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Secondary Frequency Control with Aggregations of Controllable Commercial Buildings

PSL1329

EPFL-Middle East section
Master in Energy Management and Sustainability

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Zürich, 13 September 2013
Abstract

This thesis is concerned with the development of a control strategy for secondary control reserve provision in a commercial building aggregation. Since a large fraction of the world energy is consumed in buildings, there is a strong motivation for turning such end-consumers into ancillary service providers. The objective of this thesis is to take the advantage of the inherent thermal storage capacity of the commercial buildings to explore the reserve potential. A day-ahead centralized reserve determination phase, a decentralized MPC-based scheduling phase and a decentralized real-time proportional controller are included in the controller design to optimize Heating, Ventilation, and Air Conditioning (HVAC) of an aggregated commercial building pool. Benchmarks of building population are carried out for Intergrated Room Automation (IRA) models. The practicability of the benchmark and the controller are investigated by validation and real-time simulations in MATLAB. The feasibility of the secondary control reserve provision via demand response (DR) is shown in real-time simulation.
Preface

This Master Thesis was conducted at the Power System Laboratory of ETH Zürich during the spring semester 2013.

First of all, I would like to express my sincere thanks to my supervisors Evangelos Vrettos and Frauke Oldewurtel for their support and patience throughout this thesis. I really appreciate the helpful ideas you always gave to me in every discussion.

I would like to thank Matthias Haller for giving me the opportunity to do such ‘real’ design of the grid.

I would like to thank Prof. Göran Andersson for giving me such an opportunity to work in his research group.

I wish to express my sincere gratitude to Prof. Maher Kayal for being my supervisor in EPFL. I’m really proud of being the first generation of MES program and being a member of ELAB.

Special thanks to my boyfriend Bolun Xu for helping me to find my thesis here in ETH Zürich.

My most heartfelt gratitude to all my friends for two-year accompanying. Special thanks to Lunwei and Chang-Hung for the projects and hikings we went through together. It was really nice to always have you around in these two years.

Finally I would like to thank my family for their endless support even though they have no idea what I’m doing.

Fengtian ZHU

Zürich, September 2013
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<th>Description</th>
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<tbody>
<tr>
<td>ADF</td>
<td>Affine Disturbance Feedback</td>
</tr>
<tr>
<td>AHU</td>
<td>Air Handling Unit</td>
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<tr>
<td>AS</td>
<td>Ancillary Service</td>
</tr>
<tr>
<td>BAS</td>
<td>Building Automation System</td>
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<tr>
<td>BD</td>
<td>Building</td>
</tr>
<tr>
<td>CCP</td>
<td>Common Clearing Price</td>
</tr>
<tr>
<td>CLP</td>
<td>Closed-Loop Prediction</td>
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<tr>
<td>DR</td>
<td>Demand Response</td>
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<tr>
<td>FERC</td>
<td>Federal Energy Regulatory Commission</td>
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<tr>
<td>HM</td>
<td>Hao’s Model</td>
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<td>HMD</td>
<td>Hao’s Model with Disturbances</td>
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<tr>
<td>HMDC</td>
<td>Hao’s Model with Disturbances and Chiller</td>
</tr>
<tr>
<td>HVAC</td>
<td>Heating, Ventilation, Air Conditioning</td>
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<td>IAQ</td>
<td>Indoor Air Quality</td>
</tr>
<tr>
<td>IRA</td>
<td>Integrated Room Automation</td>
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<td>LFC</td>
<td>Load Frequency Control</td>
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<tr>
<td>LP</td>
<td>Linear program</td>
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<tr>
<td>LTI</td>
<td>Linear Time Invariant</td>
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<td>MPC</td>
<td>Model Predictive Control</td>
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<tr>
<td>NMPC</td>
<td>Nominal Model Predictive Control</td>
</tr>
<tr>
<td>OLP</td>
<td>Open-Loop Prediction</td>
</tr>
<tr>
<td>PBP</td>
<td>Pay as Bid Price</td>
</tr>
<tr>
<td>PID</td>
<td>Proportional Integral Derivative</td>
</tr>
<tr>
<td>PLC</td>
<td>Programmable Logic Controller</td>
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<tr>
<td>QP</td>
<td>Quadratic Program</td>
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<tr>
<td>RBC</td>
<td>Rule-Based Control</td>
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<tr>
<td>RHC</td>
<td>Receding Horizon Control</td>
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<tr>
<td>RMPC</td>
<td>Robust Model Predictive Control</td>
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<td>RP</td>
<td>Regulated Price</td>
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<td>SMPC</td>
<td>Stochastic Model Predictive Control</td>
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<td>TABS</td>
<td>Thermally Activated Building System</td>
</tr>
<tr>
<td>TSO</td>
<td>Transmission System Operator</td>
</tr>
<tr>
<td>VAV</td>
<td>Variable Air Volume</td>
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List of Symbols

Throughout the thesis, scalars and vectors are defined with lower case letters \((a, b, ..., \alpha, \beta, ...\))
matrices are denoted with upper case letters \((A, B, ..., A^T, B^T, ...)\), and sets are denoted
with upper case blackboard bold letters \((X, U, ..., N, \mathbb{R})\) for constraints sets and number sets and
with upper case calligraphic letters \((\mathfrak{A}, \mathfrak{B}, ...)\) for general sets.

**General Operators and Relations**

- \(\cdot\) general place-holder
- \(\ldots\) and so forth
- \(:=\) left-hand side is defined by the right-hand side
- \(\mid\) such that
- \(\in\) is element of
- \(\forall\) for all
- \(\exists\) there exists

**Sets, Space, and Set Operators**

\(\{\ldots\}\) set or sequence
\(\mathbb{R}\) real numbers
\(\mathbb{R}^+\) set of non-negative real numbers
\(\mathbb{R}^n\) space of \(n\)-dimensional (column) vectors with real entries
\(\mathbb{R}^{n\times m}\) space of \(n\) by \(m\) matrices with real entries
\(\mathbb{N}\) natural numbers (non-negative integers), \(\mathbb{N}^+ := \mathbb{N} \setminus \{0\}\)
\(\mathbb{N}^k_j\) set of consecutive non-negative integers \(\{j, \cdots, k\}\)
\((\subset)\) \(\subseteq\) (strict) subset
\((\supset)\) \(\supseteq\) (strict) superset

**Operator on Vectors and Matrices**

\([\cdot, \cdot, \ldots]\) a matrix (or a vector)
\(<, \leq, =, \geq, \cdot, \cdot\rangle^T\) element-wise comparison of vectors
\(\|v\|\) (any) vector norm
\(\|v\|_1\) vector 1-norm (sum of absolute values)
\(\|v\|_2\) vector 2-norm (Euclidian norm)
\(\|v\|_\infty\) vector \(\infty\)-norm (largest absolute element)
System and Control Theory

\( n_x \) number of states, \( n_x \in \mathbb{N}_+ \)
\( n_u \) number of inputs, \( n_u \in \mathbb{N}_+ \)
\( n_w \) number of disturbances (used in Chapter 3), \( n_w \in \mathbb{N}_+ \)
\( n_v \) number of disturbances (used from Chapter 4), \( n_v \in \mathbb{N}_+ \)
\( n_y \) number of outputs, \( n_y \in \mathbb{N}_+ \)
\( n_r \) number of reserve variables, \( n_r \in \mathbb{N}_+ \)
\( x \) state, \( x \in \mathbb{N}_{n_x} \)
\( u \) control input, \( u \in \mathbb{N}_{n_u} \)
\( w \) disturbance (used in Chapter 3), \( w \in \mathbb{N}_{n_w} \)
\( v \) disturbance (used from Chapter 4), \( v \in \mathbb{N}_{n_v} \)
\( y \) output, \( y \in \mathbb{N}_{n_y} \)
\( r \) reserve-related disturbance, \( r \in \mathbb{N}_{n_r} \)
\( \mathbf{X} \) set of state vectors, \( \mathbf{X} \in \mathbb{R}^{n_x} \)
\( \mathcal{U} \) set of control inputs, \( \mathcal{U} \in \mathbb{R}^{n_u} \)
\( \mathcal{W} \) set of disturbances (used in Chapter 3), \( \mathcal{W} \in \mathbb{R}^{n_w} \)
\( \mathcal{V} \) set of disturbances (used from Chapter 4), \( \mathcal{V} \in \mathbb{R}^{n_v} \)
\( \mathcal{R} \) set of reserve-related disturbance, \( \mathcal{R} \in \mathbb{R}^{n_r} \)

Probability Theory

\( \mathcal{N}(\mu, \sigma) \) normal distribution with mean \( \mu \) and \( \sigma \)
\( \mathcal{U}[a, b] \) uniform distribution lays in interval \([a, b]\)
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Chapter 1

Introduction

1.1 Background and Project Goal

Nowadays, as a flourishing industry, the power system is integrating multiple renewable generations. However, due to the uncertainties of natural factors, the renewable generations will bring power dispatch to the grid as well. It is a crucial problem to keep the grid run under balance and stable status, as a matter of fact, it is hard and costly to find an effective and fast way to predict such kind of power dispatch. On the other hand, due to the deregulation of the electrical power industry, power generation has been unbundled from transmission. As a result, ancillary service (AS) is raised to support the basic services of power generation, transmission and distribution [3]. Active power reserves are a type of ancillary services used to stabilize the system frequency in the presence of power imbalances due to errors in predictions of generation or demand. Traditionally, active power reserves come from the generation side. However, it is a new trend in the power industry to also exploit the demand side resources, known as demand response (DR) [4]. The idea of demand response is to manage local energy consumption with respect to supply conditions, e.g. peak demand, high market price or regulation signal.

The goal of this thesis (Figure 1.1) is to enable the participation of commercial building aggregations in secondary frequency control and exploit the potential reserve provided to the grid. An hierarchical control algorithm is proposed to enable bidding in AS markets by building aggregators, scheduling of the buildings and real-time reserve provision. The algorithm consists of a day-ahead centralized reserve determination phase, a decentralized MPC-based scheduling phase and a decentralized real-time proportional controller. Furthermore, based on the model developed in PSL, ETH Zürich [5], a benchmark population is constructed to carry out the simulations.

1.2 Reserve Optimization and Demand Response

Operation reserve, or reserve is the capacity that the power system could provide in the case of unforeseen fluctuations on the grid. Once a sudden issue happens, i.e. dispatch fault, the balancing services will in turns provide reserves to the grid instead of power plant output Figure 1.2 to keep the system back to stable state within 20 minutes. A three-stage progress (primary, secondary and tertiary control) will be activated to keep the electrical grid at the constant frequency of 50 Hz, which is determined by the active power balance.
1.3 Power Consumption in Commercial Buildings

Typically, a commercial building usually refers to an office building, warehouses or retail markets. This thesis focuses on the energy consumption optimization of a group of commercial buildings. There are several reasons to choose the heat ventilation air-conditioning system (HVAC system) of a commercial building to be the target. First of all, commercial buildings consume 40% of electricity energy in the year of 2012, comparing with 32% for transportation and 28% for industry (Figure 1.3) [8]. It would be interesting to investigate and make improvements on the largest portion. Second, due to the application characteristics of a commercial building, it needs to be served with HVAC system to guarantee the air supply while
CHAPTER 1. INTRODUCTION

Figure 1.2: The sequence in activation of frequency control reserves after an outage has occurred [6]

keep the indoor temperature within comfort range. In real world, the HVAC system counts up to 50% power consumption of a commercial building [9]. At the same time, the popularized use of the Building Automation System (BAS) helps to make the local control easier to realize. Moreover, it is possible to provide operating reserve by loosening the temperature range or adjusting the operating power. Above all, commercial buildings have large potential to consume the energy in an economical way and being more energy efficiency.

1.4 Project Organization

Part I Part I provides some background knowledge from the relevant literature and studies based on which developed this thesis. Chapter 2 introduces the general idea of the ancillary services and the ancillary service market, especially the economic features and term definitions. Then the current situation in Switzerland is shown. Chapter 3 provides the reader with the basic principle of the Model Predictive Control (MPC). Especially, different types of MPC are defined and formulated for later applications in this thesis. Chapter 4 begins with a brief summary of the OptiControl project which provides state-space models of commercial buildings in Switzerland used in this thesis. Then the definition of the actuators, build type and constraints used for building climate control are introduced.

