three basic characteristics: reactivity, pro-activeness and social ability. Reactivity refers to the ability of agent in reacting to the changes in its external environment; pro-activeness indicates the goal-directed behavior of an agent; social ability indicates an agent should be able to interact with other agents based on an agent communication language, which allows agents to converse rather than simply passing data [26], [27].
The design of a multi-agent system for building comprises multiple agents collaborating in a building environment. It is worth noting that there is no overall system goal in a multi-agent system, but simply local goals of each separated agents. The system’s objectives can only be realized by coordinating multiple intelligent agents with local goals corresponding to a subpart of these objectives. Some system goals can only be accomplished by the cooperation of multiple agents, which indicates that these intelligent agents must be capable of communicating with each other.

Agents in a multi-agent system are designed to accomplish complex tasks in a collaborative fashion. In a multi-agent system, to attain the capability of seamless cooperation between agents, they require abilities such as collaboration between individuals, coordination of actions, and resolution of conflicts by themselves [28][29]. Here collaboration deals with the distribution of tasks and resources among agents. Coordination is concerned about organizing the actions of different agents in time and space. In addition, resolution of conflicts usually requires negotiation techniques to enhance the system’s performance.

Agent technology allows for a distribution of intelligence. Therefore, the design of a multi-agent system is in fact a process of realizing the intended functionality of each agent as well as enabling them to collaborate with each other to accomplish the overall system goals. It also provides an open architecture in which agents can be easily configured, and new agents can be added without interfering with the normal operations of the system. Moreover, the agents in a multi-agents system will be designed differently with respect to different building types.

3.1.3 Multi-agent Technology for Building Automation
Agent technology has gained increasing attention in the building automation field due to its ability in tackling complex systems. System’s control goals can be realized by coordinating multiple intelligent agents with local goals corresponding to a subpart of these objectives [26], [30]. It can be embedded in an intelligent environment to perform a life-long learning of the user’s particular behaviors [31]. Multi-agent technology has been utilized to develop intelligent control systems for building’s energy management [28]-[32].

In this chapter, a multi-agent system will be developed to enable the building to interact with its users for achieving the goal of user-centered control. Moreover, it features an open architecture so that it can be adapted to different building environments with various functionalities. Based on this multi-agent architecture, complicated building control systems can be built where each agent acts as an expert operator for an individual system and cooperates with each other to create a well-behaved overall system.

The developed multi-agent system aims to achieve both energy saving and customer satisfaction via user-centered services. Energy saving is accomplished by intelligent control of the energy equipment such as HVAC and lighting devices. Customer satisfaction is achieved by user-centered designs that adapt to the building environment according to occupant’s preferences. On the other hand, when the building is intelligently controlled to meet occupants’ preferences by adjusting heating/cooling and lighting level, these preferences need to be well interpreted and learned through the feedbacks or behaviors of occupants. This ability requires the corresponding agent to recognize and learn from users to predict occupants’ behaviors. The learning process is carried out
interactively based on the reinforcement mechanism through learning the actions taken by agents and the corresponding reactions of the occupants.

Energy efficiency and user’s satisfaction toward an indoor environment may not be the only demand that the designed multi-agent system needs to satisfy. An intelligent building automation system may also be concerned with other aspects that relate to the normal operation of the building or users’ experience of living. For instance, a safety system is requisite to a building that would alarm people when any emergency occurs; or the application and control of a magnetic card and access system is necessary for a building that requires high security.

3.2 An Overview of the Proposed Multi-agent System Framework for Intelligent Buildings

A multi-agent system framework is developed to implement control in the building environment. Figure 3-1 provides an overview of the multi-agent system involving sensor and actuator networks in a building environment[33]. The multi-agent system takes data from sensors and occupants as inputs and makes decisions to implement control on actuators.
Figure 3-1: Overview of multi-agent system framework for intelligent buildings.

Sensors are distributed in the entire building to monitor its performance. Three kinds of data including environmental data, occupancy data and energy data can be obtained from the sensor network. Environmental data refer to building’s environmental parameters such as indoor and outdoor temperature, illumination level, CO$_2$ concentration, or even the detection of intrusion or fire alarm signals. Occupancy data usually include the number of occupants and presence/absence of occupants. Energy data mainly focus on the status of energy supply such as the condition of the utility grid, the electricity price, and the availability of the renewable resources. These measured data will be used by different local agents for deciding their respective behaviors.

To realize the effective user-centered control of the building system, another significant input for the multi-agent system is the behavior pattern of occupants. Personal agents in the multi-agent system are developed to learn and predict occupants’ preferences through their behaviors. Learning occupant’s preferences is conducted by
observing their behavior and identifying the person who took the actions. By providing personal agent with the identity of a specific occupant and observing his/her behavior, the personal agent will be able to learn the preferences of this specific user instead of all occupants in the building.

Policies, as principles or rules to guide decisions, define the constraints that agents should comply with. Each policy specifies the condition for its validation and its privilege among other policies. Policies are deployed in the multi-agent system to make regulations for agents.

The multi-agent system controls the building environment through the actuators. Figure 3-1 lists several fundamental actuators for building automation, including the HVAC system, electrical lighting system, power grid management system, safety/emergency system.

3.3 System Architecture and the Functionality of Agents

Figure 3-2 illustrates specifically the interior architecture of the multi-agent system for building automation. It gives an example including three local agents to control the HVAC system, the electrical lighting system, utility grid management system and renewable resources management system. This section will illustrate how agents interact with each other to perform the control tasks of actuators.
There are three kinds of agents in the proposed multi-agent system: central agent, local agent, and personal agent. In this multi-agent system, personal agent communicates with local agent to provide information of occupant’s preferences and receive feedback from local agent concerning the environmental changes and the interactions between humans and their environment. Local agents are designed to control each subsystem. For example, the local HVAC agent obtains the measurements of the temperature and the CO₂ concentration levels from thermostats and CO₂ concentration sensors respectively to evaluate the thermal comfort and the indoor air quality in the ambient environment. Based on these environmental parameters, the local HVAC agent can locally perform

Figure 3-2: Architecture of the proposed multi-agent system.
some controls on its corresponding HVAC system. The local lighting agent takes the illumination level as input to evaluate occupant’s visual comfort and controls the electrical lighting system. The local power management agent monitors the conditions of the utility grid and the renewable energy availability, and it can react to the power supply changes and report the real-time information to the central agent. The central controller continuously interacts with multiple local agents for achieving the overall control goals in the ever-changing operating conditions.

3.3.1 Personal Agent

In order to realize the effective user-centered control in building automation, personal agents are proposed to respond to their occupants for facilitating user-interaction. It acts like an assistant for managing occupant’s information, observing external environment, and presenting feedback from other agents to its occupant.

The personal agent is capable of identifying users so that it can build a profile for each occupant. In this way, if any actions have been taken to adjust the indoor environment, the personal agent will track who makes the decision and then learn the preferences of this specific user instead of all the occupants in the building.

Learning occupant’s preferences is conducted by observing their behavior and identifying the person who took the actions. User’s preferences include measurable parameters such as temperature, illumination level, CO₂ concentration. The values of these parameters are usually accompanied by appropriate descriptive data such as the outdoor environment, time, etc. If an occupant is satisfied with the environment, the personal agent would assume that the ambient environment is acceptable to the occupant and then update its rule set for calculating his/her preferences accordingly. On the other
hand, occupants change the environmental settings via their personal agents and provide
feedback on their satisfaction levels.

The personal agent communicates with both the occupants and the local agents for
data acquisition and feedbacks. It provides user’s profile information to the local agents if
needed. It also receives feedbacks from local agents of the environmental changes, and
displays messages to users to inform them about these changes.

The function of a personal agent varies in order to adapt to different building types.
Different types of buildings have different control objectives and require different user-
specific parameters. The personal agent should be able to learn occupant’s personal
preferences under various operating circumstances.

3.3.1.1 Representation of User’s Thermal Comfort

Most occupants in a building can tolerate a certain degree of discomfort. This is
mainly because most people are insensitive to temperature variations within several
Celsius degrees. Therefore, instead of a single temperature point, a range of temperature
may be felt comfortable for occupants. Temperature outside of this range will be felt
uncomfortable for most occupants, and user’s satisfaction will decrease dramatically with
temperature that goes far from the comfort range. Besides the approach of evaluation of
user’s comfort in Chapter 2, this kind of characteristic regarding the occupants’ thermal
comfort can also be represented using a Gaussian function as follows:

\[
f(x) = e^{- \frac{(x-\mu)^2}{2\sigma^2}}
\]  \hspace{1cm} (3.1)

The curve for a Gaussian function is shown in Figure 3-3. There are two
characteristic parameters in this function that decide the shape of this curve: the mean \( \mu \)
and the standard variance $\sigma$. $\mu$ is the mean that is the location of the peak; it can be used to represent the temperature in which the best user comfort locates. $\sigma$ is the standard variance. Within one standard variance from the mean, the comfort is decreased to 60.65\% of the peak comfort; within twice variances, the comfort will decrease to 13.5\% of the peak comfort.

![Gaussian function characteristic curve](image)

**Figure 3-3:** The characteristic curve for a gaussian function.

In this case, $\mu$ and $\sigma$ can be used as characteristic parameters which are identical for each occupant to evaluate his/her thermal comfort. The mean $\mu = T_{\text{bestcomf}}$ is where the occupant’s maximum comfortable temperature locates. The standard variance $\sigma$ is used to represent occupant’s tolerance of discomfort. Therefore, the thermal comfort of an occupant $i$ has the following relationship with the actual indoor temperature:

$$
\text{thermalcomf}_i = e^{-\frac{(T_{\text{actual}}-T_{\text{bestcomf}})^2}{2\sigma_i^2}}
$$

(3.2)

Table 3.1 illustrates the physical meaning of the value of occupants’ thermal comfort level $\text{thermalcomf}$ with respect to the user’s satisfaction degree towards the thermal comfort.
Table 3.1: Degree of occupants’ satisfaction towards thermal comfort.

<table>
<thead>
<tr>
<th>$T_{actual} - T_{bestcomf}$</th>
<th>$[0, \sigma]$</th>
<th>$[\sigma, 2\sigma]$</th>
<th>$[2\sigma, 3\sigma]$</th>
<th>$[3\sigma, \infty]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{thermal}_{\text{comf}}$</td>
<td>[1, 0.61]</td>
<td>[0.61, 0.14]</td>
<td>[0.14, 0.01]</td>
<td>[0.01, 0]</td>
</tr>
<tr>
<td>User’s satisfaction</td>
<td>Highly satisfied</td>
<td>Less satisfied</td>
<td>Not satisfied but acceptable</td>
<td>Unacceptable</td>
</tr>
</tbody>
</table>

For the indoor temperature within one standard derivation from $T_{bestcomf}$, that is, when the value of comfort is higher than 0.6065, the indoor thermal comfort is considered as highly satisfactory to occupants.

3.3.1.2 Learning Procedure in Personal Agent

Both parameters are critical for each occupant and they should be learned through the personal agent. One of the major tasks for the personal agent is to learn these two identical parameters from users to determine their own preference of indoor temperature. Through this learning procedure, the personal agent will be able to know and predict user’s preferences (in this case, favorite temperature and tolerance range) to help local agent to implement the suitable control strategy on the HVAC system. These parameters of preferences are related to different environmental variables, such as time and the outdoor environment [34].

The personal agent observes user’s actions on adjusting his/her preferences towards the environment and the information of outdoor temperature from the local agent as inputs for training. User’s preferred temperature can be obtained through multiple ways: a simpler one is to ask user directly for his preferred temperature set point; another one is to observe whether the user has taken any action to adjust the set point for HVAC system in a stable thermal environment: If he/she does not take any action, the current temperature is considered as comfortable temperature for record. The standard variance $\sigma$
can be seen as a parameter representing user’s tolerance. The less frequently the occupants need to instruct the building, the more tolerant the user is. Similarly, the more frequently the occupant instructs the building, the more intolerant this occupant is, and the less $\sigma$ is.

The learning procedure is conducted by artificial neural network (ANN) techniques to learn the relationship between environmental variables and user’s preferences. User’s preferred indoor temperature is highly related to the outdoor environment and user’s activities. The outdoor environment can be represented in terms of the outdoor temperature; user’s activity is related to time of the day. In this case, the outdoor temperature and time are utilized as two inputs for ANN training. An experiment with 1000 sample data is conducted to train $T_{\text{bestcomf}}$. Levenberg-Marquardt back-propagation approach is applied to train this neural network. 800 samples are utilized as the training data. 200 samples are used as the validation data, which are used to measure network generalization, and to halt training when generalization stops improving. 100 independent samples are used as testing data to measure the performance of the neural network. A 2-layer neural network with 10 hidden neurons is trained for this problem. A neural network model is generated in this process which has two inputs (outdoor temperature and time), and one output (preferred indoor temperature). This neural network can be used to predict user’s preferred indoor temperature with the information on outdoor temperature and associated time.

With such a learning procedure, the personal agent will be able to determine user’s preferences under certain ambient circumstances.

### 3.3.2 Local Agent
Local agents play a significant role in the multi-agent system. They act as a mediator, information provider, decision maker and control executor in this multi-agent system.

**Mediator:** The local agent can act as a mediator to solve the conflicts between contending preferences from different occupants.

A reconciliation procedure is executed in the local HVAC agent to coordinate different users for determining the temperature’s set point in HVAC control. The primary principle is to fulfill occupants’ comfort need as much as possible. This can be achieved by defining an overall comfort index for occupants and maximizing it. Its objective can be described as follows:

To maximize the overall thermal comfort among occupants,

\[
overall_{\text{thermalcomf}} = \frac{1}{n} \cdot \sum_{i=0}^{n} w_i \cdot thermalcomf_i
\]

\[ (3.3) \]

where \( n \) is the total number of existing occupants; \( w_i \) is the weight for each occupant. Usually it is same for each person. But sometimes, individuals like building manager can possess high priority for parameter settings.

Figure 3-4 shows the result of an experiment with 6 sets of different occupants’ preferences. The highest overall thermal comfort is achieved at the point with an indoor temperature of 20.2 °C. Therefore, the set point for indoor temperature will be set at 20.2 °C to achieve maximum thermal comfort among the occupants.
Information provider: The local agents collect information from various sensors to monitor the external environment. This information includes environmental parameters, occupancy data, and energy information. These parameters can be used for multiple purposes: some of them are used for local agent’s decision making; some of them are fed back to personal agent for preference learning; some of them may be invoked by the central agent for decision making at an upper layer.

Decision maker: The local agents are capable of making decision as a controller to control its corresponding actuators. Only actions that involve other agents would require local agent to interact with the central controller. The control approaches in the local agent include ON/OFF control, optimal control, fuzzy control, and etc.