Part II Part II provides a detailed explanation of the VAV model extension and controller design. Chapter 5 first rebuilds a HVAC model with VAV box in a U.S. building from the literature. Then to apply MPC, the model is linearized and extended by a functional
1.4. PROJECT ORGANIZATION

Figure 1.3: Energy consumption in EU [8][10]

Note: Energy consumption in agriculture, fishing and “other” makes up 3% of final energy consumption, and is not included in the above figure.
Source: DG Energy: EU Energy in Figures 2012

- 32% of all energy in the EU is used for transport
- 25% of all energy in the EU is used by industry
- 40% of all energy in the EU is used by buildings

component. Tests are done to validate these models. Chapter 6 provides the complete progress of designing the target controller of this thesis. First, the detailed definitions and assumptions are listed. Then the concept of hierarchical control is explained with the formulation and derivation of the controller.

Part III Part III contains some investigations on the modified models and the controller. Chapter 7 first defines the validation tests necessary for the modified models. Then defines the controller design parameters and the tests to exploit their characteristics. Chapter 8 shows the results and discussions on the investigations. Then a detailed analysis of the building aggregation reserve provision behavior will be presented. Chapter 9 gives the final conclusion of this thesis.
Part I

Background
Chapter 2

Ancillary Services

2.1 Ancillary Service Market in Switzerland

The definition of Ancillary Services (AS) given by FERC [7] is “those services necessary to support the transmission of electric power from seller to purchaser given the obligations of control areas and transmitting utilities within those control areas to maintain reliable operations of the interconnected transmission system.” The ancillary services provided by Swissgrid include [6]: active power control reserve (primary control, secondary control and tertiary control), voltage support, compensation of active power losses, black start and island operation capability, system coordination, operational measurement.

Figure 2.1: Overview of ancillary service market [11]
In this thesis, we focus on the secondary frequency control which is one of the control reserves (Figure 2.1). The active power control reserve (or frequency power control) aims at rapidly balancing the unforeseen dispatch between the feed-in and feed-out electrical energy in the network. The grid should be kept at 50 Hz frequency so as to guarantee a secure and reliable operation. Furthermore, the flexibility of the generators/loads to alter their outputs/consumptions to respond to major contingencies is defined as generation-side/demand-side operation reserve [13].

2.2 Economic Features [1]

2.2.1 Types of Procurement Methods

Generally, it is the responsibility of the TSO to procure all the ancillary services via four procurement methods: compulsory provision, bilateral contracts, tendering and spot market.

**Definition 2.1. Compulsory provision** According to compulsory provision, a certain class of users is required to provide up to a certain amount of a certain ancillary service upon TSO request. Such requirement is part of the connecting conditions.

**Definition 2.2. Bilateral contracts** A bilateral contract is a reciprocal arrangement between the TSO and providers, where they reach a certain agreements on the quantity, quality...
2.2. ECONOMIC FEATURES [1]

and price of the services to be provided.

**Definition 2.3. Tendering** The tendering is the bidding process that the TSO makes offers among the bids made by the provider.

**Definition 2.4. Spot Market** A spot market is a financial market where standardized products are exchanged, the products are usually of short duration and immediate delivery.

Compulsory provision is considered to be “fair” since the certain users are required to provide same absolute/relative amount of ancillary services. But in reality, a simplified compulsory provision is generally applied due to fairness and transparency. Such simplification would probably cause the dispatch between ancillary services supply and demand so that extra costs are generated. Moreover compulsory provision cannot distinguish potentially low cost providers from more expensive ones since they are treated on the same basis.

Though the bilateral contract avoids the two problems above, it is a private contract thus it lacks transparency when TSO is monopoly. Moreover, due to the high transaction cost of the negotiation processes, the price and quantity of bilateral contracts will last for a long time. Both tendering and spot market have good transparency and fair competition while such procedures would call for specific operating organization and extra data management cost.

### 2.2.2 Types of Remuneration Methods

Ancillary services can be non-remunerated or paid according to the remuneration method: a regulated price (RP), a pay as bid price (PBP), or a common clearing price (CCP).

**Definition 2.5. Regulated price (RP)** A regulated price is the unit price (e.g., €/MW) set by TSO or the regulator and all the providers use the same price.

**Definition 2.6. Pay as bid price (PBP)** All the suppliers receive the prices they bid for in the ancillary service market.

**Definition 2.7. Common clearing price (CCP)** All the successful providers are offered with a price which is either the most expensive accepted price or the least rejected offer.

Generally, RP is not preferred because it cannot reflect the actual cost of providing a given ancillary service. While in a PBP system, there is no incentive for the providers to bid for their marginal cost. Such method is suitable when there is large difference on the quality of provided ancillary services. On the other hand, in a CCP system, providers have incentive to bid for the marginal cost but then it’s hard to differentiate the products.

### 2.2.3 Structure of Remuneration

**Definition 2.8. Fixed allowance** Fixed allowance ($Q_{fix}$ in €) remunerate the providers for providing ancillary services to TSO.

**Definition 2.9. Availability price** Availability price remunerates the providers for promising to provide a certain quantity ($R$ in MW) of an ancillary service.

**Definition 2.10. Utilization payment** Utilization payment remunerates the providers for the actual quantity ($r$ in MW) of an ancillary service provided to TSO.
Definition 2.11. Utilization frequency payment  Utilization frequency payment remunerates the providers for the extra costs occurred from the number of calls \((n_{\text{call}})\) received from TSO over a given time period.

Definition 2.12. Compensation for opportunity cost  Compensation for opportunity cost remunerates the providers for the potential profits \((Q_{\text{opp}})\) they would have made if not providing ancillary services.

Above all, the total remuneration of a provider could be written as:

\[
\text{Total remuneration} = Q_{\text{fix}} + k_1 R + k_2 r + C_{\text{freq}} n_{\text{call}} + Q_{\text{opp}}
\]  

(2.1)

where \(k_1, k_2\) (in \(\text{€/MW}\)) are the unit price for the ancillary services, \(C_{\text{freq}}\) is the average cost generated from response to each request.

Remark 2.1. In this thesis, we set up the problem according to the following table:

<table>
<thead>
<tr>
<th>Feature</th>
<th>Swiss market</th>
</tr>
</thead>
<tbody>
<tr>
<td>Procurement method</td>
<td>Tendering (Appendix B)</td>
</tr>
<tr>
<td>Remuneration method</td>
<td>Pay as bid price</td>
</tr>
<tr>
<td>Structure of remuneration</td>
<td>Availability price, utilization price</td>
</tr>
</tbody>
</table>

Table 2.1: Ancillary service market in Switzerland (secondary control) [14]
Chapter 3

Model Predictive Control [2]

3.1 Model Predictive Control (MPC) Overview

MPC or Receding horizon control (RHC) is an intuitive and advanced method of constrained control and it has been applied to many industrial areas in the past decades. MPC distinguishes the variables into dependent and independent ones. Dependent variables represent control objectives. Those independent variables which could be changed by the controller are set as states while the ones could not be changed are set as disturbances. Different from common PID control, MPC is able to deal with a dynamic system with time delays by predicting change of dependent variables.

A typical model of the discrete-time LTI system with constraints is shown in Eq. 3.1:

\[ x_{t+1} = Ax_t + Bu_t + Ew_t \]
\[ x_t \in \mathcal{X}, u_t \in \mathcal{U}, w_t \in \mathcal{W} \] (3.1)

A measurement of the state \( x_t \) will be taken at an interval of time \( t \). The MPC will predict the system’s behavior over a finite prediction horizon \( N \) according to the measurement and model dynamics. An optimization problem defined by cost function and constraints will be solved then.

For the purpose of distinguishing between measurement and prediction, denote \( x_{t+k|t} \in \mathbb{R}^{n_x} \) as the prediction of the state \( x_{t+k} \in \mathbb{R}^{n_x} \) at time \( t \), where \( t \in \mathbb{R}^N_0 \). Bold letters are used to denote vectors (and matrices) that contain the prediction of a variable along the whole prediction horizon, i.e. \( \mathbf{x}_t := \{ x_{t|t}, x_{t+1|t}, \cdots, x_{t+N|t} \} \) is the prediction of state \( x \) at time \( t \).

By solving the optimization problem, a sequence of optimal control input is available, which minimizes the objective function while satisfying all the dynamics and constraints.

\[ \mathbf{u}_t^* := \{ u_{t|t}^*, u_{t+1|t}^*, \cdots, u_{t+N-1|t}^* \} \] (3.2)

However, only the first term \( u_{t|t}^* \) will be applied to the system in the current time step and another measurement will be taken in the next step. Thus a new optimization problem based on new initial values is raised and has to be solved so on and so forth. The reason of taking only the first time step is to take model errors and/or disturbances into consideration. The complete logic is represented below [2]:
Algorithm 1 Receding horizon control

1: measure the state $x_t$ at time $t$
2: obtain $u_t^*(x_t) := \{u_{t|t}^*, u_{t+1|t}^*, \ldots, u_{t+N-1|t}^*\}$ by solving an optimization problem with horizon $N$
3: apply the first control input $u_{t|t}^*$ to the system
4: proceed to time step $t + 1$
5: go to step 1.

3.2 MPC for Building Climate Control

Now we come to the topic of applying MPC to the commercial buildings to realize inside climate control. The flowchart (Figure. 3.1) below shows how the system works: first, we take a measurement of current building states (e.g., temperature, illumination) to serve as the initial state. Based on the initial state, dynamic model, physical limits (e.g., capacity), design constraints (e.g., comfort range) and predicted disturbance (e.g., internal gains), the MPC schedules a control plan (e.g., heating or cooling) over the prediction horizon. Then the first time step of the control plan is applied to the building and the states will change accordingly. After that, the algorithm moves on to the next time step further to repeat the above procedures until the MPC completes the whole simulation horizon.

![MPC scheme for building climate control](image)

Figure 3.1: MPC scheme for building climate control [2]

The Problem 3.1 below explains the structure of a common finite-horizon optimal control problem:

Problem 3.1. Generic MPC problem
3.2. MPC FOR BUILDING CLIMATE CONTROL

\[ J^*(x_t) = \min_{u_{t|t} \cdots u_{t+N-1|t}} V_f(x_{t+N|t}) + \sum_{k=0}^{N-1} l_k(x_{t+k|t}, u_{t+k|t}) \]

subject to \( (x_{t+k|t}, u_{t+k|t}) \in \mathcal{X} \times \mathcal{U} \)

Terminal constraint
\( x_{t+N|t} \in \mathcal{X}_f \)

Current state
\( x_{t|t} = x_t \)

Dynamics
\( x_{t+k+1|t} = Ax_{t+k|t} + Bu_{t+k|t} \)

Remark 3.1. \( N \) is the prediction horizon, \( k \in \mathbb{N}_0^{N-1} \) is the prediction time step, \( l_k : \mathbb{R}^{n_x} \times \mathbb{R}^{n_u} \rightarrow \mathbb{R}_{+0} \) is the stage cost, and \( V_f : \mathbb{R}^{n_x} \rightarrow \mathbb{R}_{+0} \) is the terminal cost.

Remark 3.2. Cost function The design of cost function is critical to the MPC design cause it reflects the performance target and desired behavior of one optimization problem. Generally, a cost function could be quadratic or linear (Table 3.1). The quadratic cost function provide a trade-off between input and state while the linear cost function is suitable for economically motivated target.

<table>
<thead>
<tr>
<th>Cost function type</th>
<th>Mathematical description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quadratic cost</td>
<td>( l_k(x_{t+k</td>
</tr>
<tr>
<td></td>
<td>( V_f(x_{t+N</td>
</tr>
<tr>
<td>Linear norm cost</td>
<td>( l_k(x_{t+k</td>
</tr>
<tr>
<td></td>
<td>( V_f(x_{t+N</td>
</tr>
</tbody>
</table>

Remark 3.3. Constraints Similar to the cost function, a constraint could be quadratic or linear or in some other forms (Table 3.2), which reflects the physical limits or given criteria of the system.

<table>
<thead>
<tr>
<th>Cost function type</th>
<th>Mathematical description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear constraint</td>
<td>( Ax_{t+k</td>
</tr>
<tr>
<td>Convex quadratic constraint</td>
<td>((x_{t+k</td>
</tr>
<tr>
<td>Chance constraint</td>
<td>( \text{Pr}[Ax_{t+k</td>
</tr>
<tr>
<td>Second order cone constraint</td>
<td>( | Ax_{t+k</td>
</tr>
<tr>
<td>Switched constraint</td>
<td>if condition, then ( A_1 x_{t+k</td>
</tr>
<tr>
<td>Non-linear constraint</td>
<td>( h(x_{t+k</td>
</tr>
</tbody>
</table>

Remark 3.4. Current state An initial state sequence (measurement or estimation) is required to solve the optimization problem while a new measurement will be made in the next time step after applying the optimal input. It could also be the case that the state cannot be measured, then a state estimator (e.g.: a Kalman filter) is introduced to estimate the state sequence.
Remark 3.5. Dynamics  The dynamic of the system (building) is required to reach a certain precision to have a good control behavior. The model used in this thesis is introduced in Chapter 4, 5.

3.3 Nominal MPC

Note that the way to properly model and deal with the disturbance is a key issue. It decides not only the type of the cost function and/or a constraint, but also the formulation of the MPC problem. In this section, typical formulations of a MPC problem are introduced.

Problem 3.2. Nominal MPC

\[
J^*_n(x_t) = \min_{u_{t|t}, \ldots, u_{t+N-1|t}} V_f(x_{t+N|t}) + \sum_{k=0}^{N-1} l_k(x_{t+k|t}, u_{t+k|t})
\]

subject to

\[
x_{t+k|t} \in \mathcal{X}, u_{t+k|t} \in \mathcal{U} \\
x_{t+N|t} \in \mathcal{X}_N \\
x_{t+k+1|t} = Ax_{t+k|t} + Bu_{t+k|t} \quad x_{t|t} = x_t
\]

3.4 Robust MPC

In the previous section, we only considered the nominal MPC which neglected the disturbance or uncertainty. However, simply ignoring the disturbance could be acceptable only with small uncertainties, when dealing with large uncertainties a proper treatment is expected to have a better performance.

In Robust MPC, the assumption has been made that the disturbance is bounded and lies in a known uncertainty set, \( w_t \in \mathcal{W} \subset \mathbb{R}^n \) and tightening constraints are applied to fulfill all the criteria throughout the whole horizon. Commonly, three kinds of cost functions are implemented: the nominal cost (Problem 3.2), the min-max cost and expected value cost. Theoretically, applying the min-max cost would be the most robust among the three since it makes sure that even the worst case could satisfy all the criteria. But at the same time, the optimization problem with min-max cost would have a smaller feasible set or even be infeasible. By contrast, the optimization problem with expected value cost could provide more practical solutions. The formulation of an open-loop robust MPC is shown below:

Problem 3.3. Open-loop min-max MPC

\[
J^*_o(x_t) = \min_{u_{t|t}, \ldots, u_{t+N-1|t}, w_{t|t}, \ldots, w_{t+N-1|t}} \max_{w_{t+k|t}} V_f(x_{t+N|t}) + \sum_{k=0}^{N-1} l_k(x_{t+k|t}, u_{t+k|t})
\]

subject to

\[
x_{t+k|t} \in \mathcal{X}, u_{t+k|t} \in \mathcal{U} \\
x_{t+N|t} \in \mathcal{X}_N \\
x_{t+k+1|t} = Ax_{t+k|t} + Bu_{t+k|t} + Ew_{t+k|t} \\
w_{t+k|t} \in \mathcal{W} \\
x_{t|t} = x_t \\
\forall k \in \mathbb{N}_0^{N-1}
\]
Chapter 4

IRA Model

4.1 Overview

This chapter aims at providing necessary knowledge of the building models developed by IFA, ETH Zürich to the reader. These models have been developed during the OptiControl project which is focusing on the Integrated Room Automation (IRA) (Figure 4.1). In the two years progress report, IRA is defined as “Relevant building types, types of heating, cooling, ventilation, blind and lighting subsystems, control operation types, and representative building locations were identified, the subsystems were sized properly, and meaningful energy usages/costs were specified. The hierarchical architecture of modern Building Automation and Control systems was considered from begin on in order to ensure that the solutions developed could be easily integrated therein later on. [5]” In brief, IRA is to control the system to keep it within the designed comfort range while using the possible minimal cost.

Figure 4.1: Example for an IRA technical set up [5]

To control the HVAC system of a commercial building including heating, cooling, ventilation, blinds, and lighting, one need to model the thermal behavior of the building, which could be done by deriving the thermal dynamic equation based on physical specifications. In IRA, the individual zones are considered as the control targets and for the purpose of defining
boundary conditions, the following assumption has been made:

**Assumption 4.1.** In this study, it is assumed that the neighbor zones are identical to the modeled zones.

However, there is a trade-off between the accuracy and complexity, choices are made based on following requirements: (1) The model should be detailed enough to truly reflect the building dynamics and control mechanism. (2) The model should be simple enough for MPC implementation. (3) The model should also be capable of doing large-scale simulation studies.

As the result, a lumped-parameter model is chosen to model the control target. In the model, nodes are assumed in the walls, floors and ceiling to describe the respective temperatures. Then the heat transfer rate between node $\vartheta_i$ and node $\vartheta_e$ could be written as [2]:

$$
\frac{dQ}{d\vartheta_i} \cdot \frac{d\vartheta_i}{dt} = A \cdot \frac{U_{\text{net}}}{1/R_{\text{net}}} (\vartheta_e - \vartheta_i)
$$
4.2 HVAC SYSTEMS [2]

Remark 4.1. $t$ is time, $Q$ is thermal energy, $C_i$ is the thermal capacitance of layer $i$, $A$ is the cross-sectional area, $U_{ie}$ the heat transmission coefficient, and $R_{ie}$ is the resistance between node $i$ and $e$.

In Figure 4.2 is a thermal RC network model to illustrate the actuator influences. Then to be adapted with MPC, the corresponding physical installation should be done in the simulation model. Recall that in a state-space model, variables are classified into states, control inputs and outputs. In Figure 4.2, control inputs are high-lighted in blue, disturbances are high-lighted in green and the constants are in black.

Assumption 4.2. In this study, it is assumed that the users cannot change the actuator settings directly Instead, all the control behavior is done via control system interface.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure4.3}
\caption{Overview and abbreviations of subsystems considered for modeling [5]}
\end{figure}

4.2 HVAC Systems [2]

Figure 4.3 lists all the actuators (subsystems) of a building zone or room, e.g.: heating, ventilation, air-conditioning, blind positioning and electrical lighting. With different combination of those actuators (subsystems), five HVAC systems\footnote{only the ones related in this thesis are introduced in detail} are considered in the simulation (Table 4.1).

Artificial lighting (eLighting) or electric lighting mainly affects the room illuminance. However, it provides some heat gains at the same time. The illuminance is linear to the electrical consumption of the lighting with the coefficient $\beta = 70 \text{lm/W}$. Radiator heating (hPowRad) is a direct power input into the node. The distribution system is not included. TABS refers to a HVAC model with Thermally Activated Building System (TABS), which is
commonly applied to a commercial building in Europe. The system as well as the building mass serve as a thermal energy storage and it is composed of the tube system inside the slabs. Once a slab is activated by the storage, heating or cooling could be done by pumping the heated or cooled medium through the slabs. The idea of using this kind of model is to cooling or heating the building in an economical way while increasing the efficiency of energy use.

Table 4.1: Five HVAC systems and their automated subsystems [2]

<table>
<thead>
<tr>
<th>Automated subsystems</th>
<th>S1</th>
<th>S5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical lighting</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Radiator heating</td>
<td>✓</td>
<td>-</td>
</tr>
<tr>
<td>Thermally activated building systems for heating/cooling</td>
<td>-</td>
<td>✓</td>
</tr>
</tbody>
</table>

4.2.1 Building Type

According to the OptiControl definition, a building could be classified into a certain type via the following 5 parameters:

- building standard ∈ {swiss average(sa), passive house(pa)}
- construction type ∈ {heavy(h), light(l)}
- window area fraction ∈ {high(wh), low(wl)}
- facade orientation ∈ {North(N), South(S), South+East(SE), South +West(SW)}
- internal gains level ∈ {high(ih), low(il)}

Remark 4.2. In the OptiControl project, the building type is at first classified by the first 4 parameters (physical factors), but after introducing the disturbance into the system (Section 4.2.3), the internal gains level is used to differentiate the building population from customer usage point of view.

![Figure 4.4: Room temperature comfort range](image)
4.2.2 Comfort Range and Setbacks

In the study, a comfort range has been designed with a minimum and a maximum temperature. Meanwhile, the comfort range is loosen during non-working hours (Figure 4.4).

4.2.3 Disturbance

Weather There are three weather variables considered in this study: air temperature ($T_{\text{air}}$, $T_{\text{fresh}}$), web bulb temperature ($T_{\text{freeCool}}$), and solar radiation (to compute $sG_{\text{sol}}$, $dG_{\text{sol}}$, $l_{\text{illum}}$ and $d_{\text{illum}}$). The historical data is provided from MeteoSwiss as well as the measurements of the year 2007.

Assumption 4.3. Perfect prediction In this study, it is assumed that a perfect disturbance prediction is available.

Internal gains The internal gains are defined as the heat gains generated from people occupancy or equipments (e.g.: printers). The values of internal gains are regular and closely related to the working-hour. During working hour, the internal gains are much higher then that of the non-working hour.
Part II

Model Development and Controller Design
Chapter 5

Modeling

5.1 IRA Building Aggregation

Since the thesis is to focus on an aggregation of buildings, we need to decide the proportion of each kind of building in the population. Generally, the main idea of choosing buildings in the population are: (1) It should be a combination that reflects the real situation in Switzerland. Each building could be served as a general sample of a Swiss building. (2) The combination could show the potential of providing the ancillary services. However, in this thesis, only the HVAC system S1 and S5 are chosen to be our targets to include both buildings with fast heat dynamics (radiator) and slower dynamics (TABS).

5.2 HVAC with VAV Boxes

A HVAC system different from that of IRA building is used in United States. The components of the HVAC system in a typical American commercial building are: air handling unit (AHU), supply fan and variable air volume (VAV) boxes. As shown in Figure 5.1, an air handling unit is a device that is in charge of conditioning and circulating air. Fresh air is taken from outside by a ventilator and mixed with return air. The mixture ratio is controlled by a damper. Then the mixed air is filtered and goes through heating or cooling elements to be adjusted to the proper temperature (depends on the set-point temperature, usually 13°C). The supply fan will send the mixed air into the supply duct and then into each zone accordingly. The VAV boxes at the entrance of each zone will change the damper position to decide the air flow rate and sometimes reheat the air according to the set point temperature. The thermal model of a commercial building has been developed and validated by Hao [9], on which our study is based.

5.2.1 Hao’s Model

This model is developed based on the following first principles thermal model of a commercial building

\[ C \frac{dT}{dt} = - \frac{1}{R_w} (T - T_{oa}) + c_p \dot{m} (T_{la} - T) + Q_x, \]  

where the three terms on the RHS represent:

(1) the heat loss due to heat conduction through walls
Figure 5.1: The HVAC system of a four-zone building [9]

(2) the heat gain from the air conditioner
(3) the heat gain from reheating solar occupants, lights, etc.