Control executor: The local controllers control the actuators, such as HVAC system and lighting system, to perform control over the building environment.
3.3.3 Central Agent

Central agents have two major functions: agent system configuration and facilitating collaboration between local agents. Agent system configuration is a typical service provided by the central agent, which allows operators to start or stop agents, deploy or delete agents, and modify cluster information for local agents. In addition, it provides a platform for local agents to communicate and collaborate with one another. If conflicts between agents arise, the central agent can act as a negotiator to solve the conflict based on the pre-defined rules or policies.

3.3.3.1 Interaction between the Central Agent and the Local Agent

This section gives an example of the interaction between the central agent and the local power system agent. Suppose the building is supplied by both the utility grid and the renewable energy resources such as wind power and solar power. The local power management agent monitors the conditions of the utility grid and the renewable energy supply in the micro-grid, and it is able to react to the power supply changes and report the relevant information to the central agent.

Once an unacceptable disturbance occurs in the utility grid or the grid interconnection, the local power system agent will make decision to island the building from the utility grid to protect the building facilities. The power system agent will inform the central agents about this change. In this case, the building is supported by the renewable energy resources which provides limited amount of energy to the building system. If energy required by the HVAC system and the local lighting system is larger than the energy that can be supplied, central agent will act as a coordinator to negotiate
with other agents that involves energy consumption activities to determine the adjusted amount of energy to be dispatched to each local control system.

3.3.3.2 Negotiation between Local Agents in Central Agent

This section gives an example of the negotiation between local HVAC agent and local lighting agent in the central agent. The building control system aims to save energy while maintaining occupants’ comfort. Occupants’ comfort is determined by three basic comforts that are thermal comfort, visual comfort and indoor air quality comfort, which can be controlled by the local HVAC agent and the local lighting system, respectively. Since maintaining higher occupants’ comfort will lead to the higher energy consumption, the central agent needs to find an optimized scheme to determine energy dispatch between the HVAC system and electrical lighting system.

Suppose the control variables are the assigned energy to the HVAC system $E_{HVAC}$ and the assigned energy to the electrical lighting system $E_L$, the objectives of this optimization mechanism is to maximize occupants’ comfort $Comfort$ and to minimize the total energy consumption for controlling these two systems $E_{total}$. We have

$$E_{total} = E_{HVAC} + E_L$$ (3.4)

The occupants’ comfort is determined by three basic comfort factors that can be calculated by the local agents, as illustrated in Equation (2.1). They are related to user’s preference in each parameter and the energy-consumption characteristics of the actuators. For this bi-objective problem, a multi-objective particle swarm optimization (MOPSO) algorithm can be implemented in the central agent to find the optimal tradeoff solutions. Solutions can be selected from the generated solution-sets to determine the energy dispatch scheme for the HVAC system and the electrical lighting system based on the
energy available from the local power agent. The detailed descriptions of integrating MOPSO algorithm into the central controller will be discussed in the next Chapter.
Chapter 4

Multi-Objective Particle Swarm Optimization for Decision-Making in Building Energy and Comfort Management

4.1 Multi-Objective Particle Swarm Optimization

In multi-objective problems, the objectives to be optimized usually are in conflict with each other, and more than one solution can be found in this type of problems. Therefore, for problems with more than one objective, a set of trade-off solutions, which is called Pareto Optimal solutions, are aimed to be found to represents the best possible compromises among the objectives [35], [36]. Particle swarm optimization (PSO) is a heuristic search method that simulates the movements of a flock of birds which aim to find food. Each bird, termed particle, in the population, called swarm, is supposed to ‘fly’ over the search space to look for promising solutions [37]. Several schemes of extending the PSO strategy for solving multi-objective have been proposed by some researchers.

The general issue in the building environment control is that the energy consumption and the users comfort are always in conflict with each other. Therefore, it can help the decision maker if a Pareto-optimal Front can be found for the problem with two objectives including the overall comfort and the energy consumption. This Chapter will
discuss how multi-objective PSO works to find the trade-off solutions between energy consumption and users’ overall comfort for intelligent buildings.

4.1.1 Basic Concept of a Multi-objective Problem

In multi-objective problems, the objectives to be optimized are usually in conflict with each other. Therefore, no single solution can be located in these problems. Instead, a set of trade-off solutions that represents the best possible compromises among the objectives can be found for the optimization problem. For multi-objective problems, it is useful to find the Pareto-optimal front which is outlined by all the Pareto-optimal solutions. A Pareto-optimal solution is the best that can be achieved for one objective without compromising other objectives.

For multi-objective problems, the original schema of PSO should be modified. A typical problem with multiple objectives can be expressed in following [35]:

Minimize

\[ \tilde{f}(\bar{x}) = [f_1(\bar{x}), f_2(\bar{x}), \ldots, f_k(\bar{x})] \]  

Subject to

\[ g_i(\bar{x}) \leq 0 \quad i = 1, 2, \ldots, p \]  
\[ h_j(\bar{x}) = 0 \quad j = 1, 2, \ldots, q \]

where \( \bar{x} = [x_1, x_2, \ldots, x_n]^T \) is the vector of the decision variables, \( f_i \) are the objective functions, \( g_i \) and \( h_i \) are the constraint functions of the problem.

For two vectors \( \bar{x}_1, \bar{x}_2 \) in the feasible domain, if \( \bar{x}_1 < \bar{x}_2 \) for all \( x_{1i} \) and \( x_{2i} \), \( i = 1, 2, \ldots, n \), then \( \bar{x}_1 \) dominates \( \bar{x}_2 \). A vector of decision variables \( \bar{x} \) is called non-
dominated or Pareto-optimal with respect to a feasible region, if there does not exist another \( \vec{x}' \) makes \( \vec{f}(\vec{x}) \prec \vec{f}(\vec{x}') \) in the solution domain, as shown in Figure 4-1. The Pareto Front is formed by all the Pareto-optimal solutions.

![Figure 4-1: The Pareto front and dominance relation in a two-objective space.](image)

**4.1.2 General Algorithm for PSO**

The algorithm for multi-objective particle swarm optimization (MOPSO) is derived from single objective PSO algorithm. This part will introduce how the general PSO strategy works to find the best solution for single objective problem. The general PSO algorithm works by updating the position of particles from a swarm to find the optimal solutions. Each particle adjusts its flying trajectory by incessantly updating its position and velocity [37]. Figure 4-2 shows the pseudo code of how PSO works.
Figure 4-2: The pseudo code of a general PSO algorithm.

First, the swarm population is initialized including the initialization of both position and velocity for each particle in the population. The personal best $pbest$ is initialized for each particle, and the corresponding global best $gbest$ is chosen to be the leader of the swarm. Then, for a maximum number of iterations, each particle flies over the search space by updating its velocity and position, using (4.4) and (4.5).

$$v_i = w \cdot v_i + c_1 \cdot rand() \cdot (pbest_i - x_i) + c_2 \cdot rand() \cdot (gbest - x_i) \quad (4.4)$$

$$x_i = x_i + v_i \quad (4.5)$$

where $v_i$ is the velocity of particle; $w$ is the inertia weight; $c_1$ and $c_2$ are the learning factors; $x_i$ is the position of particle. Evaluate the new position of the particle and compare it with its personal best. If the new position has a better fitness than its personal best $pbest$, update the personal best position $pbest$ with its new position for this particle; otherwise, the personal best remains the same. The global best position $gbest$, which can
be seen as the leader of the swarm population, also needs to be evaluated and updated in the iterations.

4.1.3 Weighted Aggregation Approach for MOPSO

In this section, a weighted aggregation approach is introduced for solving the MO problem. The weighted aggregation method converts a multi-objective problem into a single-objective problem by multiplying each objective with user-defined weights. The weights are usually selected by the importance of the corresponding objective in the overall problem. Normalization process is usually needed in weighted aggregation method in order to scale objectives into an identical order of magnitude.

For a bi-objective problem, it can be converted into a single-objective problem as follows [38]:

Minimize

\[ W \cdot f_1(\bar{x}) + (1 - W) \cdot \lambda \cdot f_2(\bar{x}) \]  

(4.6)

where the weight \( W \) varies in the range of \([0,1]\), and \( \lambda \) is the scaling factor to enable the two objectives to be equally treated.

For enhancing the search efficiency, during the optimization run of the PSO the inertia weight factor \( u \) decreases linearly as follows:

\[ u = u_{\text{max}} - \frac{u_{\text{max}} - u_{\text{min}}}{\text{iter}_{\text{max}}} \cdot \text{iter} \]  

(4.7)

where \( \text{iter}_{\text{max}} \) is the number of total iterations and \( \text{iter} \) is the current iteration number; \( u_{\text{max}} \) and \( u_{\text{min}} \) are the maximum and minimum values of the inertia weight \( u \), respectively.
4.1.4 Pareto-based Approach for MOPSO

4.1.4.1 General Algorithm

Several schemes of extending the PSO strategy for solving multi-objective problems have been proposed by researchers [39]. In multi-objective problems, the leader which each particle uses to update its position is not single for all the particles, otherwise the diversity of solutions cannot be ensured. Therefore, each particle should have a set of different leaders based on which its position can be updated. These leaders are usually stored in an external archive which is a different place from the swarm [39]. Figure 4-3 shows the general agenda for a Pareto-based MOPSO approach.

```
Begin
  Initialize swarm
  Initialize leaders in an external archive
  generation=0
  While generation<gmax
    For each particle
      Select leader
      Update velocity and position
      Evaluation
      Update pbest
    End For
    Update leaders in an external archive
    generation ++
  End While
  Output results to the external archive
End
```

Figure 4-3: The pseudo code of MOPSO algorithm.

A particle only updates its personal best \textit{pbest} when the new evaluation is non-dominated or when both are incomparable. If the new evaluation is non-dominated, \textit{pbest} will be updated by the new position. If both are incomparable, the particle will randomly
select one as its personal best \( pbest \). The selection and updating of the leader is important for the algorithm, because a wisely selected leader can help improve the search convergence in the solution space.

4.1.4.2 Selection of Leaders

To select the leader from the external archive, a Kernal density estimator [40] is employed to determine the congestion degree of a particle. The particle that is less crowded is preferred. As shown in Figure 4-4, a niche \( \sigma_i \) is defined for each particle and evaluates the number of other particles in its niche, which is \( N_i \). \( N_i \) can be utilized to represent the congestion degree of a particle. Therefore, the loose degree of a particle can be represented by \( 1/N_i \). Then, the roulette-wheel selection can be applied to select the particle that is taken as the leader by their loose degree.

![Figure 4-4: A defined niche for each particle.](image)

4.1.4.3 Archiving

The updating of the external archive which stores all the non-dominated solutions is important for keeping the diversity of leaders. The most straightforward method of
selecting particles for the archive is to retain all the non-dominated solutions with respect to all the previous populations, which means that a particle can enter the archive only if: (1) it is non-dominated to all the solutions in the archive or (2) it dominates any of the solutions in the archive, and the dominated solutions should be deleted from the archive in this case. The size of the external archive is limited, so some competitive mechanism should be carried out to limit the size of the archive and increase the diversity of the archive. Here, a $\varepsilon$-dominance approach can be applied to the PSO to bound the archive and retain valuable particles [40]. This approach defines a set of boxes and retains only one non-dominated solution for each box. The solution space is cut into a set of boxes of size $\varepsilon$ and solutions in each non-dominated box are selected. If a box contains more than one particle, the one which is closer to the box’s non-dominated convex will be selected. When using $\varepsilon$-dominance method, the size of the external archive is related to the parameter $\varepsilon$, which is a user-defined parameter. The diversity of the solutions can be well conserved through proper leader selection and updating methods.

4.2 System Configuration for Energy and Comfort Management

4.2.1 System Configuration

There are two objectives in building energy and comfort management: to maximize occupants’ comfort, and to minimize the energy consumption. Here, the three major comfort, thermal comfort, visual comfort, and air quality comfort, are considered to evaluate occupants’ comfort. And the energy consumed on the related subsystems including HVAC system and lighting system will be calculated for optimization.
Indoor temperature and indoor air quality are controlled through the operation of the HVAC system; indoor illumination level is controlled through the lighting system. The set points for these parameters are collected from the occupants from the personal agent. Local HVAC agent and local lighting agent are employed to control the operation of the related subsystems, including heating/cooling system, ventilation system, and lighting system. Fuzzy control techniques are employed by the local agents to determine the indoor power demand.

Figure 4-5 shows the configuration of this multi-agent system and the structure of its local agents. The proposed MOPSO optimizer is embedded in the central agent to determine energy dispatch to each subsystem.

![Diagram](image)

Figure 4-5: Multi-agent system with detailed structure of the local agent.

In the proposed building model, it is supposed that the indoor environment of the building under consideration is quite sensitive to the variation of the outdoor environment.
It means that the indoor building environment will closely follow the change of outdoor environment if no control is applied.

The local agent takes the adjusted power from the central agent and the error between real environmental parameters and the set points as inputs to the fuzzy controllers. Fuzzy rules are applied to calculate the required power in uncertain circumstances [41]. Comparison is carried out between the required power calculated and the adjusted power from the central agent to determine the actual power to be used. It is used to drive the actuators, which are the related subsystems, to control indoor environmental parameters that decide the users’ overall comfort level. The actuators are heating/cooling, electrical lighting and ventilating for controlling the thermal comfort, visual comfort and air quality, respectively. Thus, the indoor environmental parameters can be controlled by the corresponding actuators in local subsystems.

4.2.2 Local Agents

4.2.2.1 Local HVAC Agent for Heating/Cooling System

To calculate the required power for maintaining the indoor thermal comfort, a fuzzy PD controller is developed for this subsystem. The input of this fuzzy controller includes the error $e_T$ and the change of errors $ce_T$. $e_T$ is the difference between outdoor temperature and the temperature set point. The change of errors $ce_T$ represents the difference between the previous and present errors. The membership functions of the inputs and output of the fuzzy PD controller are shown in Figure 4-6.
The membership functions of the inputs and outputs include the following values: Negative Large (NL), Negative Medium (NM), Negative Small (NS), Zero (ZE), Positive Small (PS), Positive Medium (PM) and Positive Large (PL). The rules of the fuzzy controller are shown in Table 4.1.

Table 4.1: Fuzzy control rules for local temperature controller.

<table>
<thead>
<tr>
<th>Required Power</th>
<th>$e_{T}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>NL</td>
<td>NL</td>
</tr>
<tr>
<td>NM</td>
<td>NL</td>
</tr>
<tr>
<td>NS</td>
<td>NL</td>
</tr>
<tr>
<td>ZE</td>
<td>NL</td>
</tr>
<tr>
<td>PS</td>
<td>NL</td>
</tr>
<tr>
<td>PM</td>
<td>NL</td>
</tr>
<tr>
<td>PL</td>
<td>NL</td>
</tr>
</tbody>
</table>
The output of the fuzzy controller is the required power which maintains the indoor temperature at the set point. A negative value indicates that the heating system is working while a positive value means the cooling system is working.