The variables and parameters are described in Table 5.1:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Nominal Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T$</td>
<td>building inside temperature</td>
<td>22.4</td>
<td>°C</td>
</tr>
<tr>
<td>$C$</td>
<td>thermal capacitance of building</td>
<td>$7 \times 10^5$</td>
<td>J/°C</td>
</tr>
<tr>
<td>$R_w$</td>
<td>wall thermal resistance of building</td>
<td>$5 \times 10^{-3}$</td>
<td>°C/W</td>
</tr>
<tr>
<td>$T_{oa}$</td>
<td>outside air temperature</td>
<td>N/A</td>
<td>°C</td>
</tr>
<tr>
<td>$T_{la}$</td>
<td>leaving air temperature</td>
<td>13</td>
<td>°C</td>
</tr>
<tr>
<td>$c_p$</td>
<td>specific heat of air</td>
<td>1006</td>
<td>J/kg/°C</td>
</tr>
<tr>
<td>$\dot{m}$</td>
<td>supply air flow rate</td>
<td>6.27</td>
<td>kg/s</td>
</tr>
<tr>
<td>$Q_x$</td>
<td>heat gain from reheating, solar, etc</td>
<td>N/A</td>
<td>W</td>
</tr>
</tbody>
</table>

Moreover, to model the power consumption of the building, several assumptions have been made:

**Assumption 5.1.** The linear relation between air flow rate and fan speed:

$$\dot{m}(t) = c_1 V^{fan}(t),$$

**Assumption 5.2.** The transfer function from the control command to the fan speed is of first-order:
5.2. HVAC WITH VAV BOXES

\[ \tau \frac{dV_{fan}(t)}{dt} + V_{fan}(t) = u_{fan}(t), \quad (5.3) \]

**Assumption 5.3.** The cubic relation between fan speed and power consumption:

\[ P_{fan} = c_2(V_{fan}(t))^3, \quad (5.4) \]

**Assumption 5.4.** When outside air temperature and heat gain remain constant, there exists a steady-state for the system dynamic:

\[ 0 = -\frac{1}{R_w}(T^* - T_{oa}) + c_p\tilde{m}(T_{la} - T^*) + Q_x, \quad (5.5) \]

**Assumption 5.5.** Perturbation profiles are considered when representing the variables, where \( \tilde{T}, \tilde{\dot{m}}, \tilde{P}_{fan}, \tilde{V}_{fan} \) are the deviations from their nominal values \( T^*, \dot{m}^*, P_{fan}^*, V_{fan}^* \):

\[
\begin{align*}
T &= T^* + \tilde{T}, \\
\dot{m} &= \dot{m}^* + \tilde{\dot{m}}, \\
P_{fan} &= P_{fan}^* + \tilde{P}_{fan}, \\
V_{fan} &= V_{fan}^* + \tilde{V}_{fan}
\end{align*}
\]

(5.6)

Combining Eq. 5.1, Eq. 5.5 and 5.6, we can have:

\[ C \frac{dT}{dt} = -\frac{1}{R_w}(T^* + \tilde{T} - T_{oa}) + c_p(\dot{m}^* + \tilde{\dot{m}})(T_{la} - T^* - \tilde{T}) + Q_x \\
= -\frac{1 + c_p R_w \dot{m}^*}{R_w} \tilde{T} + c_p \dot{m}^*(T_{la} - T^*) - c_p \dot{m}\tilde{T} \quad \text{kept} \\
\]

(5.7)

\[ \frac{d\tilde{T}}{dt} = \frac{dT}{dt} = -\frac{1 + c_p R_w \dot{m}^*}{CR_w} \tilde{T} + \frac{c_p}{C}(T_{la} - T^*) \tilde{\dot{m}} \quad \text{eliminated} \]

(5.8)

Combining Eq. 5.2, Eq. 5.3 and Eq. 5.6, we can have:

\[ \tau \frac{d\dot{m}}{dt} = -\dot{m} + c_1 u_{fan} \]

\[ = -(\dot{m}^* + \tilde{\dot{m}}) + c_1(u_{fan}^* + \tilde{u}_{fan}) \quad (5.9) \]

Because \( u_{fan}^* = V_{fan}^* \), Eq. 5.9 is equal to:

\[ \frac{d\tilde{\dot{m}}}{dt} = -\tilde{\dot{m}} + c_1 \tilde{u}_{fan} \]

\[ \frac{d\dot{m}}{dt} = \frac{d\dot{m}}{dt} = -\frac{1}{\tau} \tilde{m} + \frac{c_1}{\tau} \tilde{u}_{fan} \quad (5.10) \]

Combining Eq. 5.3, Eq. 5.4 and Eq. 5.6, we can have:

\[ \frac{dP_{fan}}{dt} = 3c_2(V_{fan})^2 \cdot \frac{dV_{fan}}{dt} \]

\[ = 3c_2(V_{fan})^2 \cdot \frac{1}{\tau}(u_{fan} - V_{fan}) \]

\[ = 3c_2(V_{fan}^* + \tilde{V}_{fan})^2 \cdot \frac{1}{\tau}(u_{fan}^* + \tilde{u}_{fan} - V_{fan}^* - \tilde{V}_{fan}) \quad (5.11) \]
Because $u_{fan}^* = V_{fan}^*$, Eq. 5.11 is equal to

$$\frac{dP_{fan}}{dt} = 3c_2(V_{fan}^* + \tilde{V}_{fan})^2 \cdot \frac{1}{\tau}(\tilde{u}_{fan} - \tilde{V}_{fan})$$

$$= -\frac{3}{\tau}\tilde{P}_{fan} + \frac{3c_2(V_{fan}^*)^2}{\tau}\tilde{u}_{fan} + \frac{3c_2}{\tau}[\tilde{u}_{fan} \cdot (\tilde{V}_{fan})^2 + \tilde{u}_{fan} \cdot 2V_{fan}^* \cdot \tilde{V}_{fan}$$

eliminated

$$-\tilde{V}_{fan} \cdot (V_{fan}^*)^2 - 2V_{fan}^* \cdot (\tilde{V}_{fan})^2]$$

eliminated

$$\frac{d\tilde{P}_{fan}}{dt} = \frac{dP_{fan}}{dt} = -\frac{3}{\tau}\tilde{P}_{fan} + \frac{3c_2(V_{fan}^*)^2}{\tau}\tilde{u}_{fan}$$

(5.12)

(5.13)

Remark 5.1. Note that in Eq. 5.7, 5.12, there are several terms being eliminated. This is to avoid bi-linear/higher-order terms so as to linearize the system. The values of these terms are quite small so that the system could be linearly approached.

After combining the above equations (Eq.5.8, 5.10, 5.13), the model is linearized into the state-space form:

Formulation 5.1. Hao’s model (HM)

$$\dot{x} = Ax + Bu, y = Cx,$$

(5.14)

where the state, input and output are defined as:

$$x := [\tilde{T}, \tilde{m}, \tilde{P}_{fan}]^T, u := \tilde{u}_{fan}, y := \tilde{P}_{fan},$$

(5.15)

and the state matrix, input matrix and output matrix are:

$$A = \begin{bmatrix}
-1 + c_1 \frac{R_w}{C R_{m\infty}} & c_2 (T_{in} - T^*) & 0 \\
c_2 (T_{in} - T^*) & -1 & 0 \\
0 & 0 & -\frac{3}{\tau}
\end{bmatrix},$$

$$B = \begin{bmatrix}
0 \\
0 \\
\frac{c_2}{\tau} (V_{fan}^*)^2
\end{bmatrix},$$

$$C = [0, 0, 1].$$

The other parameters’ value are shown in Table 5.2:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c_1$</td>
<td>constant</td>
<td>0.0964</td>
<td>kg/s</td>
</tr>
<tr>
<td>$c_2$</td>
<td>constant</td>
<td>$3.3 \times 10^{-5}$</td>
<td>kW</td>
</tr>
<tr>
<td>$\tau$</td>
<td>time constant</td>
<td>0.1</td>
<td>s</td>
</tr>
<tr>
<td>$Q_o$</td>
<td>other heat gain</td>
<td>$2.3 \times 10^4$</td>
<td>W</td>
</tr>
</tbody>
</table>
5.2. HVAC WITH VAV BOXES

5.2.2 Model with Disturbances

One of the characteristics of Hao’s model is that the outside temperature and heat gain of the building are assumed to be constant all the time, which is not so realistic. Though these two variables are time-varying, the changing rate is so slow that a possible solution was proposed in his paper, that is, to repeat the linearization process every few minutes. However, to merge the dynamic model with the IRA models we have so far, we decided to derive from Eq. 5.1 again and consider these two variables as disturbance variables.

First of all, let’s take the derivative of Eq. 5.1,

\[
C \frac{dT}{dt} = -\frac{1}{R_w} (T - T_{oa}) + c_p \dot{m}(T_{la} - T) + Q_x
\]

\[
= -\frac{1}{R_w} \dot{m}^* \tilde{T} + c_p \tilde{m}(T_{la} - T^*) + \frac{1}{R_w} (T_{oa} - T^*) + Q_x
\]

\[
+ c_p \tilde{m}^*(T_{la} - T^*) - c_p \tilde{m} \tilde{T}
\]

\[(5.16)\]

\[
\frac{d \tilde{T}}{dt} = \frac{dT}{dt} = -\frac{1}{CR_w} \tilde{T} + \frac{c_p}{C} (T_{la} - T^*) \tilde{m} + \frac{1}{CR_w} T_{oa} + \frac{1}{C} Q_x
\]

\[
- \frac{1}{CR_w} \tilde{m}^* \tilde{T} + \frac{c_p \tilde{m}^*}{C} T_{la}
\]

\[(5.17)\]

Similar as before, combine Eq. 5.2 and Eq. 5.3 and take the derivative of Eq. 5.4 we can get

\[
\frac{d \tilde{m}}{dt} = \frac{d \dot{m}}{dt} = -\frac{1}{\tau} \dot{m} + \frac{c_1}{\tau} \tilde{u}_{fan}
\]

\[(5.18)\]

\[
\frac{d \tilde{P}_{fan}}{dt} = \frac{d P_{fan}}{dt} = -\frac{3}{\tau} \tilde{P}_{fan} + \frac{3c_2 (V_{fan}^*)^2}{\tau} \tilde{u}_{fan}
\]

\[(5.19)\]

In detail, the outside temperature \(T_{oa}\) and heat gain \(Q_x\) has been considered as disturbance variables. To keep the same form of the internal gains in the IRA models, the heat gains are separated into 2 parts as well, that is, the internal gains caused by equipments \(Q_{equip}\) and by person \(Q_{pers}\). The data are gained from historical data. After combining the above equations (5.16 - 5.19), the model could be linearized into the state-space form:

**Formulation 5.2. Model with disturbances (HMD)**

\[
\dot{x} = Ax + Bu + B_v v, \quad y = Cx,
\]

\[(5.20)\]

where the state, input and output are defined as:

\[
x := [\tilde{T}, \tilde{m}, \tilde{P}_{fan}]^T, \quad u := \tilde{u}_{fan},
\]

\[(5.21)\]

\[
v := [T_{oa}, Q_{pers}, Q_{equip}, T^*, T_{la}]^T, \quad y := [\tilde{T}, \tilde{P}_{fan}]^T.
\]

and the state matrix, input matrix and output matrix are:
CHAPTER 5. MODELING

\[
A = \begin{bmatrix}
-\frac{1+c_p R_w \dot{m}^*}{C R_w} & \frac{c_p (T_{in}-T^*)}{C} & 0 \\
0 & -\frac{1}{\tau} & 0 \\
0 & 0 & -\frac{3}{\tau}
\end{bmatrix},
B_u = \begin{bmatrix}
0 \\
\frac{q_T}{\tau}
\end{bmatrix},
B_v = \begin{bmatrix}
\frac{1}{C R_w} & \frac{1}{C} & \frac{1}{C} & -\frac{1+c_p R_w \dot{m}^*}{C R_w} & \frac{c_p \dot{m}^*}{C}
\end{bmatrix},
C = \begin{bmatrix}
1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0
\end{bmatrix}.
\]

Remark 5.2. Note that there are two constant terms in Eq. 5.17, to keep them in the system dynamics, two columns of constant disturbances are used (Eq. 5.21).

5.2.3 Model with Chiller

Figure 5.2 shows a simple bilinear model of an AHU for MPC done by IFA, ETHZ [15]. Each individual part was modeled based on the heat-flux balance $\vartheta$. $\vartheta_{\text{return}} = \sum_{i=1}^{R} w_{i} \vartheta_{\text{room},i}$ with $\sum_{r=1}^{R} w_{i} = 1$ is the weighted sum of the individual room temperatures.

\[\dot{m} = u_{\dot{m},s}\]
\[n M_{\min} \leq u_{\dot{m},s} \leq n M_{\max}\]
\[\text{Costs}_{\dot{m}} = K_1 u_{\dot{m},s}\]
\[\dot{q}_{\dot{m}} = (K_1 + C_r \vartheta_{\text{outside}}) u_{\dot{m},s} - C_r \vartheta_{\text{return}} u_{\dot{m},s} \quad (5.22)\]

With $\dot{m}$ being the supply air massflow and $u_{\dot{m},s}$ the aggregated air massflow out of the rooms, $n M_{\min}$ and $n M_{\max}$ the minimum required and maximum deliverable air mass flow and $K_1$ being used in linearly approximate the power per unit air mass needed by the ventilation. $C_r \vartheta_{\text{return}} u_{\dot{m},s}$ is the heat flux of the air flow leaving the rooms.

One advantage of this model is that the supply air temperature is treated as a control input while one disadvantage is that the model linearly approximate the power per unit air mass needed by the ventilation (which would make more sense when of higher order). However, in Hao’s model, the power consumption is already assumed to be proportional to the cubic of air mass flow, thus we decided to keep this feature and apply the supply air temperature as one more control input.
Referring to the thermal model of a heating system based on heat pump [17], the chiller model could be represented in a similar way.

\[
C_{\text{chiller}} \frac{dT_s}{dt} = \dot{m} c_p (T_r - T_s) + \dot{Q}_{th}
\]
\[
= (\dot{m} + \tilde{\dot{m}}) c_p (T_r^* + \tilde{T}_r - T_s^* - \tilde{T}_s) + P_{th}
\]
\[
= \tilde{\dot{m}} c_p (\tilde{T}_r - \tilde{T}_s) + P_{th} + \dot{m} c_p (T_r^* - T_s^*) + \tilde{\dot{m}} c_p (T_r^* - T_s^*)
\]
\[
\text{kept} + \tilde{\dot{m}} c_p (\tilde{T}_r - \tilde{T}_s)
\]
\[
\text{eliminated}
\]
\[
= \dot{m} c_p (T_r^* - T_s^*)
\]
\[
(5.23)
\]

**Remark 5.3.** In reality, the elimination of the boxed term physically means that the mass flow rate during the cooling procedure keeps in a constant speed.

**Remark 5.4.** The thermal power provided by the chiller is not equal to the electrical power used by the chiller. To get the value of it, the idea of Coefficient of Performance (COP) has to be introduced.

**COP** The COP is defined as the ratio of cooling capacity provided over the electrical power consumed. It is a measure of the power cycling efficiency of a heat pump or a chiller.

\[
\text{COP} = \frac{\text{Cooling power}}{\text{Input power}} = \frac{P_{th}}{P_{ele}}
\]
\[
(5.24)
\]
Then the Eq. 5.23 could be rewrite as:

\[
\frac{dT_s}{dt} = \frac{dT_s}{dt} = \frac{\dot{m}^* c_p}{C_{\text{chiller}}} (\tilde{T}_s - \tilde{T}_s) + \frac{1000 \cdot \text{COP}}{C_{\text{chiller}}} \cdot P_{\text{ele}} + \frac{\dot{m}^* c_p}{C_{\text{chiller}}} (T_r^* - T_s^*) \tag{5.25}
\]

**Remark 5.5.** The coefficient 1000 is generated from transferring unit from kW to W.

**Assumption 5.6.** The parameter \( C_{\text{chiller}} \) represents the thermal capacity of the media (air) in the building under the supply temperature \( T_s \). This parameter is related to several factors such as the thermal capacity of air, the capacity (size) of the chiller, the chiller specification and so on. And here we chose the value, \( 3.5 \times 10^4 J/K \), which is the \( 1/20 \) of the building thermal capacitance used in Hao’s model (which is named \( C_{\text{Bd}} \) from now on).

Moreover, adding supply temperature as a state variable will also change the related terms in Eq. 5.17. Let \( T_s = T_s^* + \tilde{T}_s \) and \( T_s^* = T_{oa} \), then

\[
\frac{dT_r}{dt} = \frac{dT_r}{dt} = -\frac{1}{R_w} (T_r^* + \tilde{T}_r - T_{oa}) + c_p (\tilde{m}^* + \tilde{\dot{m}})(T_s^* + \tilde{T}_s - T_r^* - \tilde{T}_r) + Q_x
\]
\[
= -\frac{1 + c_p R_w \tilde{m}^*}{R_w} \tilde{T}_r + c_p \tilde{\dot{m}} (T_s^* - T^*) + \left[\frac{c_p \tilde{m}^* \tilde{\dot{m}}}{C_{\text{Bd}}} + \frac{1}{R_w} T_{oa} + Q_x\right] - \frac{1 + c_p R_w \tilde{m}^*}{R_w} T^* + c_p \tilde{\dot{m}} T_s^* + \text{eliminated}
\]

\[
\frac{d\tilde{T}_s}{dt} = \frac{d\tilde{T}_s}{dt} = -\frac{1}{C_{\text{Bd}} R_w} C_{\text{Bd}} \frac{\dot{m}^*}{R_w} \tilde{T}_r + \frac{c_p}{C_{\text{Bd}}} (T_s^* - T^*) \tilde{\dot{m}} + \frac{c_p \tilde{m}^*}{C_{\text{Bd}}} \tilde{T}_s
\]
\[
+ \frac{1}{C_{\text{Bd}} R_w} T_{oa} + \frac{1}{C_{\text{Bd}}} Q_x - \frac{1 + c_p R_w \tilde{m}^*}{C_{\text{Bd}} R_w} T^* + \frac{c_p \tilde{m}^*}{C_{\text{Bd}}} T_s^* \tag{5.26}
\]

Above all, two parts has been added into the model: (1) the disturbance (2) the chiller. And the whole model become

**Formulation 5.3. Model with disturbances and chiller (HMDC)**

\[
\dot{x} = Ax + Bu + Bv, \quad y = Cx + Du + Dv,
\]

where the state, input and output are defined as:

\[
x := [\tilde{T}_r, \tilde{\dot{m}}, \tilde{\dot{\dot{m}}}, \tilde{T}_s]^T, \quad u := [\tilde{u}_{\text{fan}}, \tilde{P}_{\text{ele}}]^T, \quad v := [T_{oa}, Q_{\text{pers}}, Q_{\text{equip}}, T^*, T_{la}]^T, \quad y := [\tilde{T}_r, \tilde{P}_{\text{fan}}, \tilde{T}_s, \tilde{P}_{\text{ele}}]^T.
\]

and the state matrix, input matrix and output matrix are:
\[ A = \begin{bmatrix} \frac{1+c_p R_w \dot{m}^*}{C_Bd R_w} & \frac{c_p T_{la}}{C_Bd} & 0 & 0 & \frac{c_p \dot{m}^*}{C_Bd} \\ 0 & -\frac{1}{\tau} & 0 & 0 & 0 \\ 0 & 0 & -\frac{3}{\tau} & 0 & -\frac{c_p \dot{m}^*}{C_{chiller}} \\ \frac{c_p \dot{m}^*}{C_{chiller}} & \frac{c_p T_{la} - T^*}{C_{chiller}} & 0 & 0 & 0 \\ 0 & 0 & 0 & -\frac{1000 \cdot \text{COP}}{C_{chiller}} & 0 \end{bmatrix}, \]

\[ B_u = \begin{bmatrix} 0 \\ 0 \\ \frac{c_1}{\tau} \\ 0 \\ 0 \end{bmatrix}, \]

\[ B_v = \begin{bmatrix} 1 \frac{1+c_p R_w \dot{m}^*}{C_Bd R_w} & \frac{1}{C_Bd} & \frac{1}{C_Bd} & -\frac{1+c_p R_w \dot{m}^*}{C_Bd R_w} & \frac{c_p \dot{m}^*}{C_Bd} \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ \frac{c_1}{\tau} & \frac{3 c_2 (V^{fan*})^2}{\tau} & 0 & 0 & 0 \end{bmatrix}, \]

\[ C = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \end{bmatrix}, \quad D_u = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}, \quad D_v = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}. \]

The other variables’ value are shown in Table 5.3:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Nominal value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T_s )</td>
<td>supply air temperature</td>
<td>13</td>
<td>°C</td>
</tr>
<tr>
<td>( P_{th} )</td>
<td>thermal power</td>
<td>59.2</td>
<td>kW</td>
</tr>
<tr>
<td>( P_{ele} )</td>
<td>chiller power</td>
<td>14.8</td>
<td>kW</td>
</tr>
<tr>
<td>( \text{COP} )</td>
<td>coefficient of performance</td>
<td>4.0</td>
<td>/</td>
</tr>
</tbody>
</table>

**Assumption 5.7. Nominal value of chiller power**  Eq.5.23 represents the heating transfer function of the chiller. The nominal value of the chiller power is defined such that with all the ventilation variables (e.g.: mass flow) being corresponding nominal values, the chiller running at nominal power could keep a constant supply temperature of 13°C.

\[
0 = \dot{m}^* c_p (T_r^* - T_s^*) - 1000 \cdot \text{COP} \cdot P_{ele}^* \\
P_{ele}^* = \frac{1}{1000 \cdot \text{COP}} \cdot \dot{m}^* c_p (T_r^* - T_s^*) 
\]

(5.29)

### 5.2.4 Benchmark and Population

**Discretization [18]** Note that the dynamic mode in state-space form is a continuous one while the model required by MPC is a discrete one. Thus before apply the MPC algorithm, the first thing to do with the model is to transfer the model into a discrete one. In the MPC application, the state and input of the system are observed and changed in a designed time step (e.g.: 1 hour, 15 min). Thus the continuous model we got from previous sections should
be discretized over a proper sample period to correctly reflect the model dynamics of the
certain time step.

Given a linear time invariant (LTI) continuous-time state-space model:
\[
\dot{x} = A^c x + B^c u \\
y = C^c x + D^c u
\] (5.30)
where \( x \in \mathbb{R}^n \), \( u \in \mathbb{R}^m \), \( y \in \mathbb{R}^p \) are state vector, input vector and output vector, \( A^c \in \mathbb{R}^{n \times n} \),
\( B^c \in \mathbb{R}^{n \times m} \), \( C^c \in \mathbb{R}^{p \times n} \), \( D^c \in \mathbb{R}^{p \times m} \) are system matrix, input matrix, output matrix and
throughput matrix.

Rewrite the system into ODE form
\[
\dot{x}(t) = A^c x(t) + B^c u(t)
\]
with initial condition \( x_0 := x(t_0) \), then the solution would be:
\[
x(t) = e^{A^c(t-t_0)}x_0 + \int_{t_0}^{t} e^{A^c(t-\tau)}B^c u(\tau) d\tau
\] (5.31)
where \( e^{A^c t} := \sum_{n=0}^{\infty} \frac{(A^c t)^n}{n!} \).

Then choose \( t_0 = t_k, t = t_{k+1} \),
and apply
\[
t_{k+1} - t_k = T_s, u(t) = u_{t_k} \quad \forall t \in [t_k, t_{k+1})
\]
\[
x(t_{k+1}) = e^{A^c(T_s)}x(t_k) + \int_{t_k}^{t_{k+1}} e^{A^c(t_{k+1}-\tau)}B^c u(t_k) d\tau
\]
\[
= e^{A^c(T_s)}x(t_k) + \int_{0}^{T_s} e^{A^c(T_s-\tau)}B^c u(t_k) d\tau
\]
\[
= A x(t_k) + B u(t_k)
\] (5.32)

Practically, discretization is done by applying the continuous-to-discrete function provided
by MATLAB toolbox. Besides, the further application is either with 1-hour time step or 15-
minute time step thus we chose the sample time to be 1 hour or 15 minutes when doing the
discretization.

Constraints and disturbances All the automation actuators in model HMDC and their
physical constraints are defined here.