4.2.2.2 Local Air Quality Agent

CO₂ concentration is used as an index to indicate air quality in the building environment, which is measured in ppm. A fuzzy controller is implemented in the ventilation subsystem to calculate the required power for ventilation. The input of the local fuzzy controller is the error between the CO₂ concentration and the indoor set point \( e_A \). The output is the required power to be consumed in the ventilation system which helps maintain indoor air quality. The membership functions of the input and output of the fuzzy controller are shown in Figure 4-7. The rules of the local ventilation controller are shown in Table 4.2.

![Figure 4-7: Membership functions of local ventilation controller.](image-url)
Table 4.2: Fuzzy control rules for local ventilation controller.

<table>
<thead>
<tr>
<th>Error</th>
<th>LOW</th>
<th>OK</th>
<th>SH</th>
<th>LH</th>
<th>HIGH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Required Power</td>
<td>OFF</td>
<td>ON</td>
<td>SL</td>
<td>SH</td>
<td>HIGH</td>
</tr>
</tbody>
</table>

The output of the fuzzy controller will be compared to the adjusted power from the central coordinator-agent. If the adjusted power is sufficient, the power used for ventilation control equals the required power. Thus the indoor comfort will be maintained; otherwise, the indoor comfort will be compromised. The actual consumed power drives the actuators to control the indoor environmental comfort.

4.2.2.3 Local Illumination Agent

In the local illumination agent, illumination level is utilized as measured parameters to indicate visual comfort, which is measured in lux. The input of the local fuzzy illumination controller is the error between the outside illumination level and the indoor set point \( e_L \). The output is the required added power to be consumed by the lighting system. The membership functions of the input and output of the local illumination controller are shown in Figure 4-8. The rules of the local illumination controller are shown in Table 4.3.
Figure 4-8: Membership functions of local illumination controller.

Table 4.3: Fuzzy control rules for local illumination controller.

<table>
<thead>
<tr>
<th>$e_L$</th>
<th>VS</th>
<th>Small</th>
<th>LS</th>
<th>SS</th>
<th>OK</th>
<th>Large</th>
</tr>
</thead>
<tbody>
<tr>
<td>Required added power</td>
<td>VL</td>
<td>Large</td>
<td>LL</td>
<td>SL</td>
<td>OK</td>
<td>Small</td>
</tr>
</tbody>
</table>

4.3 Problem Formulation for the Multi-objective Particle Swarm Optimizer

4.3.1 Problem Formulation
There are two objectives in building energy and comfort management: to maximize occupants’ comfort, and to minimize the energy consumption. Here, the three major comfort, thermal comfort, visual comfort, and air quality comfort, are considered to evaluate occupants’ comfort. And the energy consumed on the related subsystems including HVAC system and lighting system will be calculated for optimization. The problem is formulated as follows.

Suppose the initial status of the building environment, in which no control strategy has been applied yet, is that the initial temperature $T_{\text{initial}} = T_0$, the initial CO2 concentration $A_{\text{initial}} = A_0$, and the initial illumination level $L_{\text{initial}} = L_0$. To build the objective functions of the total comfort and the energy consumption, the target temperature $x_1$, and the target CO2 concentration $x_2$, the target illumination level $x_3$, are set as the vectors of decision variables. Then, it is necessary to build the energy consumption function and the comfort function with respect to the control vectors.

One of the control objectives is to maximize the comfort value. Here, the evaluation approach in Equation (2.1) is utilized:

Maximize the indoor comfort value:

$$\text{Comfort} = w_T[1 - (e_T / T_{\text{set}})^2] + w_A[1 - (e_A / A_{\text{set}})^2] + w_L[1 - (e_L / L_{\text{set}})^2]$$

Maximizing the indoor comfort is equivalent to minimizing the discomfort value. This objective is set as:

Minimize the discomfort value:

$$\text{Discomfort} = 1 - \text{Comfort}$$

$$= 1 - \{w_T[1 - ((x_1 - T_{\text{set}}) / T_{\text{set}})^2] + w_A[1 - ((x_2 - A_{\text{set}}) / A_{\text{set}})^2] + w_L[1 - ((x_3 - L_{\text{set}}) / L_{\text{set}})^2]\}$$
Another objective function is the total energy consumption with respect to the vectors of decision variables:

Minimize the total power consumption:

\[ E_{total} = E_T(x_1) + E_A(x_2) + E_L(x_3) \]  

(4.10)

where \( E_T(x_1) \), \( E_A(x_2) \) and \( E_L(x_3) \) are the energy required to improve the initial environment parameters to the target parameters \( x_1, x_2 \) and \( x_3 \), respectively. \( E_T(x_1) \) is the energy consumed on the heating/air conditioning subsystem; \( E_A(x_2) \) is the energy consumed on the ventilation system, \( E_L(x_3) \) is the energy consumed on the lighting system. To get the values of \( E_T(x_1) \), \( E_A(x_2) \) and \( E_L(x_3) \), the amount of energy consumption corresponding to different target parameters under the set initial status can be obtained by running the building subsystem models.

### 4.3.2 Experimental Results

In this experiment, the initial temperature is \( T_0 = 50 \degree F \); the initial CO\(_2\) concentration is \( A_0 = 1100 \text{ppm} \); and the initial illumination level is \( L_0 = 400 \text{lux} \). The set points of each comfort index are \( T_{\text{set}} = 71.6 \degree F \), \( A_{\text{set}} = 800 \text{ppm} \) and \( L_{\text{set}} = 800 \text{lux} \), in which the comfort value can reach 1. The weight factors for each comfort are set equal as \( w_T = w_A = w_L = 1/3 \).

Thus, the first objective function about the discomfort value is:

\[ f_1(x_1, x_2, x_3) = \text{Discomfort} \]
\[ = 1 - \left\{ \frac{1}{3} \left[ 1 - \left( \frac{x_1 - 71.6}{71.6} \right)^2 \right] + \frac{1}{3} \left[ 1 - \left( \frac{x_2 - 800}{800} \right)^2 \right] + \frac{1}{3} \left[ 1 - \left( \frac{x_3 - 800}{800} \right)^2 \right] \right\} \]

(4.11)

The second objective function is:
\[ f_2(x_1, x_2, x_3) = E_{total} = E_T(x_1) + E_A(x_2) + E_L(x_3) \] (4.12)

\[ E_T(x_1), E_A(x_2), E_L(x_3) \] are generated by curve fitting with respect to the set initial status.

MOPSO algorithm is applied to optimize the parameters that can satisfy both objectives. For this bi-objective problem, more than one set of optimal solutions can be generated. The position of particles is expressed as a three-dimension vector \((x_1, x_2, x_3)\), and their fitness are evaluated by the two objective functions.

Here, the MOPSO algorithm selects the inertia weight \(w = 0.4\), and the learning factors \(c_1 = 0.25\) and \(c_2 = 0.25\). After applying the MOPSO algorithm, the Pareto-optimal front \(f_1(x_1, x_2, x_3)\) versus \(f_2(x_1, x_2, x_3)\) is generated, as shown in Figure 4-9. Through the insight into the behavior of the problem, users are free to choose an appropriate set of \(x_1, x_2\) and \(x_3\).

Figure 4-9: Pareto-optimal front of energy consumption versus overall comfort.
Table 4.4 shows several sample solutions from the Pareto front. The decision-maker may choose a specific solution from the pool of the tradeoff solutions based on the specific design requirements.

Table 4.4: Selected sample solutions from the MOPSO optimizer.

<table>
<thead>
<tr>
<th>$x_1$</th>
<th>$x_2$</th>
<th>$x_3$</th>
<th>$f_1(\tilde{x})$</th>
<th>$f_2(\tilde{x})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target temperature (°F)</td>
<td>Target CO$_2$ concentration (ppm)</td>
<td>Target illumination (lux)</td>
<td>Comfort</td>
<td>$E_{total}$ (kW)</td>
</tr>
<tr>
<td>67.18</td>
<td>808.7</td>
<td>772.9</td>
<td>0.9983</td>
<td>33.52</td>
</tr>
<tr>
<td>55.91</td>
<td>845.24</td>
<td>739.17</td>
<td>0.9810</td>
<td>20.84</td>
</tr>
<tr>
<td>50.10</td>
<td>963.03</td>
<td>617.48</td>
<td>0.9388</td>
<td>10.21</td>
</tr>
</tbody>
</table>

Assume that the target temperature under 60K is unacceptable to occupants, and a constraint is added to this optimization problem. In this case, the constraint can be expressed as $x_1 \geq 60$. The derived Pareto-optimal front is shown in Figure 4-10. The span of the Pareto front for this problem with the temperature constraint obviously becomes much narrower as compared with that of the original problem without constraint. The MOPSO generates a set of tradeoff solutions, from which users can select a specific one based on their preferences. The developed MOPSO is flexible to incorporate new constraints based on the specific optimization requirements.
4.4 Conclusion

The major issue for energy and comfort management in building automation is to balance the conflict between the users’ comfort and the total energy consumption. In this Chapter, the Pareto-optimal front is derived for the formulated bi-objective functions including the building energy consumption and the overall comfort value. The PSO algorithm is extended to deal with multi-objective optimization problems with two or more objectives. Since the definition of leader is vague in multi-objective problems, the selection and updating of leaders is vital in MOPSO. The optimal selection and updating of the leaders will be a topic in the future research to further improve the MOPSO efficiency. Multi-objective optimization is important for energy and comfort management in building automation since tradeoff solutions are useful and meaningful for balancing different conflicting design or control objectives in the complex building energy and comfort management applications.

Figure 4-10: Pareto-optimal front with a temperature constraint.
Chapter 5


5.1 Introduction

In the previous Chapter, the discussions for building management based on the assumption that the building shares a uniform environment conditions. Many buildings have more complicated interior structure that the internal environment is different from space to space. This Chapter extends the discussion of building management to multi-zone buildings, in which a building is represented as a network of zones [42]. In a multi-zone building, a zone is defined as an air volume in which the space shares uniform environmental conditions. In general, each room in a building can be defined as a zone. Multiple rooms can be combined and considered as one zone if they possess similar environmental conditions; and one space may be divided into several zones if the environmental conditions are not uniform in a space.

By employing renewable sources as energy supply, buildings could meet the requirement of environmental friendliness. Such building can be seen as a micro-grid system, which is made up of distributed generators, distributed storage and controllable loads. Micro-grid is a promising technology for meeting the increasing challenges faced by modern power systems such as environmental concerns, high requirements on power
quality and reliability, growing social and industry demands, and aging infrastructure of the current power grid. Since generators and storage devices geographically locate close to the controllable loads, a variety of benefits can be achieved such as improved reliability and reduced transmission losses. A micro-grid system can be connected to and disconnected from the upstream utility grid according to the current condition in order to minimize the disruption to the loads. The Chapter discusses the intelligent control of a multi-zone building that is supplied from distributed energy resources when islanded from the utility grid.

### 5.2 Agent-based System for Multi-zone Building Control

Chapter 3 proposed a Multi-agent system framework that is composed of three different types of agents. Each agent is capable of making decisions autonomously, taking appropriate actions, and interacting with each other to achieve the overall control goal. Each agent has several significant characteristics including pro-activity, reactivity and social ability, so that it is able to act independently while also being able to cooperate with others [43].

An extended multi-agent architecture is designed based on the proposed multi-agent system framework. Figure 5-1 shows the designed multi-agent architecture for multi-zone building control. The control system for a multi-zone building model mainly focuses on maximizing the occupants’ comfort while minimizing the energy consumption and solving the conflicts between zones. An additional type of agent called ‘zone agent’ is deployed between the central agent and related local agents, in order to adapt to the control requirements of a multi-zone building. It is designed to resolve the conflict between the energy consumption and the occupants’ comfort as well as the conflict...
between different zones’ demands. The personal agent obtains occupant’s preference and communicates with the local agent. The central agent makes decisions to determine the power distribution scheme for all the zones.

Figure 5-1: Multi-agent system architecture for multi-zone building control.

To realize control over the multi-agent building, this central agent has two major functions: communication and decision making. The central agent communicates with the building manager to collect relevant information and enables the manager to monitor the building operations through a human-computer interface. The central agent also communicates with the zone agents and the local power management agent to obtain the status of each zone and power supply condition. The central agent makes corresponding
decisions based on information collected, sends the decisions back to the zone agents, and reports to the building manager.

Each zone agent is responsible for energy management in its specific zone. Zone agent communicates with local agents and determines the amount of power that should be dispatched to each local agent through a suitable control algorithm. In addition, the zone agent collects the environmental parameters from the local agents to analyze the comfort condition of this zone and reports it to the central agent.

In each zone, three types of local agents including local temperature controller agent, local illumination controller agent and local air quality controller agent are utilized to control the thermal comfort, the visual comfort and the IAQ comfort, respectively. They are distributed locally in each zone for monitoring and controlling the building environment through corresponding sensors and actuators, and returning the environmental parameters to the zone agents. To implement control in the physical environment, heaters, air conditioners, electrical lights, blinds, and ventilators are utilized as actuators to control the zone environment.

5.3 Mathematical Model and Algorithm for the Proposed Multi-agent Control Architecture

5.3.1 Central Agent

The central agent aims at maximizing the building’s overall comfort with a certain amount of energy supplied by the distributed renewable energy sources. Through a human-computer interface, the central agent receives the manager’s instruction about each zone’s priority, which is mathematically represented as a weighting factor. The
A particle swarm optimizer is employed by the central agent to determine the energy distribution among zones. A general algorithm for PSO has been presented in 4.1.2. Since this optimization problem has two constraints, the general PSO algorithm needs to be modified for a constrained optimization problem. The pseudo-code of the constraint PSO algorithm is demonstrated in Figure 5-2 [44]. As compared to a general PSO algorithm, this algorithm features two modifications: 1) During initialization, every particle in the swarm is repeatedly initialized until it satisfies all the constraints. 2) When updating the
personal best and the global best, only those particles with positions in the feasible space are counted.

For each particle {
    Do {
        Initialize particle
    } While particle satisfies all the constraints
}

Do {
    For each particle {
        Evaluate fitness
        Update $p_{best}$ if the fitness value is better than the $p_{best}$ in history AND the particle is in the feasible space
    }
    Choose the particle with the best $p_{best}$ of all the particles as the $g_{best}$
    For each particle {
        Update the velocity and position
    }
} While maximum iterations and minimum error is not reached

Figure 5-2: The pseudo-code of the constraint PSO algorithm.