**Definition 5.1. State vector** \( x_k := [x_{k,1}, x_{k,2}, x_{k,3}, x_{k,4}]^T \):
\[
x_{k,1} = \text{room temperature [°C]} \quad \text{if occupied, } 21 \leq x_{k,1} \leq 26 \quad \text{else } 5 \leq x_{k,1} \leq 40
\]
\[
x_{k,2} = \text{mass flow rate [kg/s]} \quad 0 \leq x_{k,2} \leq 100
\]
\[
x_{k,3} = \text{supply fan power [kW]} \quad 0 \leq x_{k,3} \leq 33
\]
\[
x_{k,4} = \text{supply air temperature [°C]} \quad 10 \leq x_{k,4} \leq 22.4
\]
5.2. HVAC WITH VAV BOXES

Definition 5.2. Input control vector $u_k := [u_{k,1}, u_{k,2}]^T$:

$u_{k,1} =$ fan control command [%] \hspace{1cm} 0 \leq u_{k,1} \leq 100
$u_{k,2} =$ chiller power [kW] \hspace{1cm} 0 \leq u_{k,2} \leq 50

Definition 5.3. Disturbance vector $v_k := [v_{k,1}, v_{k,2}, v_{k,3}]^T$:

$v_{k,1} =$ outdoor temperature [°C]
$v_{k,2} =$ internal gain (equipment) [W]
$v_{k,3} =$ internal gain (person) [W]

Definition 5.4. Output vector $y_k := [y_{k,1}, y_{k,2}, y_{k,3}, y_{k,4}]^T$:

$y_{k,1} =$ room temperature [°C] \hspace{1cm} \text{if occupied, } 21 \leq y_{k,1} \leq 26 \hspace{1cm} \text{else } 5 \leq y_{k,1} \leq 40
$y_{k,2} =$ supply fan power [kW] \hspace{1cm} \text{0} \leq y_{k,2} \leq 33
$y_{k,3} =$ supply air temperature [°C] \hspace{1cm} \text{10} \leq y_{k,3} \leq 22.4
$y_{k,4} =$ chiller power [kW] \hspace{1cm} \text{0} \leq y_{k,4} \leq 50

Remark 5.6. The choice of upper/lower bound for model HMDC are based on validation simulations. Take the example of chiller power, when the simulation is run with an infinite upper limit, the maximum power used is 50kW which is set as the upper limit.

Table 5.4: VAV model check-list

<table>
<thead>
<tr>
<th>Model</th>
<th>States</th>
<th>Inputs</th>
<th>Disturbances</th>
<th>Outputs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$x_{k,1}$</td>
<td>$x_{k,2}$</td>
<td>$x_{k,3}$</td>
<td>$x_{k,4}$</td>
</tr>
<tr>
<td>HM</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>HMD</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>HMDC</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

Table 5.5: Disturbance parameter

<table>
<thead>
<tr>
<th>Building standard</th>
<th>Construction type</th>
<th>Working hour</th>
</tr>
</thead>
<tbody>
<tr>
<td>sa</td>
<td>h</td>
<td>07:00 - 18:00</td>
</tr>
<tr>
<td>sa</td>
<td>l</td>
<td>08:00 - 19:00</td>
</tr>
<tr>
<td>pa</td>
<td>h</td>
<td>08:00 - 19:00</td>
</tr>
<tr>
<td>pa</td>
<td>l</td>
<td>09:00 - 20:00</td>
</tr>
</tbody>
</table>

To have a group of building, we need to have different sub-types of HMDC building. Recall that in Section 4.2.2, an IRA building is classified by 5 factors: building standard, construction type, window area fraction, facade orientation, internal gains level. According to 16 different combinations, different model dynamic, system constraints and disturbance predictions are assigned to the system.

However, in the HMDC model, we don’t have enough building data to validate different model dynamics or different system constraints. These parameters could be helpful only when
classifying the HMDC system by disturbance. In HMDC design, the disturbance used are outside temperature and internal gains (person and equipment) where the previous one is ambient and the later two are classified by internal gains level. Table 5.5 illustrates assigning different disturbance prediction via changing building standard and construction type. Besides, a large or small building could be chosen via building area $\in \{4000, 20000\}$ (unit: $m^2$). So far with the combination of these four parameters, we can have 16 different HMDC buildings in the pool.
Chapter 6

Controller Design

6.1 Problem Setting

Recall that the goal of this thesis is to develop a controller which will provide a certain amount of reserve as the ancillary services via demand response (DR). The algorithm consists of a day-ahead centralized reserve determination phase, a decentralized MPC-based scheduling phase and a decentralized real-time proportional controller (Figure 1.1, 6.1). The purpose of the controller is to exploit the potential reserve amount in the target building group by maximizing the available payment. Meanwhile the controller has to incorporate future disturbance (Assumption 6.1) and cannot violate the designed comfort range.

Assumption 6.1. Perfect prediction In this thesis, we have assumed that a perfect disturbance prediction is available for the weather and internal gains.

Figure 6.1: Controller design illustration
6.1.1 Reserve Vector Definition

Control sequence As a matter of fact, the reserve provision via demand response is to increase/decrease electricity consumption according to the call signal from TSO. Thus, the reserve is provided by one of the actuators or the combination of several actuators. As the result, the reserve variables play similar roles as the control inputs in the model dynamics. The formulation of model dynamics now changes to:

\[
\begin{align*}
  x_{t+1} &= Ax_t + B_u u_t + B_v v_t + B_r r_t \\
  y_t &= C x_t + D_u u_t + D_v v_t + D_r r_t \\
  x_t &\in X, u_t \in U, v_t \in V, r_t \in R
\end{align*}
\]  

(6.1)

Remark 6.1. The matrices \( B_r \in \mathbb{R}^{n_r \times n_r} \) represents the impact of reserve \( r_t \) to the states of next time step. The matrices \( D_r \in \mathbb{R}^{n_r \times n_r} \) represents the impact of reserve \( r_t \) to current outputs. As a matter of fact, only the lighting will influence current output (illuminance) while all the other actuators will influence the outputs (temperatures) in next time step. Such influence is done via \( B_r \rightarrow x_{t+1} \rightarrow y_{t+1} \).

To distinguish which one(s) of the actuators is(are) chosen to provide reserve, an indicator vector \( w_{flag} \) is defined. The reason of distinguishing reserve variables from control inputs is not only to know the amount, but also to adapt to a different unit price (availability price and utilization price) of reserve.

Definition 6.1. Reserve indicator The reserve indicator is a vector of the same size as the control input vector. The elements in the indicator are either 0 or 1, where 1 means the corresponding actuator is used for reserve and vice versa. For instance, given a control input vector: \( u_k := [u_{k,1}, u_{k,2}, u_{k,3}, u_{k,4}] \) with a reserve indicator \( w_{flag} = [0 \ 1 \ 0 \ 1] \), then it means the actuators \( u_{k,2} \) and \( u_{k,4} \) are used for reserve provision.

Cost vector The corresponding columns of control input cost vector are kept to be the reserve cost vector.

Matrices Similarly, for the coefficient matrices, the columns related to reserve are taken to be the coefficient matrices of reserve \( r_t \). For instance, given matrices \( B_u \in \mathbb{R}^{3 \times 4}, D_u \in \mathbb{R}^{4 \times 4} \) with a reserve indicator \( w_{flag} = [0 \ 1 \ 0 \ 1] \), the corresponding coefficient matrices \( B_r, D_r \) for \( r_t \) are:

\[
B_u := \begin{bmatrix}
    b_{11} & b_{12} & \ldots & b_{14} \\
    b_{21} & b_{22} & \vdots & \vdots \\
    \vdots & \vdots & \ddots & \vdots \\
    b_{41} & \ldots & \ldots & b_{44}
\end{bmatrix},
B_r = B_u(:, [2 \ 4]) = \begin{bmatrix}
    b_{12} & b_{14} \\
    \vdots & \vdots \\
    \vdots & \vdots \\
    b_{42} & b_{44}
\end{bmatrix}
\]

(6.2)

\[
D_u := \begin{bmatrix}
    b_{11} & b_{12} & \ldots & b_{14} \\
    b_{21} & \vdots & \ldots & \vdots \\
    \vdots & \ddots & \ddots & \vdots \\
    b_{31} & \ldots & \ldots & b_{34}
\end{bmatrix},
D_r = D_u(:, [2 \ 4]) = \begin{bmatrix}
    b_{12} & b_{14} \\
    \vdots & \vdots \\
    \vdots & \vdots \\
    b_{32} & b_{34}
\end{bmatrix}
\]

(6.3)
6.1. PROBLEM SETTING

6.1.2 Building Aggregation

To fulfil the goal in an aggregation of commercial buildings, an aggregator is key role to serve as the “information exchanger” between the TSO and buildings. In brief, an aggregator has two main functions:

1. Before the real-time operation, the aggregator has to know the possible reserve amount of the building group as well as the proportion of each building. Then the aggregator bid the total amount in the reserve market at a proper price (Figure 6.2a).
2. During the real-time operation, the aggregator receives call signal from TSO and split the target amount to each building according to the decided proportion (Figure 6.2b).
Assumption 6.2. Independent individual  In this thesis, we have assumed that the communication is only between the aggregator and each individual, there is no communication between each building.

Practically, the aggregator would merge the dynamic models and system constraints of all the building members into one large system to do the centralized calculation.

State, control input, disturbance and output  In individual model, all these four variables are in column vector form throughout the time horizon. In the aggregation, the variable is still in time order, and in a particular time step, it is aggregated from building 1,2,...,L (Eq. 6.4).

\[
x_t := \begin{bmatrix}
  x_1^{t+1} \\
  \vdots \\
  x_L^{t+1} \\
  \vdots \\
  x_1^{t+N} \\
  \vdots \\
  x_L^{t+N}
\end{bmatrix},
\quad
u_t := \begin{bmatrix}
  u_1^{t} \\
  \vdots \\
  u_L^{t} \\
  \vdots \\
  u_1^{t+N-1} \\
  \vdots \\
  u_L^{t+N-1}
\end{bmatrix},
\quad
v_t := \begin{bmatrix}
  v_1^{t} \\
  \vdots \\
  v_L^{t} \\
  \vdots \\
  v_1^{t+N-1} \\
  \vdots \\
  v_L^{t+N-1}
\end{bmatrix},
\quad
y_t := \begin{bmatrix}
  y_1^{t} \\
  \vdots \\
  y_L^{t} \\
  \vdots \\
  y_1^{t+N-1} \\
  \vdots \\
  y_L^{t+N-1}
\end{bmatrix}
\]  

System constraints  The aggregation of the constraints are similar to that of variables, except that the constraints of state might be time-variant while constraints of control input are time-invariant.

\[
x_{max,t} := \begin{bmatrix}
  x_1^{max,t+1} \\
  \vdots \\
  x_L^{max,t+1} \\
  \vdots \\
  x_1^{max,t+N} \\
  \vdots \\
  x_L^{max,t+N}
\end{bmatrix},
\quad
u_{max,t} := \begin{bmatrix}
  u_1^{max} \\
  \vdots \\
  u_L^{max}
\end{bmatrix}
\]  

Matrices  When aggregating the building models, the certain matrices of building 1,2,...,L are allocated in the diagonal. The aggregated matrices are block diagonal since the dynamics of individual buildings are not coupled. The buildings are coupled through the cost function.

\[
A_t := \begin{bmatrix}
  A_1^{t} & \cdots & 0 & \cdots & 0 \\
  0 & A_2^{t} & \cdots & 0 & \cdots & 0 \\
  \vdots & \ddots & \ddots & \ddots & \ddots & \ddots \\
  0 & \cdots & 0 & A_L^{t}
\end{bmatrix},
\quad
B_{u,t} := \begin{bmatrix}
  B_{u_1,t}^{1} & \cdots & \cdots & \cdots & 0 \\
  0 & B_{u_2,t}^{2} & \cdots & \cdots & 0 \\
  \vdots & \ddots & \ddots & \ddots & \ddots & \ddots \\
  0 & \cdots & 0 & B_{u,L,t}
\end{bmatrix}
\]
6.1. PROBLEM SETTING

The aggregator executes the algorithm to find and divide the largest possible reserve, while not violating the comfort range.

Figure 6.3: Controller schematic

6.1.3 Control Approaches

However, it is not necessary for the aggregator to always hold all the information and carry out all the calculations for all the members in the group. The centralized calculation and information communication could be so complicated that require high budget and equipment investigation. Thus, a decentralized control is used after scheduling (Figure 6.1, 6.3). The advantages of applying decentralized control in our case are:

1. Distribute the calculation load of the aggregator to each building.
2. Avoid the cost of equipment set up to carry out large-scale calculation and operation.
3. Increase the flexibility of the group. Adding/removing a member into/from the group won’t affect the other members much.
4. Increase the system efficiency and avoid redundant data exchange.