5.3.2 Zone Agent and Local Controller-agents

The comfort value of a zone is calculated by its zone agent via analyzing the environmental parameters and the occupants’ preferences. The comfort value of zone $i$ is represented as follows:

$$ comfort_i = \begin{cases} 
\mu i [1 - (T_i - T_{set_i})/T_{set_i}] + \mu l_i [1 - (L_i - L_{set_i})/L_{set_i}] + \mu a_i [1 - (A_i - A_{set})/A_{set}] & \text{if } A_i > A_{set} \\
\mu l_i [1 - (T_i - T_{set_i})/T_{set_i}] + \mu a_i [1 - (L_i - L_{set})/L_{set_i}] & \text{if } A_i \leq A_{set} 
\end{cases} $$

(5.4)

$$ \mu i + \mu l_i + \mu a_i = 1 $$

(5.5)
where $\mu_t$, $\mu_l$, and $\mu_a$ are the weighting factors for thermal comfort, visual comfort and IAQ comfort in zone $i$, respectively; $T_i$, $L_i$, and $A_i$ are the environmental parameters in the zone $i$; $T_{set_i}$, $L_{set_i}$, and $A_{set_i}$ are the set points for temperature, illumination level and carbon dioxide concentration, respectively. The weighting factors $\mu_t$, $\mu_l$, $\mu_a$, and the set points $T_{set_i}$, $L_{set_i}$, $A_{set_i}$ are preset by the occupants in the zone based on their preferences.

The local controller-agents obtain the environmental parameters from the sensors and report them to the zone agent for further analysis. The local controller-agents control the environmental parameters by driving corresponding actuators.

### 5.3.3 Collaboration of Agents

When a building is islanded from the power grid, the distributed renewable energy sources are the only power resources. The goal of the control system is to achieve maximum comfort with limited power supply. Utilizing the particle swarm optimizer, multi-agent system tries to find the optimal solution for energy distribution to maximize the building’s overall comfort. In order to implement the algorithm, agents in the system collaborate with each other in the following ways:

#### 5.3.3.1 Analysis

The central controller communicates with the building manager and communicates with power resources to obtain the available power supply. The local controller-agents collect the environmental parameters from the sensors and calculate the demanded power. The zone agent summarizes all environmental parameters and demanded power from the local controller-agents to calculate the comfort and report them to the central controller.
5.3.3.2 Optimization

With the information about power demanded $P_{demand}(i)$, weighting factor $w(i)$, and available power supply $P_{given}$, the central controller determines the power distribution to each zone. If the available power is larger than the total power demand, the central controller distributes the demanded power to each zone and the overall comfort will be maximized to 1. Otherwise, the central controller employs the particle swarm optimizer to find an optimal solution to maximize $OverallComfort$ defined in (5.1). The position of the particle is the vector of power distribution to each zone, which is $\tilde{x}_j = [P(1)_j,...,P(i)_j,...,P(n)_j]$, for all the particles in the population. The constraints in equations (5.2) and (5.3) are applied to the algorithm during initialization of the swarm, and then the personal best and the global best are updated as discussed previously in this section. During the fitness evaluation of each particle, every zone agent calculates its comfort based on the position of this particle and feeds it back to the central controller. On the other hand, the central controller collects the comfort value from each zone to calculate the overall comfort, which is the fitness of the particle. Utilizing the particle swarm optimizer, the central controller is able to find the best possible solution $g_{best}$ for the maximum overall comfort level of the building.

5.3.3.3 Implementation

With the best solution for power distribution, the local controller-agents applies the corresponding power in the actuators; the zone agents calculate the comfort value in the zones; the central agents calculate the overall comfort of the building and report it to the building manager through the human-computer interface.
5.4 Case Study and Simulation Results

In this section, a case study of a multi-zone building control is presented. This building is divided into four occupied zones. The floor plan is shown in Figure 5-3. The floor area of the building is 46 ft by 45 ft, with 8 ft in height [45].

Figure 5-3: Floor plan of four zones in a building.

The weighting coefficients are \( w = \{0.4, 0.15, 0.15, 0.3\} \) for Zone 1, Zone 2, Zone 3, and Zone 4, respectively. The set points of parameters for each zone are listed as follows:

\[
[Tset_1, Lset_1, Aset_1] = [71.6, 800, 800],
[Tset_2, Lset_2, Aset_2] = [71.6, 600, 800],
[Tset_3, Lset_3, Aset_3] = [71.6, 600, 800],
[Tset_4, Lset_4, Aset_4] = [71.6, 600, 800].
\]

Figures 5-4, 5-5, 5-6, and 5-7 show the variations in environmental parameters over a day (24-hours) for each zone before the intelligent control is applied, including the variations of temperature, illumination level, and CO\(_2\) concentration.
Figure 5-4: Environmental parameters for zone 1.

Figure 5-5: Environmental parameters for zone 2.
Figure 5-6: Environmental parameters for zone 3.

Figure 5-7: Environmental parameters for zone 4.
Figure 5-8 shows the variation of the overall comfort in the building before any control is applied. The overall comfort is mainly around 0.6.

![Overall Comfort Graph](image)

Figure 5-8: Overall comfort.

Figure 5-9 shows the available power supply from renewable resources and the overall power demand of the building. In most times of the day, the distributed energy resources cannot fulfill the total demand of the building. It requires the control system to distribute the available power wisely for maximizing the overall comfort level. In the simulation studies the time scale (i.e., the sampling interval) is set as one hour, thus 24 time periods are sampled.
Figure 5-9: Available power and demanded power.

Table 5.1 shows the best solutions for power distribution and the corresponding overall comfort in each time period.

**Table 5.1: Best solutions and overall comfort.**

<table>
<thead>
<tr>
<th>Time Period</th>
<th>$P(1)$</th>
<th>$P(2)$</th>
<th>$P(3)$</th>
<th>$P(4)$</th>
<th>Overall Comfort</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>18.838</td>
<td>2.342</td>
<td>2.334</td>
<td>2.323</td>
<td>0.9874</td>
</tr>
<tr>
<td>2</td>
<td>20.927</td>
<td>2.344</td>
<td>2.331</td>
<td>2.317</td>
<td>0.9925</td>
</tr>
<tr>
<td>3</td>
<td>23.271</td>
<td>2.264</td>
<td>2.281</td>
<td>2.277</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>18.182</td>
<td>2.166</td>
<td>2.188</td>
<td>2.180</td>
<td>0.9906</td>
</tr>
<tr>
<td>5</td>
<td>17.558</td>
<td>2.152</td>
<td>2.161</td>
<td>2.173</td>
<td>0.9891</td>
</tr>
<tr>
<td>6</td>
<td>12.209</td>
<td>2.047</td>
<td>2.097</td>
<td>2.101</td>
<td>0.9779</td>
</tr>
<tr>
<td>7</td>
<td>10.857</td>
<td>2.222</td>
<td>2.691</td>
<td>3.686</td>
<td>0.9847</td>
</tr>
<tr>
<td>8</td>
<td>2.632</td>
<td>5.485</td>
<td>5.552</td>
<td>6.524</td>
<td>0.9746</td>
</tr>
<tr>
<td>9</td>
<td>2.233</td>
<td>7.428</td>
<td>0.638</td>
<td>9.725</td>
<td>0.9415</td>
</tr>
<tr>
<td>10</td>
<td>2.203</td>
<td>5.016</td>
<td>0.567</td>
<td>11.812</td>
<td>0.8999</td>
</tr>
<tr>
<td>11</td>
<td>4.127</td>
<td>2.482</td>
<td>3.548</td>
<td>12.960</td>
<td>0.8822</td>
</tr>
<tr>
<td>12</td>
<td>2.498</td>
<td>2.233</td>
<td>8.335</td>
<td>11.352</td>
<td>0.9604</td>
</tr>
<tr>
<td>13</td>
<td>4.033</td>
<td>5.281</td>
<td>6.757</td>
<td>9.006</td>
<td>0.9954</td>
</tr>
<tr>
<td>14</td>
<td>3.348</td>
<td>5.824</td>
<td>6.744</td>
<td>11.298</td>
<td>0.9999</td>
</tr>
<tr>
<td>15</td>
<td>3.377</td>
<td>5.123</td>
<td>7.385</td>
<td>10.473</td>
<td>0.9713</td>
</tr>
<tr>
<td>16</td>
<td>2.220</td>
<td>3.757</td>
<td>6.292</td>
<td>12.509</td>
<td>0.9059</td>
</tr>
<tr>
<td>17</td>
<td>2.282</td>
<td>2.179</td>
<td>9.083</td>
<td>9.954</td>
<td>0.9479</td>
</tr>
<tr>
<td>18</td>
<td>2.757</td>
<td>5.259</td>
<td>8.320</td>
<td>8.245</td>
<td>0.9840</td>
</tr>
<tr>
<td>19</td>
<td>2.543</td>
<td>3.091</td>
<td>3.506</td>
<td>7.421</td>
<td>0.9821</td>
</tr>
<tr>
<td>20</td>
<td>6.080</td>
<td>1.347</td>
<td>1.352</td>
<td>3.518</td>
<td>0.9560</td>
</tr>
<tr>
<td>21</td>
<td>7.453</td>
<td>0.605</td>
<td>0.695</td>
<td>2.781</td>
<td>0.9342</td>
</tr>
<tr>
<td>22</td>
<td>8.125</td>
<td>2.240</td>
<td>0.609</td>
<td>2.558</td>
<td>0.9465</td>
</tr>
<tr>
<td>23</td>
<td>10.110</td>
<td>2.266</td>
<td>2.221</td>
<td>2.241</td>
<td>0.9696</td>
</tr>
<tr>
<td>24</td>
<td>10.888</td>
<td>2.316</td>
<td>2.337</td>
<td>2.357</td>
<td>0.9693</td>
</tr>
</tbody>
</table>
Figures 5-10, 5-11, 5-12, and 5-13 show the environmental parameters for each zone after the intelligent control is applied. Figure 5-14 shows the overall comfort after optimization is used.

Figure 5-10: Environmental parameters in zone 1 after optimization.
Figure 5-11: Environmental parameters in zone 2 after optimization.
Figure 5-12: Environmental parameters in zone 3 after optimization.
Figure 5-13: Environmental parameters in zone 4 after optimization.
The result shows that in spite of a large quantity of energy shortage, the intelligent controller has turned out to be able to distribute the energy appropriately to maintain the high overall comfort levels. The designed multi-agent system is able to perform intelligent control over the indoor environment of a multi-zone building. According to the results from the case study, PSO has shown to be useful for maintaining the high comfort level in a building environment when the total energy supply is in a shortage.
Chapter 6

Development of an Optimal Control Strategy for HVAC System in Building Energy Management

Heating, Ventilation and Air Conditioning (HVAC) system provides a relatively constant and comfortable temperature as well as fresh and filtered air with a comfortable humidity range to the buildings. Generally, HVAC system consumes more than 40% of the total electrical power for buildings. It is one of the most important subsystems in building automation that affects occupants’ thermal and air quality comfort. Therefore, effective energy management of the HVAC system is important in building energy management system. This Chapter proposes an optimal control strategy for a typical HVAC system in building energy management. Without sacrifice of thermal comfort, to reset the suitable operating parameters can also achieve energy saving purpose [46].

6.1 Introduction

In HVAC system, the heating, ventilating and air-conditioning units are coordinated to provide a comfortable thermal environment and high indoor air quality to inhabitants. The HVAC units should be carefully chosen and designed based on different building characteristics and varying climatic conditions for meeting the need of the building without abusing installations.
The operation of an HVAC system has impacts on two kinds of comfort: the thermal comfort and the indoor air quality comfort [47]. The indoor air temperature usually serves as an index to indicate the thermal comfort. In cold weather, comfortable indoor temperatures can only be maintained by the heating system which provides heat to the space at the same rate as the space is losing heat. Similarly, in hot weather, heat should be removed from the space at the same rate that the space is gaining heat. Therefore, in order to maintain a stable thermal environment, heat balance that determines the indoor temperature needs to be properly controlled by the heating and cooling system.

The indoor air quality comfort can be indicated by the carbon dioxide (CO₂) concentration inside the building space. Carbon dioxide comes from inhabitants and other pollutant sources in the building. For efficient control of the indoor air quality, demand-controlled ventilation systems are usually deployed to reduce energy consumption and improve the indoor air quality. A demand-controlled ventilation system determines the amount of outside air that should be brought into the building according to actual occupants’ need. It adjusts the amount of outside air taken into the building based on the number of the occupants as well as the ventilation demands from the occupants [48]. Since the HVAC system already contains ventilation hardware, the demand-controlled ventilation system typically involves a modification incorporating extra components into the existing HVAC system design.

There are usually two major control objectives in designing control systems for HVAC: saving energy usage and maintaining indoor thermal comfort and air quality comfort. In this paper, a hierarchical control system is developed to control the operation
of HVAC system. An intelligent optimizer is embedded to coordinate each HVAC unit for achieving high energy efficiency. The proposed optimizer utilizes swarm intelligence to find the optimal solution that fulfills the control objectives. In order to determine the suitable control variables of the optimizer and find their impact on occupant's comfort and energy consumption, the thermal and ventilation model of building environment as well as the energy model of HVAC system are studied in section II. The proposed control system and its detailed design is illustrated in section III. Section IV gives a case study to demonstrate the performance of the proposed strategies. Section V wraps up the whole paper.

6.2 HVAC System Modeling

In this section, the HVAC system model as well as the building model for heat exchange and CO₂ concentration ventilation will be discussed. Figure 6-1 demonstrates the system model for a typical HVAC system with the air circulation procedure. The supply air, which is heated or cooled by the reheat coil or cooling coil, leaves the air handler through the supply air fan, down to the ductwork and into the building space. The supply air can warm up or cool down the building space. In order to maintain a constant indoor air pressure, the supply air mass flow rate is usually equal to the air flow rates leaving the space through the return fan. One portion of the return air mixes with outside fresh air in a mix chamber and returns to the air handler through the filters. In the air handler unit, the supplied air will be warmed up or cooled down by passing through the heating/cooling coils with the operation of the heating/cooling system. The damper in the air handler is throttled to regulate the air flow. Coordinated with the damper, the speed of the supply fan is altered to maintain the constant duct static pressure that can be sensed.
by a pressure sensor. The humidifier can be water spray or steam, and it is utilized to add humidity to air that is too dry.

![Diagram of HVAC system model](image)

**Figure 6-1:** A typical HVAC system model.

### 6.2.1 Thermal and Ventilation Models for Building Environment

The thermal and ventilation models are developed to study the impact of HVAC system operations on the indoor temperature variation and indoor CO₂ concentration variation.

#### 6.2.1.1 Heat Balance Model

In this model, the building is considered as a single thermal zone, and the heat balance should be maintained in order to achieve a constant comfortable temperature. If the building is gaining or losing energy, the indoor temperature will change accordingly.
Based on a heat balance on the building air, the indoor temperature variation can be formulated as follows [49]:

\[
m c_p \frac{dT}{dt} = \dot{Q}_{\text{internal}} + \dot{Q}_{\text{convection}} + \dot{Q}_{\text{infiltration}} + \dot{Q}_{\text{system}}
\]  

(6.1)

where \( m \) is the air mass of the building area (kg), \( c_p \) is the specific heat capacity of air (J/kg • °C), \( T \) is the indoor temperature (°C), \( \dot{Q}_{\text{internal}} \) is the internal loads; \( \dot{Q}_{\text{convection}} \) is the convective heat transfer from the wall and ceiling surfaces [50]; \( \dot{Q}_{\text{infiltration}} \) is the heat transfer due to infiltration of outside air; and \( \dot{Q}_{\text{system}} \) is the thermal transfer from the HVAC system.