6.1.4 Hierarchical Control Concept

In Figure 6.1 is an illustration of the controller structure, the controller is divided into four levels. The upper two levels are centralized control while the lower two levels are decentralized control.

Remark 6.2. Level 0 In Level 0, the aggregator has to decide the proper values of the availability price $k_1$ and utilization price $k_2$. The prices give incentive to the buildings and will directly influence the reserve amount. On the other hand, the availability price $k_1$ is indeed the bidding price for the aggregator to bid.

$^3$Utilization payment is a revenue received after real-time operation and it’s hard to quantify during schedule. Thus, in current design it is not included in the optimal cost function.
Remark 6.3. Level 1 In Level 1, the aggregator will solve an overall optimization problem to predict the possible reserve and allocation of the following 48 hours. Then this schedule will be send to each building.

Remark 6.4. Level 2 In Level 2, each building will solve an optimization problem by robust MPC. The problem is solved every 15 minutes to have a control sequence which guarantees the reserve provision based on current initial state. Meanwhile, the states of next time step will be updated after considering both schedule control sequence and TSO Load Frequency Control (LFC) signal.

Remark 6.5. Level 3 In Level 3, the controller will send requests to the interface (e.g.: PLCs, terminal unit controller) every 10 seconds to change the setting of actuator so that the real-time control sequence is implemented.

Moreover, the following assumptions related to reserve characteristic have been made to clarify our target. Investigations will be done in Chapter 7 to further exploit the potential.

Assumption 6.3. Daily bid In this thesis, we have assumed that the reserve is bid in the reserve market every day, which means the market is cleared every 24 hours.

Assumption 6.4. Constant amount In this thesis, so far we assume that a constant amount of reserve is bid by the provider everyday.

Assumption 6.5. Symmetric In this thesis, we have assumed that the reserve schedule is symmetric all the time, which means the maximum positive amount equals to the maximum negative amount.

6.2 Controller Formulation

6.2.1 0 Level Controller

In this level, the aggregator choose the value of availability price $k_1$ by setting the corresponding coefficient in the cost vector for the reserves.

Assumption 6.6. Constant electrical price and availability price In this thesis, we have assumed that the electrical price to pay is the retail price, 18 cents/kWh while the availability price is constant throughout the whole prediction horizon.

6.2.2 1st Level Controller

Problem 6.1. 1st level controller

\begin{align*}
\text{minimize} & \quad c^T u_t^{sch} + c^T r_t - k_1 \sum_{t=1}^{N} \sum_{b=1}^{L} r_{t,b} \\
\text{subject to} & \quad x_{lb}^{t+1} = Ax_{lb}^t + B_u u_t^{sch} + B_v v_t - B_r r_t \\
& \quad x_{ub}^{t+1} = Ax_{ub}^t + B_u u_t^{sch} + B_v v_t + B_r r_t \\
& \quad y_{min} \leq y_t^l = Cx_t^l + D_u u_t^{sch} + D_v v_t - D_r r_t \leq y_{max} \\
& \quad y_{min} \leq y_t^u = Cx_t^u + D_u u_t^{sch} + D_v v_t + D_r r_t \leq y_{max} \\
& \quad u_{min} \leq u_t^{sch} + r_t \leq u_{max} \\
& \quad Sr_t = 0 \\
& \quad x_t^l, x_t^u, u_t^{sch}, r_t \in \mathbb{R}, v_t \in \mathbb{V}, r_t \in \mathbb{R}
\end{align*}
6.2. CONTROLLER FORMULATION

Remark 6.6. \( c \in \mathbb{R}^{n_u N} \) is the cost vector of control input \( u_t \in \mathbb{R}^{n_u N} \), \( k_1 \in \mathbb{R}^{n_r N} \) is known as the availability price, that is the revenue for providing reserve \( R \). \( r_{t,b} \in \mathbb{R}^{n_r} \) represents the reserve provided by building \( b \) at time \( t \). Thus, \( \sum_{b=1}^{L} r_{t,b} \) is the total reserve provided by the building group at time \( t \). Related reserve expressions are:

\[
\begin{align*}
    r_{t+k|t} &= \{r_{t+k,1}, r_{t+k,2}, \ldots, r_{t+k,L}\}, \forall k = 0, \ldots, N - 1 \\
    r_t &= \{r_{t|t}, r_{t+1|t}, \ldots, r_{t+N-1|t}\}
\end{align*}
\]

(6.7) (6.8)

The three terms in the cost function represent:
1. The electrical cost of each actuator to follow the scheduled control inputs throughout the prediction horizon.
2. The electrical cost of those actuators to provide the reserves throughout the prediction horizon.
3. The availability payment of those actuators to provide the reserves throughout the prediction horizon.

The controller has to deal with the trade-off between total electrical cost and availability payment while respect the system constraints.

Remark 6.7. Constant amount The constraint \( S r_t = 0 \) is the matrix representation of the constraint

\[
\sum_{b=1}^{L} r_{1,b} = \sum_{b=1}^{L} r_{2,b} = \cdots = \sum_{b=1}^{L} r_{N,b}
\]

(6.9)

which assumes a constant reserve amount is provided each day.

Remark 6.8. Symmetric The worst case is to provide amount \( R \) with respect to the schedule input (both positive and negative) during every time step, which means the regulation power is assumed to be equal to the reserve throughout the whole time horizon.

\[
\sum_{b=1}^{L} r_{t+k,b} = R \quad \forall k = 0, \ldots, N - 1
\]

(6.10)

Remark 6.9. \( x_t^{lb} \in \mathbb{R}^{n_x N}, y_t^{lb} \in \mathbb{R}^{n_y N} \) are the state and output when providing the largest positive regulation power. \( x_t^{ub} \in \mathbb{R}^{n_x N}, y_t^{ub} \in \mathbb{R}^{n_y N} \) are the state and output when providing the largest negative regulation power. Moreover, the state series with considering the scheduled control inputs \( u_t^{sch} \) only is defined:

\[
x_{t+1}^{sch} = A x_t^{sch} + B_u u_t^{sch} + B_v v_t
\]

(6.11)

6.2.3 2nd Level Controller

Problem 6.2. 2nd level controller
with the other robust constraint in the same way and the optimization problem now becomes:

\[
\begin{align*}
& \text{minimize} \quad c^T u_t^{sch} \\
& \text{subject to} \\
& \max_{r_t \in \mathcal{R}^b} x_{t+1}^{ub} = Ax_{t}^{ub} + Bu_t^{sch} + B_v v_t + B_r r_t \\
& \min_{r_t \in \mathcal{R}^b} x_{t+1}^{lb} = Ax_{t}^{lb} + Bu_t^{sch} + B_v v_t + B_r r_t \\
& y_{min} \leq y_t^{ub} = Cx_{t}^{ub} + Du_t^{sch} + D_v v_t \leq y_{max} \\
& y_{min} \leq y_t^{lb} = Cx_{t}^{lb} + Du_t^{sch} + D_v v_t \leq y_{max} \\
& x_t^{ub}, x_t^{lb} \in \mathcal{X}, u_t^{sch} \in \mathcal{U}, r_t \in \mathcal{R}^b, v_t \in \mathcal{U}
\end{align*}
\]

**Remark 6.10.** \(y_t^{lb}, y_t^{ub}\) are the outputs when providing the largest positive or negative regulation power. The state series \(x_t\) consider the scheduled control inputs \(u_t^{sch}\) only. There is only one term in this cost function, which is the total electrical cost of the actuators to follow the scheduled control input sequence. Then the robust MPC has to use the least power to provide promised reserve amount while respect the system constraints.

**Remark 6.11.** In this level, the regulation power \(r_t\) is bounded by a reserve schedule assigned by aggregator, denoted as \(r_t \in \mathcal{R}^b\), which equals to

\[
-r^b \leq r_t \leq r^b \quad (6.12)
\]

where \(r^b = r^b_t = \{r^b_{t|0}, r^b_{t|1}, \ldots, r^b_{t|N-1}\}\). While the input schedule has to leave enough buffer to provide the regulation power up to amount \(r^b\), that is,

\[
u_{min} + r^b \leq u_t^{sch} \leq u_{max} - r^b \quad (6.13)
\]

**Remark 6.12.** Symmetric The regulation power with opposite sign \(-r_t\) are used as mirror case to represent the maximum and minimum outputs \(y_t^{lb}, y_t^{ub}\).

To solve the robust constraints involving maximization, one have to follow the approach made standard in the robust programming and to calculate the dual of the optimization problem. Here we take the example of the state upper limit:

\[
\begin{align*}
& \max \quad x_{t+1}^{ub} = Ax_{t}^{ub} + Bu_t^{sch} + B_v v_t + B_r r_t \\
& \text{s.t.} \quad -r^b \leq r_t \leq r^b 
\end{align*} \quad (6.14)
\]

First, the optimization problem should be rewritten into a standard form:

\[
\begin{align*}
& \min \quad -x_{t+1}^{ub} = -Ax_{t} + Bu_t^{sch} - B_v v_t - B_r r_t \\
& \text{s.t.} \quad r_t - r^b \leq 0 \\
& \quad -r_t - r^b \leq 0 
\end{align*} \quad (6.15)
\]

Then apply the Lagrangian multipliers \(\lambda_{u,1}, \lambda_{u,2}\) to the problem:

\[
\begin{align*}
& \max \quad -x_{t+1}^{ub} = -Ax_{t} - Bu_t^{sch} - B_v v_t - B_r r_t - r^b \lambda_{u,1} - r^b \lambda_{u,2} \\
& \text{s.t.} \quad \lambda_{u,1} - \lambda_{u,2} = B_r \\
& \quad \lambda_{u,1}, \lambda_{u,2} \geq 0 
\end{align*} \quad (6.16)
\]

By duality, when the strong duality holds, we can drop the maximization. Similarly, we deal with the other robust constraint in the same way and the optimization problem now becomes:
## Problem 6.3. 2nd level controller with dual constraints

\[
\begin{align*}
\text{minimize} & \quad c^T u^{sch} \\
\text{subject to} & \quad x_{t+1}^{ub} = A x_t^{ub} + B_u u_t^{sch} + B_v v_t + r^b \lambda_{u,1} + r^b \lambda_{u,2} \\
& \quad x_{t+1}^{lb} = A x_t^{lb} + B_u u_t^{sch} + B_v v_t - r^b \lambda_{u,1} - r^b \lambda_{u,2} \\
& \quad y_{min} \leq y_t^{ub} = C x_t^{ub} + D_u u_t^{sch} + D_v v_t \leq y_{max} \\
& \quad y_{min} \leq y_t^{lb} = C x_t^{lb} + D_u u_t^{sch} + D_v v_t \leq y_{max} \\
& \quad \lambda_{u,1} - \lambda_{u,2} = B_r \\
& \quad x_t^{ub}, x_t^{lb} \in \mathcal{X}, u_t^{sch} \in \mathcal{U}, v_t \in \mathcal{V} \\
& \quad \lambda_{u,1}, \lambda_{u,2} \geq 0
\end{align*}
\]

**Remark 6.13.** Due to the symmetric assumption, when solving the second robust constraint, the mirror case of upper bound is simply applied to be the lower bound.

### 6.2.4 3rd Level Controller

In this level, the controller is to transfers the scheduled control sequence \( u_t^{sch} \) from Level 2 into a 10-second real-time control sequence \( u_t^{rt} \). The transformation is first done by extending the first control input \( u_t^{sch} \) into a 10-second time step format. Then the real-time LFC signal with 10 seconds interval will be applied.