Internal loads are thermal loads generated by human and equipment, which are related to the number of occupants in the room [51].

\[
\dot{Q}_{\text{internal}} = \alpha \ast N + \beta
\]

(6.2)

where \( N \) is the number of occupants in the building; \( \alpha \) and \( \beta \) are coefficients related to internal loads generation rate in a building.

The convective heat transfer from the zone surfaces \( \dot{Q}_{\text{convection}} \) can be formulated as in (6.3).

\[
\dot{Q}_{\text{convection}} = \sum_{i=1}^{n_{\text{surfaces}}} h_i A_i (T_{si} - T)
\]

(6.3)

where \( h \) is the internal convective coefficient of the walls and the ceiling (W/m² • °C); \( A \) is the area of the heat transfer surfaces (m²); \( T_s \) is the surface temperature (°C).

\[
\dot{Q}_{\text{infiltration}} = \dot{m}_{\text{inf}} c_p (T_{out} - T)
\]

(6.4)
where \( \dot{m}_{inf} \) is the mass flow rate of the infiltration air (kg/s). \( T_{out} \) is the temperature of the outdoor fresh air (°C).

\[
\dot{Q}_{system} = \dot{m}_{supply} c_p (T_{supply} - T)
\] (6.5)

where \( \dot{m}_{supply} \) is the mass flow rate of the supply air (kg/s); \( T_{supply} \) is the temperature of the supply air (°C).

By plugging (6.2) - (6.5) into the variables in (6.1), the indoor temperature equation can be rewritten as follows:

\[
mc_p \frac{dT}{dt} = \alpha * N + \beta + \sum_{i=1}^{n_{surfaces}} h_i A_i (T_{si} - T) + \dot{m}_{inf} c_p (T_{out} - T) + \dot{m}_{supply} c_p (T_{supply} - T)
\] (6.6)

By observing (6.6), it can be seen that the indoor temperature can be controlled by the mass flow rate and temperature of the supply air.

### 6.2.1.2 Ventilation Model

For a well-ventilated space, the indoor CO\(_2\) concentration can be derived from the following equation [52]:

\[
V \frac{dA}{dt} = G_{supply} \cdot (A_{supply} - A) + N \cdot L
\] (6.7)

where \( V \) is the volume of the ventilated space (\( m^3 \)); \( A \) is the CO\(_2\) concentration in the ventilated space; \( L \) is the average CO\(_2\) concentration generation rate per person; \( G_{supply} \) is the volume flow rate of the supply air (\( m^3/s \)), and it has

\[
G_{supply} = \dot{m}_{supply} / \rho
\] (6.8)
in which \( \rho \) is the air density. \( A_{\text{supply}} \) is the \( \text{CO}_2 \) concentration in the supply air in the ventilated space, and it indicates the \( \text{CO}_2 \) concentration of the mixed air \( A_{\text{mix}} \) that is mixed by the bypass air and the intake air. It can be calculated as follows [53]:

\[
A_{\text{supply}} = \left( (G_{\text{supply}} - G_{\text{bypass}}) \cdot A_{\text{out}} + G_{\text{bypass}} \cdot A \right) / G_{\text{supply}} \quad (6.9)
\]

Suppose \( T_{\text{mix}} \) is the temperature of the mixed air from the mix chamber, and it can be represented as follows:

\[
T_{\text{mix}} = \left( (G_{\text{supply}} - G_{\text{bypass}}) \cdot T_{\text{out}} + G_{\text{bypass}} \cdot T \right) / G_{\text{supply}} \quad (6.10)
\]

Apply (6.10) to (6.9), \( A_{\text{supply}} \) can be represented by the mixed air temperature \( T_{\text{mix}} \) as follows:

\[
A_{\text{supply}} = \left( (T - T_{\text{mix}}) \cdot A_{\text{out}} + (T_{\text{mix}} - T_{\text{out}}) \cdot A \right) / (T - T_{\text{out}}) \quad (6.11)
\]

In a short period of time, we can assume that \( N, A_{\text{supply}} \), and \( A \) are constants, and (6.7) can be solved as follows:

\[
A = A_{\text{supply}} + \frac{N \cdot L}{G_{\text{supply}}} + (A(0) - A_{\text{supply}} - \frac{N \cdot L}{G_{\text{supply}}}) \cdot e^{-It} \quad (6.12)
\]

where \( A(0) \) is the indoor \( \text{CO}_2 \) concentration at time \( t = 0 \); and \( I = G_{\text{supply}} / V \) is the space air change rate.

By observing (6.11) and (6.12), it can be concluded that the indoor \( \text{CO}_2 \) concentration can be controlled by the supply air mass flow rate, the supply air temperature, and the temperature of the mixed air.

### 6.2.2 Energy Models for HVAC Units

The energy models of the primary equipment or components will be established in advance for the sake of the whole system’s energy simulation. In a HVAC system, the
major energy consumption components are the variable speed fan and the heating and cooling system. The energy models of these components are built in this section.

6.2.2.1 Energy Model of the Fan

The power consumption of the variable speed fan is determined by the mass flow rate of the air flow. For a variable speed fan, the power is represented as follows [54]:

\[
E_{\text{fan}} = \frac{\gamma_{\text{air}} \cdot X_G^3 \cdot G_o \cdot H_o}{\eta_{\text{trans}} \cdot \eta_{\text{motor}}(X_G) \cdot \eta_{\text{vfd}}(X_G)}
\]

(6.13)

where \(\gamma_{\text{air}}\) is the specific weight of the air (N/m\(^3\)); \(X_G\) is the ratio of air volume flow rate \(G\) to the rated air volume flow rate \(G_o\) (m\(^3\)/s), and it has \(X_G = \frac{G}{G_o}\); \(H_o\) is the rated head of fan (m); \(\eta_{\text{trans}}\) is the efficiency of transmittance. Both the efficiency of motor \(\eta_{\text{motor}}(X_G)\) and the efficiency of variable-frequency driver \(\eta_{\text{vfd}}(X_G)\) vary with the variation of rotation speed. They can be modeled as follows:

\[
\eta_{\text{motor}}(X_G) = b_0 + b_1 X_G + b_2 X_G^2 + b_3 X_G^3
\]

(6.14)

\[
\eta_{\text{vfd}}(X_G) = c_0 + c_1 X_G + c_2 X_G^2 + c_3 X_G^3
\]

(6.15)

where \(b_0, b_1, b_2, b_3, c_0, c_1, c_2, \text{ and } c_3\) are experimental factors.

6.2.2.2 Energy Model of the Heating System and the Cooling System

The energy power of the heating system is as follows [53]:

\[
E_{\text{heat}} = \frac{\dot{m}_{\text{supply}} \cdot c_p \cdot (T_{\text{supply}} - T_{\text{mix}})}{\eta_{\text{heat}}}
\]

(6.16)

where \(\dot{m}_{\text{supply}}\) is the mass flow rate of the supply air; \(\eta_{\text{heat}}\) is the efficiency of the heating system;
The energy power of the cooling system is as follows,

\[ E_{cool} = \frac{n_{supply} \cdot c_p \cdot (T_{supply} - T_{mix})}{\eta_{cool}} \]  

(6.17)

where, \( \eta_{cool} \) is the efficiency of the cooling system.

The total consumed energy in the HVAC system is the sum of the energy consumed by each component, including the heating system, the cooling system, as well as the variable air volume fans. For this typical HVAC system as Figure 6-1, the total energy consumption is given as follows:

\[ E = E_{fan} + E_{heat} + E_{cool} \]  

(6.18)

where \( E_{fan} \) is the sum of the power consumption of both the supply fan \( E_{fan\_supply} \) and the return fan \( E_{fan\_return} \).

It can be seen that the energy consumption of the heating and cooling system is related to the supply air mass flow rate, the supply air temperature and the temperature of the mixed air.

### 6.3 HVAC Control System Design

In designing a HVAC control system for energy and comfort management, a hierarchical structure is employed, as shown in Figure 6-2. This control system can be embedded into the proposed multi-agent system. There are two layers of controller in this system. The first one is a primary controller, which determines the set points or comfort range of the indoor environmental parameters for the secondary controller. The secondary controller maintains the indoor environment at the set point by implementing control on the actuators in the HVAC system. An optimizer is embedded in the secondary controller to minimize the energy consumption for HVAC system in building operations.
6.3.1 Primary controller

The primary controller determines the set points of the two indoor environmental parameters: indoor temperature and CO\textsubscript{2} concentration. For the set point of the indoor temperature, an optimum temperature $T_{\text{set}}$ and an allowable range $\varepsilon$ can be defined, which means that the comfortable temperatures range for occupants is $[T_{\text{set}} - \varepsilon/2, T_{\text{set}} + \varepsilon/2]$. For the set point of indoor CO\textsubscript{2} concentration, a maximum limitation $A_{\text{max}}$ for indoor CO\textsubscript{2} concentration can be defined. Since the determination of the set points plays a vital role in a building automation system, there are multiple scenarios that can be utilized to determine the set points for environmental parameters.

*User-determined Scenario:* For some types of building such as residential houses, occupants usually require a dominated priority on the environment. In such buildings, users can determine their own preferences on the set points. The set points may vary due to different users or outdoor environment.
**Pre-defined Scenario:** For other building types like an office or a shopping mall, the set points need to be pre-defined, and certain standards can be employed. For instance, the maximum limitation for the indoor carbon dioxide concentration is 1050ppm according to ASHRAE Standard 62.1 [55]. The temperature's set point is usually related to the outdoor temperature. The temperature's set point in winter is usually lower than the one in summer. ASHRAE 55-1992 suggests the temperature range buss for overall thermal comfort as indicated in Table 6.1 [56].

Table 6.1: Suggested temperature range.

<table>
<thead>
<tr>
<th>Season</th>
<th>Clothing</th>
<th>Optimum Temperature</th>
<th>Comfortable Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter</td>
<td>Heavy slacks, long-sleeve shirts and sweaters</td>
<td>22 ºC</td>
<td>20-23.5 ºC</td>
</tr>
<tr>
<td>Summer</td>
<td>Light slacks, and short-sleeve shirt</td>
<td>24.5 ºC</td>
<td>23-26 ºC</td>
</tr>
</tbody>
</table>

**6.3.2 Secondary Controller**

For the secondary controller, the primary goal is to maintain both the indoor temperature and the indoor CO₂ concentration in the specified comfort range. In addition, an optimizer is embedded in the secondary controller, in which effective control strategy is developed to manage the indoor environment for achieving high energy efficiency.

**6.3.2.1 Problem Formulation**

Based on the discussion in section II, there are three deterministic parameters that affect the functionality and the energy consumption of the HVAC system, which are the
mass flow rate of the supply air \( \dot{m}_{\text{supply}} \), the temperature of the supply air \( T_{\text{supply}} \) and the temperature of the mixed air \( T_{\text{mix}} \). The supply air temperature and flow rate can be regulated by the heating/cooling system and the variable volume fans. The mixed air temperature is mainly regulated by the dampers connected to the mix chamber. These three variables are selected as control variables for the HVAC system.

There are two objectives in designing an HVAC controller: minimizing the energy consumption and maintaining a comfortable indoor thermal and air quality environment. This problem can be formulated as follows:

Minimize

\[
E = E(\dot{m}_{\text{supply}}, T_{\text{supply}}, T_{\text{mix}})
\]  

(6.19)

subject to two constraints,

\[
|T - T_{\text{set}}| \leq \frac{\varepsilon}{2}
\]

(6.20)

and

\[
A \leq A_{\text{max}}
\]

(6.21)

For (6.19), the total energy consumption is the summation of the energy consumption on each unit as shown in (6.18), and it is a function of the three control variables.

For (6.20), the indoor temperature should be controlled as close to the temperature's set point as possible, which means that the difference between indoor temperature \( T \) and the target temperature \( T_{\text{set}} \) should be less than the allowable \( \varepsilon \). The indoor temperature \( T \) can be calculated from (6.6), and it is a function of the mass flow rate and temperature of the supply air, as \( T = T(\dot{m}_{\text{supply}}, T_{\text{supply}}) \).
For (6.21), the indoor carbon dioxide concentration should be controlled beneath the upper bound for CO\textsubscript{2} concentration \( A_{\text{max}} \). The indoor CO\textsubscript{2} concentration \( A \) can be calculated from (6.11) and (6.12), and it is a function of the mass flow rate and temperature of the supply air and the temperature of the mixed air, which is \( A = A(\dot{m}_{\text{supply}}, T_{\text{supply}}, T_{\text{mix}}) \).

### 6.3.2.2 Particle Swarm Optimizer

To solve the formulated problem, a particle swarm optimizer is developed to minimize the energy consumption while maintaining the thermal and air quality comfort. For the formulated problem, the position of particle \( i \) is set as \( \vec{p}_i = (p_i(1), p_i(2), p_i(3)) = (\dot{m}_{\text{supply}}, T_{\text{supply}}, T_{\text{mix}})_i \). While updating for the best positions, the new position with lower energy consumption satisfying both constraints will be updated as the new best. Such an optimization algorithm will enable the controller to find the solution of \( (\dot{m}_{\text{supply}}, T_{\text{supply}}, T_{\text{mix}}) \) that is able to achieve the lowest energy consumption with satisfied indoor comfort.

The computational flow of the optimization procedure for the proposed optimizer is laid out as follows:

**Step 1: Initialization.** Set the number of population and the maximum iteration number. Specify the limited range for the value of each dimension of particles and the limitations of the velocity. For each particle, initialize the position of the individuals \( \vec{p}_i \) by generating the value of each dimension of \( \vec{p}_i \) within the limited range. Check whether the generated particle satisfies the two constraints specified in (6.20) and (6.21). If not, initialize the particle again until it satisfies all constraints, and then initialize the velocity.
of the particle \( \vec{v}_i \) within the limited range. Initialize the personal best \( pbest_i \) for each particle and the global best \( gbest \) of the swarm.

Step 2: Evaluation and updating of personal best and global best. Calculate the fitness value of each particle. The fitness value of each particle is \( \text{fitness}(\vec{p}_i) = E(\vec{p}_i) = E(p_i(1), p_i(2), p_i(3)) \). If the fitness value is better (smaller) than the best fitness value in history \( \text{fitness}(\overline{pbest}_i) \) AND the particle satisfies the specified constraints \( |T(p_i(1), p_i(2)) - T_{set}| \leq \frac{E}{2} \) and \( A(\vec{p}_i) = A(p_i(1), p_i(2), p_i(3)) \leq A_{\text{max}} \), set the current position as the new personal best \( pbest_i \). Choose the particle with the best fitness value of all the particles as the global best \( gbest \).

Step 3: Updating of particle position and velocity. Update the velocity of each particle based on (6.22) and make sure the updated velocity is within the limitation. Update the position of each particle based on (6.23) and make sure each dimension of the updated position is in the limited range.

Step 4: Stop and iteration criteria. If the maximum iterations are reached, then go to Step 5. Otherwise, go to Step 2.

Step 5: Output. Output the global best as the best solution to this optimization problem.

6.4 Case Study

In order to study the performance of the developed optimizer, a simulation study is carried out based on the developed building model. The building under consideration is used for office and business purposes and consists of two floors. The floor area is
15m*20m, and the height for each floor is 3m. The whole building is considered as one thermal zone for control purpose.

When implementing control on HVAC system, the control variables should be adjusted according to the real-time environmental condition. The HVAC controller uses information from previous time steps to predict system response in the next time step and make decisions accordingly. The proposed building is continuously controlled by implementing the proposed control strategy in HVAC system for a 24-hour period. The control time step for decision making is 15 minutes, that is, the system needs to adjust its control variables in every 15 minutes based on the environmental changes.

As specified by the occupants, the optimum temperature $T_{set}$ is set as 22°C, and the allowable range $\varepsilon$ is 1°C. Thus, the comfort range for temperature is [21.5 °C, 22.5 °C]. The limit of the indoor CO$_2$ concentration $A_{max}$ is set as 1000ppm. The outdoor CO$_2$ concentration $A_{out}$ remains at 350ppm for the whole day. The variation of occupancy in a day is shown in Figure 6-3. The CO$_2$ generation per person is $L = 0.0052 * 10^{-3} m^3/s/person$ in an office building. At the time of $t = 0$, the indoor temperature $T_{in}(t = 0) = 7.8°C$, and the indoor CO$_2$ concentration $A_{in}(t = 0) = 600 ppm$. The outdoor temperature variation in a day is shown in Figure 6-4.
In order to study the performance of the developed optimizer, a comparison study is carried out based on the developed building model. The control performance of the optimizer is compared with a conventional ON-OFF controller. After running the
optimizer for 96 times, the simulation results of the variation of indoor temperature and indoor CO₂ concentration for both controllers are shown in Figure 6-5 and Figure 6-6, respectively. As shown in Figure 6-5, the indoor temperature is well maintained within the range of [21 °C, 23 °C] from 00:30 in this cold day for both controllers. As shown in Figure 6-6, the indoor CO₂ concentration is also successfully controlled below the limit 1000 ppm for both controllers.

Figure 6-5: Indoor temperature variation in a day.

Figure 6-6: Indoor CO₂ concentration variation in a day.
The proposed optimizer is able to find solutions that fulfill the requirements of high comfort for indoor environment. The power consumption for both systems is shown in Figure 6-7. The total energy consumption is 388.6 kWh for optimal control, and is 640.3 kWh for ON-OFF control. A significant amount of energy is saved with the optimal controller.

![Figure 6-7: Energy consumption in a day.](image)

To study the impact of variable set points on the total energy consumption, a comparative study is carried out to simulate the total energy consumption with different set points, as shown in Table 6.2.

Table 6.2: Comparison of different set points.

<table>
<thead>
<tr>
<th>No.</th>
<th>$T_{set}$ (°C)</th>
<th>$\varepsilon$ (°C)</th>
<th>$A_{max}$ (ppm)</th>
<th>Energy consumption in a day (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>22</td>
<td>1</td>
<td>1000</td>
<td>394.3</td>
</tr>
<tr>
<td>2</td>
<td>21</td>
<td>1</td>
<td>1000</td>
<td>336.8</td>
</tr>
<tr>
<td>3</td>
<td>22</td>
<td>3</td>
<td>1000</td>
<td>372.3</td>
</tr>
<tr>
<td>4</td>
<td>22</td>
<td>1</td>
<td>1200</td>
<td>387.6</td>
</tr>
</tbody>
</table>
Comparing experiments No.2 with No.1, it can be seen that lower optimum temperature can lead to lower energy consumption. Comparing experiments No.3 and No.4 with No.1, it can be found that both wider temperature range and higher CO₂ concentration level allowed lead to reduced energy consumption. Thus, the energy consumption of the HVAC system is affected by both variable set points and comfort range.

6.5 Conclusion

In this chapter, the function of HVAC system in building energy and comfort management has been discussed. To effectively control the HVAC system, a hierarchal control system is proposed. A particle swarm optimizer is embedded in the control system to control the building’s indoor environment with high energy efficiency. The control strategy utilized swarm intelligence technique to determine the amount of energy dispatched to each HVAC unit. The simulation results show the effectiveness of the optimizer in maintaining indoor comfort and saving energy. Further study can be carried out on the dynamic control of the set points, which is proven to be highly related to the HVAC system energy consumption.
Chapter 7

Efficient Control of a Solar Assisted Geothermal Heat Pump System Based on Evaluation of Building Thermal Load Demand

Geothermal heat pump (GHP) systems have been rapidly developed worldwide in decades due to their high energy efficiency in comparison with other air-source heat pump systems [57], [58]. It utilizes the thermal energy generated and stored in the earth as energy source to maintain comfortable building thermal environment. Geothermal energy is cost effective, reliable, sustainable, and environmentally friendly. In this paper, a solar assisted ground-source heat pump system is proposed to provide thermal comfort for buildings. In order to improve the efficiency of the designed solar assisted ground-source heat pump system, a control strategy based on the evaluation of building thermal load demand is proposed. The system operates in different modes to adapt to outdoor and indoor environmental changes.

7.1 Introduction

In a geothermal heat pump system, the ground is used as a heat source/sink to meet building’s heating/cooling load requirement [59]. This design takes advantage of the nearly constant temperatures in the ground, which are usually between 0°C and 12°C
depending on the latitude [60], to improve the efficiency of the heat pump system. In the design and operation of a GHP system, it is important to balance the amount of heat rejected to or extract from the ground on an annual basis to ensure that the ground temperature does not change on a long-term basis. If there is annual energy imbalance, the loop fluid temperature tends to rise or drop, which would result in failure of the GHP system. This effect can be moderated by increasing the size of the ground heat exchanger. On the other hand, this would increase the cost of installation as well as the economic payback period. An alternative solution is to add an auxiliary heat source, such as solar energy, to avert the annual energy imbalance.

By using solar collectors in the GHP system, the energy collected by solar collectors can be stored in ground through seasonal borehole thermal energy storage (BTES) in hot days, and extracted by the GHP system in cold weather [61]. Moreover, a seasonal BTES can be designed using two independent U-pipe networks so that the ground can be charged and discharged simultaneously [62]. The application of a solar thermal collector can also improve energy efficiency of a GHP system [63], [64]. In this paper, a solar assisted GHP system composed of a solar thermal collector, borehole heat exchangers and a ground-source heat pump is designed to provide heat to fulfill building heating load demand [65]. This solar assisted GHP system is designed to operate in different modes to achieve the highest energy efficiency. A load demand control strategy is proposed based on the evaluation of real-time building load demand to achieve energy efficiency. The energy performance of the system in heating mode is also discussed in this paper.

7.2 Components and System Description
The schematic diagram of the proposed solar assisted GHP system is demonstrated in Figure 7-1. It shows that the system consists of four parts, which are solar collector, borehole heat exchangers, heat pump unit, and fan coil units.

![Schematic diagram of the solar assisted GHP system.](image)

In this system, a flat-type solar collector is used to collect solar power to heat the building and charge the BTES which consists of U-pipe borehole heat exchangers (BHE). The borehole heat exchangers is buried in the ground so that the heat can be directly stored in the ground. U-pipes, as the ground heat exchangers, are inserted into vertical boreholes to build a huge heat exchanger. While water is running in the u-pipes, heat can be charged into or discharged from the ground. The BTES is designed using two independent U-pipe networks. A heat insulation layer is placed at the top of the BTES to reduce heat losses to the surface. This type of design allows additional boreholes to be connected easily so that the BTES can grow with the size of load demand. A heat pump...
unit is installed in the system to pump the heat from the energy source to inject or reject heat to the fan coil units which input the transferred heat into the building.

### 7.2.1 Evaluation of Building Thermal Load Demand

To evaluate the real-time thermal load demand of the building, the building is considered as a thermal zone, and the heat balance should be maintained in order to achieve a constant comfortable temperature. If the building is gaining or losing energy, the indoor temperature will change accordingly. Based on a heat balance on the building air, the indoor temperature variation can be formulated as follows [49]:

\[
m_{\text{building}} c_{p,\text{air}} \frac{dT_{\text{indoor}}}{dt} = \dot{Q}_{\text{system}} - \dot{Q}_{\text{loss}}
\]

where \( m_{\text{building}} \) is the air mass of the building area, \( c_{p,\text{air}} \) is the specific heat capacity of air, \( T_{\text{indoor}} \) is the indoor air temperature, \( \dot{Q}_{\text{system}} \) is the thermal transfer rate from the heating system, \( \dot{Q}_{\text{loss}} \) is the building's total thermal loss rate. It includes the heat loss due to infiltration of outside air \( \dot{Q}_{\text{infiltration}} \), convective heat loss from the wall and ceiling surfaces \( \dot{Q}_{\text{convection}} \), heat loss through the extracting of indoor air for ventilation \( \dot{Q}_{\text{extracted}} \), and internal loads gain from occupants and equipment \( \dot{Q}_{\text{internal}} \).

\[
\dot{Q}_{\text{loss}} = \dot{Q}_{\text{convection}} + \dot{Q}_{\text{infiltration}} + \dot{Q}_{\text{extracted}} - \dot{Q}_{\text{internal}}
\]

The energy gain from the system is illustrated as follows:

\[
\dot{Q}_{\text{system}} = \dot{m}_{\text{fan,air}} c_{p,\text{air}} (T_{\text{supply}} - T_{\text{indoor}})
\]

where \( \dot{m}_{\text{fan,air}} \) is the mass flow rate of the air out of the fan coil units, \( T_{\text{supply}} \) is the temperature of the supply air.
If the thermal energy transferred from the heating system $\dot{Q}_{\text{system}}$ fulfills the thermal demand of building on the heating system $\dot{Q}_{\text{system,demand}}$, the indoor temperature shall remain at the set point. Otherwise, the indoor temperature will vary. Therefore, for each control step $t_{\text{step}}$, the system demand at time $t \dot{Q}_{\text{system,demand}}(t)$ can be evaluated based on the variation of temperature.

$$
\dot{Q}_{\text{system,demand}}(t) = \dot{Q}_{\text{loss}} + m_{\text{building}} c_{\text{p,air}} \frac{T_{\text{set}} - T_{\text{indoor}}(t)}{t_{\text{step}}} \\
= \dot{Q}_{\text{system}}(t - t_{\text{step}}) - m_{\text{building}} c_{\text{p,air}} \frac{T_{\text{indoor}}(t) - T_{\text{indoor}}(t - t_{\text{step}})}{t_{\text{step}}} \\
+ m_{\text{building}} c_{\text{p,air}} \frac{T_{\text{set}} - T_{\text{indoor}}(t)}{t_{\text{step}}} 
$$

(7.4)

The system thermal load demand is calculated through (7.4). The heat transfer rate from the heating system $\dot{Q}_{\text{system}}(t)$ at time $t$ should be equal to $\dot{Q}_{\text{system,demand}}(t)$ in order to maintain the indoor temperature at the set point temperature $T_{\text{set}}$.

### 7.2.2 Fan Coil Unit Characteristics

In a fan coil unit, the mixed air stream passes through the heating coil to be heated. The energy transferred to the air stream is given by the following equation:

$$
\dot{Q}_{\text{air}} = m_{\text{fan,air}} c_{\text{p,air}} (T_{\text{supply}} - T_{\text{mix}}) 
$$

(7.5)

where $m_{\text{fan,air}}$ is the air mass flow rate of the fan, and $T_{\text{mix}}$ is the temperature of air into the fan coil unit, which is the mix air from the outside fresh air and reheated air from part of the exhausted air. In order to maintain the indoor temperature at the set point, the heat brought into the building by the air stream should fulfill the system thermal load demand. According to (7.3), we have the demanded supply air temperature,
\[ T_{\text{supply}} = \frac{\dot{Q}_{\text{system demand}}}{m_{\text{fan,air}}c_{p,\text{air}}} + T_{\text{indoor}} \]  

(7.6)

The supply air temperature varies with the supply air flow rate of the fan to meet the required building thermal load demand.

In a fan coil unit, the maximum amount of energy that can be transferred between air stream and fluid is determined by the minimum capacitance side. The minimum capacitance is determined by

\[
C_{\text{min}} = \text{MIN}(\dot{m}_{\text{liq}}c_{p,\text{liq}}, \dot{m}_{\text{fan,air}}c_{p,\text{air}}) \]  

(7.7)

where \( \dot{m}_{\text{liq}} \) is the mass flow rate of the fluid running in the heating coil and \( c_{p,\text{liq}} \) is the specific heat capacity of the fluid. Therefore, to ensure high heat transfer effectiveness in the fan coil, the rated fluid flow rate \( \dot{m}_{\text{liq,\text{rated}}} \) should have the following relation with the rated fan flow rate \( \dot{m}_{\text{fan,\text{rated}}} \):

\[
\dot{m}_{\text{liq,\text{rated}}} > \frac{\dot{m}_{\text{fan,\text{rated}}}c_{p,\text{air}}}{c_{p,\text{liq}}} \]  

(7.8)

When the solar energy directly supplies heat to the building, it must be guaranteed that the solar energy gain is able to satisfy the building thermal load demand \( \dot{Q}_{\text{system demand}} \). The mass flow rate of the fan cannot exceed its rated value, so there is such a relationship:

\[
\dot{m}_{\text{fan,\text{air}}} \leq \dot{m}_{\text{fan,\text{rated}}} \]  

(7.9)

Therefore, the supply air temperature cannot be lower than a certain value \( T_{\text{supply,\text{threshold}}} \) which can be calculated through (7.6), as

\[
T_{\text{supply}} \geq T_{\text{supply,\text{threshold}}} = \frac{\dot{Q}_{\text{system demand}}}{\dot{m}_{\text{fan,\text{rated}}}c_{p,\text{air}}} + T_{\text{indoor}} \]  

(7.10)
According to the thermodynamics, when condition (7.8) is satisfied, the thermal energy in the fluid is transferred furthest into the air stream. The supply air temperature out of the fan coil unit is as (7.11), and it cannot exceed the supply air temperature threshold:

\[ T_{\text{supply}} = \frac{T_{\text{fluid}} + T_{\text{mix}}}{2} \geq T_{\text{supply,threshold}} \quad (7.11) \]

It can be concluded that the temperature of the inlet fluid value into the heating coil \( T_{\text{fluid,in}} \) should satisfy the condition in (7.12) in order to satisfy the building thermal demand while heating the building directly from the solar energy.

\[ T_{\text{fluid,in}} \geq 2\left(\frac{\dot{Q}_{\text{system,demand}}}{m_{\text{fan, rated}} c_{p, air}} + T_{\text{indoor}}\right) - T_{\text{mix}} \quad (7.12) \]

### 7.2.3 Heat Pump Characteristics

In this study, a water-to-water heat pump unit is used to transfer the energy from the low temperature side (source side) to the high temperature side (load side) in the heating mode. The heat pump consists of four parts, a compressor, an expansion valve, and two water heat exchangers that serve as either condenser or evaporator depending on the heat pump’s operation mode [66]. The compressor, which forces the refrigerant to move from the low temperature/pressure side to high temperature/pressure side to release its latent energy, is the electric energy-consuming unit in the heat pump.

The heat pump performance at different operation conditions is evaluated by the coefficient of performance (COP), which is the ratio of the heat gain at the load side to energy consumed in heat pump [67].
\[ COP = \frac{Q_{load,h}}{W_{hp}} = \frac{Q_{load,h}}{Q_{load,h} - Q_{source}} \] (7.13)

For a given fluid flow rate, the heat pump characteristics can be modeled according to the source side inlet fluid temperature \( T_{source} \) and the load side inlet fluid temperature \( T_{load} \) [68]. Both higher source side inlet fluid temperature and lower load side inlet temperature could increase the energy efficiency of the heat pump.

### 7.3 System Operation Modes

#### 7.3.1 Operation Modes for Building Heating

In order to increase the efficiency of the system and utilize solar energy completely, the system should be operated in different modes corresponding to the change of indoor thermal load demand and outdoor weather variations. The operation modes for heating building are discussed as follows.

*Mode 1.* Solar energy directly heats building without heat pump and simultaneously charges/discharges the BTES through BHE. The recycling loop is as follow,

Solar collector-V2-Pump1-Fan coil units-V3-V4-V8-V12-BHE-V11-V7-Solar collector.

Valves V1, V5, V6, V9, V10, V13, V14, Heat pump unit, Pump2 and Pump3 are off in this mode.

*Mode 2.* Solar energy and BTES together are used as heat source of the heat pump to heat building. There are two recycling loops in this mode.


Valves V2, V3, V5, V8, V9, and Pump1 are off in this mode.

Mode3. The ground source heat pump heats building. This mode also has two recycling loop.

Heat pump source side loop: BHE-V11-V7-V5-V6- Heap pump source side heat exchanger-Pump2-V10-V12-BHE.


The solar collector loop is closed with the close of Valves V1, V2, V3, V4, V8, and V9.

### 7.3.2 The Conversion between System Operation Modes

The useful energy gain from solar collector depends on the solar radiation and the outdoor air temperature. Directly heating the room from the solar energy in mode1 will lead to higher energy efficiency. The only power-consuming unit except the fan-coil unit is the recycling pump that transfers the fluid to collect solar energy. The excessive heat is stored in BTES charging network by the ground heat exchanger. While the system is operated in mode 1, suppose there is no heat loss in heat transmission, the temperature of the heating coil inlet fluid value $T_{\text{fluid, in}}$ is the solar collector’s outlet fluid temperature $T_{\text{solar, out}}$. Therefore, it must satisfy (7.12) to ensure the solar collector can fulfill the building thermal demand. That is,
\[ T_{\text{solar, out}} \geq T_{\text{solar, require}} = 2(\frac{\dot{Q}_{\text{system, demand}}}{m_{\text{fan, rated}}c_{\text{p, air}}} + T_{\text{indoor}}) - T_{\text{mix}} \] (7.16)

The solar collector’s outlet fluid temperature \( T_{\text{solar, out}} \) must be higher than the minimum required solar outlet temperature \( T_{\text{solar, require}} \) in order to operate in mode 1.

When the solar energy gain cannot satisfy the building load demand, the system will switch to mode 2, in which the solar energy gain is used to heat the fluid from the BTE to increase the COP of the heat pump. When the solar collector cannot gain enough energy and starts to lose energy through the surface, the system will switch to mode 3 to use the ground heat solely as heat source to the heat pump. The conversion can be determined by the temperature out of the BTE \( T_{\text{BTE, out}} \) and temperature of the absorber in the solar collector \( T_{\text{solar}} \).

The flow chart of the conversion between the system operation modes in illustrated in Figure 7-2.

![Flow Chart](image-url)
7.4 Simulation and Performance Analysis

Based on the proposed control strategy, a simulation study on system’s performance is conducted in this section for 24 hours in a cold day. The simulation time step is 15 min. The energy performance of the system is shown in this section. Figure 7-3 shows the outdoor temperature variation in 24 hours. The indoor temperature is maintained at 22 ºC.

Figure 7-3: Outdoor temperature variation.

The building thermal demand is evaluated through (7.4). Figure 7-4 shows the evaluated building thermal demand. It varies with both the outdoor environment change and the internal load gain.
Figure 7-4: Building thermal load demand.

The variation of the daily useful solar energy is shown in Figure 7-5. It mainly influenced by the solar radiation on the collector surface.

Figure 7-5: Useful solar energy gain.
Figure 7-6 shows the daily heat extraction rate from the borehole heat exchangers. Negative value means that the ground is charging heat from the solar collector. Positive value means that the system is extract heat from the ground.

\[ PF = \frac{\dot{Q}_{heating}}{W_{total}} \]  

(7.17)

where \( \dot{Q}_{heating} \) is the heat transferred into the building, and \( W_{total} \) is total electric energy consumption of all power consuming units in the heating system. Figure 7-7 shows the variation of system performance factor through 24 hours.
Figure 7-7: System performance factor.

The summarized performance of different operation modes are shown in Table 7-1.

Mode 1 has the highest performance factor, followed by Mode 2 and Mode 3.

Table 7-1: The operation characteristics of each mode in heating period.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Operation Time (h)</th>
<th>Percent (%)</th>
<th>Transferred heat (kWh)</th>
<th>Power Consumption (kWh)</th>
<th>Average PF of the system</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode 1</td>
<td>[12:30,14:00]</td>
<td>6.25</td>
<td>2.78</td>
<td>0.33</td>
<td>8.42</td>
</tr>
<tr>
<td>Mode 2</td>
<td>[10:15,12:30], [14:00, 17:00]</td>
<td>21.88</td>
<td>10.73</td>
<td>3.40</td>
<td>3.16</td>
</tr>
<tr>
<td>Mode 3</td>
<td>[0:00, 10:15], [17:00, 24:00]</td>
<td>72.92</td>
<td>75.04</td>
<td>30.38</td>
<td>2.47</td>
</tr>
</tbody>
</table>

In this Chapter, a solar assisted GHP system is proposed to provide thermal comfort for buildings. The method for evaluating building thermal load demand is developed. Based on the building thermal load demand, a control strategy is proposed to determine the conversion between different operation modes. Using the control approach, the indoor temperature can be maintained at the desired value. The overall system performance is
studied by introducing a performance factor to compare the performance in different modes. The result shows that heating directly from the solar power has the highest energy efficiency, but also requires high solar energy collection. Using independent charging/discharging network, the redundant solar energy can also be charged into ground for storage. In this way, the heat collected from the solar collector in summer days can be stored for winter usage.
Chapter 8

Development of a Cloud Based Optimal Control System for Water Loop Heat Pump System

8.1 Introduction

Water loop heat pump systems are a type of HVAC systems that can be used to satisfy the thermal need of a building or a house. As one of the basic components in a water loop heat pump system, heat pumps transfer heat from a source to other locations by employing a refrigeration cycle. Heat pump can be used both for space heating in the cold weather and for cooling/air conditioning in hot weather. In the refrigeration cycle, a refrigerant is compressed and then expanded to absorb and remove heat. During cold weather, the heat pump operates in heating mode and transfers heat to the space to be heated. While during hot weather, the heat pump reverses this operation and extracts heat from the same space to be cooled[69]. The heat pumps are more efficient than electric heating and combustion heating. Based on the concept of coefficient of performance (COP), one share of electric energy can usually generate 2 to 5 times of heating energy.

The water loop heat pump system offers individual comfort for each thermal zone and uses the existing internal thermal load to balance the heating or cooling load of the conditioned zone [70]. The energy efficiency of a water loop heat pump system is determined by the energy efficiency of the heat pumps and auxiliary heat sources during
their operations. The heat pumps are distributed in each thermal zone to satisfy the load demand for each zone, which is determined by the thermal requirement of the occupants and the environment of the specific zone. The occupants set their desired room temperature through user interfaces/panels. Based on the desired temperature and the current indoor air temperature for each zone, the operation mode of heat pump can be determined to satisfy occupants’ thermal need.

This research proposes and evaluates an optimal control system that improves the operation efficiency of this water loop heat pump system for satisfying the occupant’s thermal load requirement. In addition, the control system employs a cloud utility service to process the computing task for achieving the optimal control performance. Cloud computing is used to enable on-demand network access to a shared pool of configurable computing resources that can be rapidly provisioned and released [71]. The control system leases one piece of the cloud service to process the computing task as an alternative of operating in its own infrastructure [72]. Moreover, the control task has additional requirements including real-time response and security of the cloud computing service [73]. One major benefit brought about by the cloud based system lies in its cost-effectiveness in implementing computationally expensive engineering systems like the intelligent control system proposed in this study.

### 8.2 Water Loop Heat Pump System

Figure 8-1 shows the hydraulic loop of a conventional water loop heat pump system. The solid line represents the supply water loop, and the dashed line represents the return water loop. All the heat pumps are hydraulically connected with a closed water loop that circulates water throughout the building. The heat pumps work in two modes (heating
mode and cooling mode) to heat up or cool down building zones depending on the comfort need in each zone. The thermal loads in each zone are usually different with each other. Some zones such as the sunny side of building may require cooling, while others may require heating. Auxiliary heating and cooling devices, such as the water heater and the cooling tower, help control the loop water temperature within a feasible and efficient range.

Figure 8-1: Hydraulic loop of a water loop heat pump system.

The heat pump extracts heat from a source at a lower temperature and transfers it to a sink at a higher temperature by using the mechanical work or a high-temperature heat source. It can work in both heating mode and cooling mode. Figure 8-2 shows the
structure of a water-to-air heat pump. The source side is the water loop; and the sink side
is the air circulation that supplies cold or hot air to the thermal zone for satisfying users’
need.

Figure 8-2: Water-to-air heat pump.

The efficiency of the heat pump can be represented by the coefficient of
performance (COP) in heating mode, and energy efficiency ratio (EER) in cooling mode.

In cooling mode, the EER can be modeled as follows. The EER of the heat pump
operated in cooling mode can be obtained based on curve-fitting of the performance data
as shown in Eq. (1).

\[
\text{EER} = a_1 \times \text{EWT}^2 + a_2 \times \text{EWT} + a_3 
\]

(8.1)

where EWT is the source side entering water temperature; and \(a_1\), \(a_2\), and \(a_3\) are curve-
fitting parameters. The EER is the ratio of BTUH output to Watt input as shown in the
following:

\[
\text{EER} = \text{zoneload}/P_{\text{HP}}
\]

(8.2)

where \text{zoneload} is the thermal load for the zone, and \(P_{\text{HP}}\) is the power of the heat pump.

The leaving water temperature of the source side LWT can be obtained as follows:

\[
\text{LWT} = \text{EWT} + (\text{zoneload} \times 1000 + P_{\text{HP}} \times 3412)/(\text{GPM} \times 500)
\]

(8.3)
where GPM is the source side water flow rate in gallon per minute.

In heating mode, COP is usually used to evaluate the performance of the heat pump, and it is the ratio of BTUH output to BTUH input. The parameters of the COP model can also be evaluated through performance data curve fitting [74].

\[
\text{COP} = b_1 \times \text{EWT}^2 + b_2 \times \text{EWT} + b_3
\]

(8.4)

where \(b_1\), \(b_2\), and \(b_3\) are curve-fitting parameters. The energy consumption of the heat pump can be calculated from the COP as follows,

\[
\text{P}_{HP} = |\text{zoneload}|/(\text{COP} \times 3.412)
\]

(8.5)

And the leaving water temperature of the source side LWT is

\[
\text{LWT} = \text{EWT} - (|\text{zoneload}| \times 1000 - \text{P}_{HP} \times 3412)/(\text{GPM} \times 500)
\]

(8.6)

The thermal load of each zone is related to the current thermal condition and the expected condition. If a zone has certain amounts of heating load, it means that more heat is needed in this zone and the heat pump should be operated in heating mode; otherwise, the heat pump should be operated in cooling mode to cool the zone. The thermal load of each zone is related to the current indoor and ambient temperature and the temperature set point specified by the occupants.

### 8.3 Optimal Control Strategy for Energy Efficiency

The optimization objective is to improve the energy efficiency in heat pump system operations while satisfying buildings’ thermal load. This can be achieved by finding the optimal supply water temperature to improve the energy efficiency of the system. Besides the heat pumps, other energy-consuming devices include the water heater, the cooling tower and the pumps. Usually, only one of the heaters and coolers will be operated
depending on the total thermal load of the building. The control objective is to minimize the total power consumption of the heat pump system $P_{\text{total}}$ as follows:

$$P_{\text{total}} = \sum P_{\text{HP}} + P_{\text{heater}} + P_{\text{cooler}} + P_{\text{pump}}$$  \hspace{1cm} (8.7)

where $P_{\text{heater}}$ is the power of the water heater; $P_{\text{cooler}}$ is the power of the cooling tower; and $P_{\text{pump}}$ is the power of the pump. The power consumption of the water heater is related to the return water temperature and the desired outlet supply water temperature. The water heater can be a boiler using natural gas as its energy source and it has a different price compared to electricity. Therefore, a price ratio $\text{priceratio}$ is added to calculate the equivalent electricity power of the water heater as follows:

$$P_{\text{heater}} = \frac{m_{\text{water}} \cdot C_{\text{p,water}} \cdot (T_{\text{water,return}} - T_{\text{water,supply}})}{\text{heatefficiency} \cdot \text{priceratio}}$$  \hspace{1cm} (8.8)

where $m_{\text{water}}$ is the return water flow rate; $C_{\text{p,water}}$ is the heat capacity of water; $T_{\text{water,return}}$ is the return water temperature; $T_{\text{water,supply}}$ is the outlet supply water temperature; and $\text{heatefficiency}$ is the efficiency of the boiler.

The energy consumption components of the cooling tower consist of the fan that circulates the ambient air and the pump that circulates the water to be cooler. The pump’s power is usually constant, and thus only the fan power is considered and it varies with the fan speed. The ratio of fan’s air flow rate to its design flow rate $\gamma$ is used as a signal for fan control, and it is related to both the ambient air temperature and the returned water temperature from the heat pumps as follows:

$$\gamma = f(T_{\text{water,return}}, T_{\text{water,supply}}, T_{\text{ambient}})$$  \hspace{1cm} (8.9)

The fan power of the cooling tower is

$$P_{\text{cooler, fan}} = P_{\text{fan,nominal}} \cdot (c1 + c2 \cdot \gamma + c3 \cdot \gamma^2 + c4 \cdot \gamma^3)$$  \hspace{1cm} (8.10)
where $P_{\text{cooler, fan}}$ is the fan power of the cooling tower, and $P_{\text{fan, nominal}}$ is the nominal fan power. The pump for the heat pump system circulation can be a constant pump, thus this part of energy can be neglected.

The control variable is the supply water temperature $T_{\text{water, supply}}$, which is related to the efficiency of the heat pumps inside the system. The water heater and the cooler are used to increase or decrease the returned loop water temperature in order to maintain the supply water temperature at the desired value. Thus, $T_{\text{water, supply}}$ is critical in the optimal control and is used as the control variable. A particle swarm optimizer is used here to solve the optimization problem in (8.7). In order to take advantage of the resources that a cloud service can provide, particle swarm algorithm is programmed in a parallel computing environment. A parallel asynchronous particle swarm optimization approach is utilized in this problem [75]. The parallel asynchronous particle swarm optimization design follows a master-slave paradigm. The master processor prepares for the particles and sends them to slave processors for decision-making for individual particles. The slave processors evaluate the fitness function about the assigned particle. The flow chart for this parallel asynchronous particle swarm optimizer is illustrated in Figure 8-3.

The major tasks performed by the master processor are listed as follows:

- Initialize particle positions and velocities, and evaluate the personal best $p_{\text{best}}$ for each particle and the global best $g_{\text{best}}$;
- Hold a queue of particles to be sent to slave processors;
- Send the position, velocity, and personal best $p_{\text{best}}$ of the next particle in the queue and the global best $g_{\text{best}}$ to an available slave processor;
• Receive updated particle position, velocity and personal best $pbest$.
• Update global best $gbest$ if needed.
• Check stop criteria and outputs results.

The tasks performed by the slave processor are:
• Receive particle position, velocity, personal best $pbest$, and global best $gbest$ from master processor.
• Update the particle, evaluate its fitness, and update personal best $pbest$ if needed.
• Send updated particle position, velocity and personal best $pbest$ to the master processor.

Figure 8-3: Parallel asynchronous particle swarm optimization.
8.4 Cloud Based Control System Architecture

Cloud computing is emerging as a highly promising, disruptive technology since it is able to provide cost-effective computing capability without needing to build expensive data centers for numerous small or medium sized enterprises and companies. There is currently a trend to outsource the computationally expensive tasks to the cloud in building energy management, and cloud-enabled data analytics become compelling to achieve higher energy efficiency for building applications. In this project, a cloud service is employed for performing the computing tasks associated with system control and optimization. The computational process for the decision-making is outsourced to the cloud. The proposed control system architecture is illustrated in Figure 8-4.

The user interfaces enable the communications between the control system and users. Users can input their preferences for the indoor environment through the interfaces which send these data to the control system for further processing and decision-making. The user interfaces also display the environmental and operation parameters to users. The sensors are distributed in the building environment to measure the environment parameters including the zone air temperature, water loop temperature, ambient air temperature, etc. The actuators, including the heat pumps, water heater, cooling tower, and pump, work together to maintain a comfortable indoor environment of the building.
The central controller manages the actuators, sensors, and user interfaces while also being responsible for coordinating the interactions between the control system and the cloud service. The work flow of the central controller in one sampling time is illustrated in Figure 8-5. It obtains building environmental data from sensors and user interfaces, and sends the data to the cloud controller for analysis. The designed central controller has real-time requirement on the cloud service. That is, the cloud controller should be able to respond within a limited time period. If the central controller receives the computing results from the cloud controller on time, it will send the related control variables to the actuators for controlling the building indoor environment and display the building operation status to the occupants/operators through the user interfaces. If the central controller does not receive the response from the cloud on time, it will drop the cloud
controller from the current task queue and prepare for processing the next task. In this case, the actuators will maintain their previous operation settings and status.

![Flowchart](image)

**Figure 8-5:** Work flow chart of the central controller in one sampling time.

The cloud controller is deployed in the cloud to respond to the requests of the central controller. It allocates computing resources for computing tasks requested from the central controller. The optimal controller acts as an application service that runs in the cloud computing infrastructure to find optimal solutions for the control system. Since the control system has real-time and security requirements, the cloud controller should be able to respond to the requests from the central controller in a timely manner. Once a
computing task is received from the central controller, the cloud controller should allocate adequate computing resource to the computing task for deriving out the results on time. Otherwise, the central controller will drop the cloud controller from its current computing task queue and wait for the next computing request.

8.5 Simulation Studies

Simulation studies are conducted and discussed in this section for a building that consists of 6 thermal zones. Each zone has a water-source heat pump that can provide both cooling and heating air into the thermal zone. The efficiency of the heat pump is influenced by the supply water temperature. In each sampling time (15 mins), the zone load should be measured and evaluated for each zone. The power consumption of the heat pump is related to both the zone load and the supply water temperature. The heat pumps are connected in series, which means that the outlet water temperature of zone1 is the inlet water temperature of zone2, and so on.

The daily variation of the ambient air temperature is shown in Figure 8-6.

![Figure 8-6: Ambient air temperature.](image)
The zone loads in the building are different from each other. Figure 8-7 shows the thermal load in each zone in a day. Positive zone load means that the respective heat pump needs to be run in cooling mode to fulfill the cooling load demand. Negative zone load indicates the respective heat pump needs to be run in heating mode to fulfill the heating load demand.

![Figure 8-7: Thermal load in each zone.](image)

Based on the zone load and the ambient air temperature, the supply water temperature is optimized by a particle swarm optimizer to achieve the most energy efficient operation point. And this value should be determined in every sampling time in order to adapt to thermal load changes.

### 8.5.1 The Performance of the Cloud Based Control System
The temperature set point for each zone is 72 °F. After the control is deployed, the zone temperature for all 6 zones can be well maintained around 72 °F. The temperature variation in zone 1 and zone 2 are shown in Figure 8-8.

Figure 8-8: Indoor temperature variation in zone 1 and zone 2.

The feasible range for T_{water, supply} is [50°F, 90°F]. The optimized supply water temperatures are shown in Figure 8-9.
The total energy consumption of the optimized water loop heat pump system is shown in Figure 8-10, comparing to a constant supply water temperature of 80 °F.

The daily energy consumption for the optimized system is 65.3119 kWh, while the daily energy consumption for the non-optimized system is 71.3876 kWh. The water loop
heat pump system with optimized supply water temperature consumes less energy than the one with a constant supply water temperature.

The performance of the proposed asynchronous parallel PSO is compared with a non-parallel PSO in this study. In the PSO program, the particle number is 10, and the iteration time is 100. Thus, there are 10 slave processors in the parallel PSO. The experiment result shows that the parallel optimizer spends much more time than the parallel optimizer: 52 milliseconds for non-parallel optimizer, and 8018 milliseconds for parallel optimizer. This result is contrary to the intention of saving computing time by using parallel computing. The reason for this is that the communication time between the master processor and a slave processor is much longer than the computing time of evaluating the fitness in the slave processor. However, the computing time of evaluating the fitness function will be much longer when dealing with a larger building that processes thousands of heat pumps. An experimental study is carried out to study the performance of parallel computing in solving complex problems. To simulate the effect of a more complex fitness function that requires more computational time, a certain delay time is added to the fitness function. The results are shown in Table 8.1.

Table 8.1 Experimental results on the parallel PSO performance

<table>
<thead>
<tr>
<th>Delay time</th>
<th>Computational time by using non-parallel PSO</th>
<th>Computational time by using parallel PSO</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 ms</td>
<td>52 ms</td>
<td>8018ms</td>
</tr>
<tr>
<td>100 ms</td>
<td>100241 ms</td>
<td>14375 ms</td>
</tr>
<tr>
<td>200 ms</td>
<td>200245 ms</td>
<td>24079 ms</td>
</tr>
</tbody>
</table>

The results show that the parallel PSO will save more time than the non-parallel PSO when a long delay time is added into the fitness function. Therefore, for the control
designs which have complex fitness function and require more computational time, the parallel PSO will consume less computational time compared with the non-parallel PSO.

8.5.2 Impact of Cloud Computing Failure

8.5.2.1 Limited Cloud Resources

If the cloud resources are limited and the cloud agent cannot return proper answers on time, the actuators will maintain at its last value. Figure 8-11 shows the indoor temperature variation of zone1 if the control signal for the controller experiences a time out at 15:45. The actuator remains their control signal the same as the value they obtained at 15:30. It can be seen that the room temperature drops quickly from 15:45 to 16:00. The cloud recovers and operates normally again at 16:00, and the indoor temperature returns to 72 degree gradually. Therefore, if the cloud resource is limited and cannot process a control request on time, the building’s indoor environment will be impacted consequently.

![Figure 8-11. Indoor temperature variation in zone 1 when suffering time out](image)

8.5.2.2 Vulnerable Cloud Service
If the cloud service is under attack, malicious modifications may occur in the cloud computing and impact the control performance. Figure 8-12 shows the indoor temperature variation of zone 3 when the cloud is under attack from 9:45 to 10:15, and the control signal for the heat pump is maliciously modified to run at its maximum capacity. From 10:30, the attack is dismissed and the cloud operates normally again. Since the cloud computing experiences long and severe attack, the room temperature recovering time is long due to the limited heat pump capacity. The room temperature goes back to normal at 11:15.

Figure 8-12. Indoor temperature variation in zone 3 when the data is maliciously modified in the cloud.

The cloud-based control system has been proven to have the ability to improve the operational efficiency of this water loop heat pump system. The proposed parallel PSO algorithm has its advantage in reducing computational time when the computing task is complex. The cloud features certain limitations and vulnerabilities that may impact the performance of control system. However, cloud computing can be a powerful technology
capable of solving computationally intensive problems with less time and less cost in the
development of next-generation control systems for intelligent buildings.
Chapter 9

Conclusions and Outlook

In this chapter, conclusions are made to summarize the work presented in this dissertation. Also, some suggestions for future research in this research area will be given.

9.1 Conclusions

This dissertation discusses the development of integrated building control systems for energy and comfort management in intelligent buildings. The first part of dissertation discusses the background knowledge in intelligent buildings research and building energy and comfort management.

- Intelligent buildings use advanced computer technologies to effectively control the building facilities and provide a productive indoor environment in a cost-effective manner. The research and technologies in intelligent buildings are characterized by a hierarchical level of system integration. Energy and comfort management is the primary task in intelligent building control.

- Occupants’ comfort level is mainly determined by three basic factors: thermal comfort, visual comfort, and indoor air quality comfort. To evaluate the occupants’ comfort in the living environment, related environmental parameters are used as indices to form the function of occupant’s comfort by utilizing the actual value of the corresponding environmental parameters and occupant’s
preferences of these parameters. Building energy management is used to manage thermal and electrical energy supply sources and loads.

The second part of the dissertation presented an integrated building control system to tackle various control tasks in building management and automation.

- The proposed multi-agent system in Chapter 3 is capable of controlling the building environment effectively to satisfy occupant’s demand and reduce energy consumption. The proposed multi-agent system provides an open architecture in which agents can be easily configured, and new agents can be added without interfering with the normal operations of the whole system. Given the advantage of this open architecture, the proposed multi-agent system can be integrated into the existing automation systems for including new features.

- Multi-objective PSO is used in building automation to derive tradeoff solutions for balancing different conflicting design and control objectives in Chapter 4. By utilizing the MOPSO algorithm, the trade-off solutions can be found successfully. This algorithm reveals excellent performance in solving multi-objective problems in building automation.

- An extended multi-agent system is developed in Chapter 5 to conduct intelligent control over the indoor environment of integrated multi-zone building and micro-grid systems. An intelligent particle swarm optimizer is embedded to optimize indoor comfort when the total energy supply is in a shortage. The result shows that in spite of a large quantity of energy shortage, the intelligent
controller has turned out to be able to distribute the energy appropriately to maintain the high overall comfort levels.

The third part of the dissertation is to solve various complex and nonlinear problems in building subsystem level by applying intelligent control techniques.

- HVAC system is the most important subsystem in building automation that provides a relatively constant and comfortable temperature as well as fresh and filtered air with a comfortable humidity range to the buildings. Chapter 6 proposes an optimal control strategy for a typical HVAC system in building energy management. The results show that without sacrifice of thermal comfort, to control the suitable operating parameters can also achieve energy saving purpose.

- Geothermal heat pump systems have attracted many attentions nowadays due to their high energy efficiency in comparison with other air-source heat pump systems. It utilizes the thermal energy generated and stored in the earth as energy source to maintain comfortable building thermal environment. Geothermal energy is cost effective, reliable, sustainable, and environmentally friendly. In Chapter 7, a solar assisted ground-source heat pump system is proposed to provide thermal comfort for buildings. A control strategy based on the evaluation of building thermal load demand is proposed to improve the efficiency of the designed solar assisted ground-source heat pump system.

- In Chapter 8, the proposed cloud-based control system has been proven to have the ability to improve the operational efficiency of this water loop heat pump system. The proposed parallel PSO algorithm has its advantage in reducing
computational time when the computing task is complex. The cloud features certain limitations and vulnerabilities that may impact the performance of control system. However, cloud computing can be a powerful technology capable of solving computationally intensive problems with less time and less cost in the development of next-generation control systems for intelligent buildings.

9.2 Outlook

Building energy and comfort management is an important and promising area in intelligent building design. And there are still many open-ended challenging problems in this area. The author believes that the following several research directions are of particular importance.

- Future study in predictive and forecasting models can be conducted in this area to predict the energy demand and building performance. With the predictive information, predictive control can be applied in building automation to save energy effectively. Research on scheduling problems such as pre-cooling, pre-heating, and demand response can be discussed based on the predictive models.

- Renewable energy integration will remain a promising topic for intelligent building design. Proper design of the integrated micro-grid which might consist of PV panels, wind turbines, and energy storage can be investigated. To choose suitable and complementary renewable sources combination that fulfills the building energy requirement remains a challenging topic in this field.

- Geothermal heat pump system is a promising topic for future energy savings in building operations. The ground field temperature should remain to be balanced
in yearly operations. Otherwise, the ground field temperature might change to an unsuitable range for heat transfer in building operations. Future study concerning the seasonal performance of a geothermal heat pump system could be conducted. Auxiliary heating and cooling approaches can also be discussed to maintain the yearly balance of the ground temperature.
References