**Problem 6.4. 3rd level controller**

\[
\begin{align*}
x_{t+j+1} &= A x_{t+j} + B_u u_{t+j}^{sch} + B_v v_t + B_r r_{t+j}^{LFC}, \quad \forall j = 0, 10, 20, ..., 890 \text{ seconds} \\
y_{t+j} &= C x_{t+j} + D_u u_{t+j}^{sch} + D_v v_t + D_r r_{t+j}^{LFC}, \quad \forall j = 0, 10, 20, ..., 890 \text{ seconds} \quad (6.17)
\end{align*}
\]
Part III

Investigations
Chapter 7

Simulation

7.1 Overview

In the previous chapter, designs are done to build a controller to control an aggregation of buildings and provide reserves according to the LFC signal from the operator (Swissgrid). In this chapter, different case studies are designed to: (1) Validate the aggregation. (2) Analyze the sensitivity towards the design variables. (3) Explore the impacts of different reserve characteristics. (4) Compare different sets of building groups. In the table below is the general settings used in the tests in this chapter:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Lv1</th>
<th>Lv2</th>
<th>Parameter</th>
<th>Setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prediction horizon</td>
<td>48 hr</td>
<td>24 hr</td>
<td>Sample building</td>
<td>S1: {sa, h, wh, S, ih}</td>
</tr>
<tr>
<td>Simulation horizon</td>
<td>24 hr</td>
<td>24 hr</td>
<td></td>
<td>S5: {sa, h, wh, S, ih}</td>
</tr>
<tr>
<td>Time step</td>
<td>15 min</td>
<td>15 min</td>
<td></td>
<td>VAV: {sa, h, wh, S, ih}</td>
</tr>
<tr>
<td>Initial state</td>
<td>Nominal input</td>
<td>Sample building area</td>
<td>{4'000, 20'000} m²</td>
<td></td>
</tr>
</tbody>
</table>

7.2 VAV Model Validation

In the previous sections, literature and pilot projects have been studied to rebuild a new HVAC model with VAV boxes. Besides, two different extension models (Table 7.2) have been developed. Moreover, the controller design has been done and to lower the commission difficulties after merging with the whole system, a validation and test step is necessary for the VAV model.

<table>
<thead>
<tr>
<th>Model</th>
<th>Abbreviation</th>
<th>Disturbances</th>
<th>Chiller</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hao’s model</td>
<td>HM</td>
<td>✗</td>
<td>✗</td>
</tr>
<tr>
<td>Model with disturbance</td>
<td>HMD</td>
<td>✓</td>
<td>✗</td>
</tr>
<tr>
<td>Model with chiller</td>
<td>HMDC</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>
7.2.1 Step Response Test

The step response reflects the time behavior of a system while the settling time of a step response could help us to know how fast could the system response to fast unit change input/disturbance. Figure 7.1 shows a typical response plot. At time $t_1$ there is a unit change of the input, thus the value of the output jump from its initial value $v_1$ to a new stable value $v_2$ after the settling time $t_3 - t_1$.

**Case Study 7.1. Step response test**

**Goal:** (1) To analyze the characteristics of the original model. (2) To analyse the feasibility of introducing the disturbances and chiller into the system with VAV boxes. (3) To compare the models before and after.

**Description:** In the step response test, a fast unit change has been applied to each input/disturbance separately to see the deviation amount of the states/outputs, especially the impact to the indoor climate changing (room temperature).

7.2.2 Signal Tracking Test

In Hao’s paper [9], a signal tracking test was done to have a simulation of temperature and power consumption. For our rebuilt model, it also worth the efforts to do this test again to not only check the correctness but also check whether the model could work well with MPC. Besides, the result could help us to have an estimation of the potential reserve (in percentage of the nominal power) could be provided. To understand the signal tracking test in a practical way, one can consider that the random signal is kind of hourly control command sent to the VAV model. Whether the system is able to track the signal implies whether the VAV model can implement such control command sequence within an hour.

**Case Study 7.2. Signal tracking test (via MPC)**

**Goal:** To check the thermal behavior and reaction time of the building with respect to inputs and disturbances, which largely influence the potential reserve amount of the building group.
Description: A pseudo-random signal $r_v$ has been created to serve as the random deviation. $r_v$ is a series of i.i.d numbers (following $\mathcal{N}, \mu = 0, \sigma = 40$ ). Then the target power to be tracked is expressed as:

$$P_{fan}^* + 20\% \cdot P_{fan}^* \cdot r_v$$  \hspace{1cm} (7.1)$$

which means

$$y_{k, 2} \in [80\% P_{fan}^*, 120\% P_{fan}^*]$$  \hspace{1cm} (7.2)$$

Besides, the total power cost should be minimize at the same time. A pair of weights $P, Q \in \mathbb{N}_0^{100}$ have been used to emphasize the tracking task.

The formulation of the signal tracking test for each model is listed below:

**Problem 7.1. Signal tracking test for HM**

$$\min_{x, u} \quad R \cdot (c \tilde{P}_{fan})^2 + Q \cdot (\| \tilde{P}_{fan} - 20\% \cdot P_{fan}^* \cdot r_v \|)^2$$

subject to

$$x_{t+1} = Ax_t + Bu_t$$
$$x_{\min} \leq x \leq x_{\max}$$
$$u_{\min} \leq u \leq u_{\max}$$
$$y_{\min} \leq y \leq y_{\max}$$

**Problem 7.2. Signal tracking test for HMD**

$$\min_{x, u} \quad R \cdot (c \tilde{P}_{fan})^2 + Q \cdot (\| \tilde{P}_{fan} - 20\% \cdot P_{fan}^* \cdot r_v \|)^2$$

subject to

$$x_{t+1} = Ax_t + Bu_t + Ev_t$$
$$x_{\min} \leq x \leq x_{\max}$$
$$u_{\min} \leq u \leq u_{\max}$$
$$y_{\min} \leq y \leq y_{\max}$$

**Problem 7.3. Signal tracking test for HMDC**

$$\min_{x, u} \quad (\| (\tilde{P}_{fan} + \tilde{P}_{ele}) - 20\% \cdot (P_{fan}^* + P_{ele}^*) \cdot r_v \|)^2$$

subject to

$$x_{t+1} = Ax_t + Bu_t + Ev_t$$
$$x_{\min} \leq x \leq x_{\max}$$
$$u_{\min} \leq u \leq u_{\max}$$
$$y_{\min} \leq y \leq y_{\max}$$

7.2.3 Validation Test

The next step of model validation is to apply MPC algorithm to the model. To make the problem easier in the beginning, the simplest form of the problem has been kept: a nominal linear MPC problem with constant electrical price and setback criteria, without and soft constraints or any perturbation in the cost function.

**Case Study 7.3. Validation test (via MPC)**

**Goal:** To see the overall behavior and check the correctness of the model.
Problem 7.4. Validation test (Nominal MPC)
\[
\text{minimize} \quad c^T \tilde{P}_{\text{fan}} \\
\text{subject to} \quad x_{t+1} = Ax_t + Bu_t(\pm E_{\nu_t}) \\
x_{\text{min}} \leq x \leq x_{\text{max}} \\
u_{\text{min}} \leq u \leq u_{\text{max}} \\
y_{\text{min}} \leq y \leq y_{\text{max}}
\]

Besides, two different sets of initial value has been tried to run the MPC.

Definition 7.1. Nominal values state: \([T_r, \dot{m}, P_{\text{fan}}, T_s]^T = [22.4, 6.27, 9.06, 13]^T\)

Definition 7.2. Zero power state: \([T_r, \dot{m}, P_{\text{fan}}, T_s]^T = [21.4, 0, 0, 22.4]^T\)

7.3 IRA Aggregation Validation (S1)

This section concerns a small building aggregation of three identical S1 samples. Simulations focus on sensitivity analysis, assumption impacts and validation are performed. Table 7.3 is the general settings of the simulation environment. From Table 7.3, one can see there are several design parameters need to be decided and in the following sections, different tests are developed to exploit the design variable features.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Setting</th>
<th>Parameter</th>
<th>Setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soft constraints</td>
<td>no</td>
<td>Profit rate</td>
<td>110%</td>
</tr>
<tr>
<td>Penalty coefficient</td>
<td>Lv1:100’000</td>
<td>Real-time simulation</td>
<td>no</td>
</tr>
<tr>
<td></td>
<td>Lv2:100’000</td>
<td>Constant reserve asmp.</td>
<td>yes</td>
</tr>
</tbody>
</table>

7.3.1 Impact of Soft Constraints

Recall that when we design the optimization problem, each optimal variable has an upper bound as well as a lower bound. For the temperature, a comfort range of 21-26°C is used, but during the calculation one might meet with the situation that the optimization problem is infeasible because there is a set of solution whose temperature is slightly below or above the comfort range (e.g.: 20.97°C or 26.02°C). However, in reality, the customers won’t be so sensitive to such difference. Thus, the soft constraints are used to allow MPC to violate the comfort range once it’s necessary.

Given an optimization problem
\[
\text{minimize} \quad c^T x \\
\text{subject to} \quad Ax = b \\
A_i x \leq b_i
\]

And we want to soften the inequality constraint \(A_i x \leq b_i\), then we introduce a non-negative slack variable into this constraint:
\[
A_i x - s \leq b_i \\
s \geq 0
\]
Once the slack variable is positive, it means the controller chooses to violate the constraint to gain an optimal solution. Meanwhile, another variable, penalty coefficient $H_p$, is introduced to control how easy it is to violate the border. The optimization problem could be rewritten as:

$$\begin{align*}
\text{minimize} & \quad c^T x + s^T H_p s \\
\text{subject to} & \quad Ax = b \\
& \quad A_i x - s \leq b_i \\
& \quad s \geq 0
\end{align*}$$

Generally, the value of the penalty coefficient would be set so high that the controller won’t easily violate a constraint. In our design, we chose to soften the temperature constraints.

**Case Study 7.4. Impact of soft constraints**

**Goal:** to compare the result before and after applying the soft constraints.

**Description:** in this test, the test runs twice with or without soft constraints, while all the other parameter settings remain same (Table 7.4).

<table>
<thead>
<tr>
<th>Parameter Setting Parameter Setting</th>
<th>Parameter Setting Parameter Setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soft constraints before: no Profit rate after: yes</td>
<td>Profit rate 110%</td>
</tr>
<tr>
<td>Penalty coefficient Lv1:100'000 Real-time simulation no</td>
<td>Lv2:100'000 Constant reserve asmp. yes</td>
</tr>
</tbody>
</table>

### 7.3.2 Sensitivity towards Profit Rate

Recall that in the design of the controller, an availability price $k_1$ is chosen in Level 0. Theoretically, a bidding price higher than the retail electrical price already gives incentive for reserve provision. However, it is interesting for us to know how the available price will affect the reserve amount. Thus, here we introduce another design variable, profit rate $\eta$.

**Definition 7.3. Profit rate** is defined as the ratio of reserve profit and cost. In our case, the revenue would be the availability payment $k_1 \cdot R$, the cost would be the electricity cost $P_{\text{retail}} \cdot R$. Thus, the profit rate is defined as:

$$\eta = \frac{k_1 \cdot R - P_{\text{retail}} \cdot R}{P_{\text{retail}} \cdot R} = \frac{k_1}{P_{\text{retail}}} - 1$$

**Case Study 7.5. Profit rate**

**Goal:** explore the relation between the profit rate and reserve amount.

**Description:** in this set of tests, the profit rate of the optimization problem is set from 10% to 150% with an increment of 10% while all the other parameter settings remain same\(^1\) (Table 7.5). Note that to increase the flexibility, the soft constraints are considered.

\(^1\)This investigation is done with a 24-hour prediction horizon in Level 1
Table 7.5: Simulation environment: sensitivity analysis towards profit rate

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Setting</th>
<th>Parameter</th>
<th>Setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soften constraints</td>
<td>yes</td>
<td>Profit rate</td>
<td>10%, 20%, ..., 150%</td>
</tr>
<tr>
<td>Penalty coefficient</td>
<td>Lv1: 100’000</td>
<td>Real-time simulation</td>
<td>no</td>
</tr>
<tr>
<td></td>
<td>Lv2: 100’000</td>
<td>Constant reserve asmp.</td>
<td>yes</td>
</tr>
</tbody>
</table>

7.3.3 Validation

After the analysis of design variables, the validation tests are carried out in this section. The system with three S1 samples is required to do simulations of a complete day (a Monday) under certain settings. Moreover, for the higher level control, the simulations are performed first with the constant reserve assumption and then without the assumption to see the impact to the scheduling. For the lower level control, the simulations are performed first with a zero LFC signal (nominal case) and then with the real-time LFC signal to see the behavior of aggregated model. The historical data of LFC signal in the year 2012 is provided by Swissgrid.

With constant reserve provision

Case Study 7.6. Validation test with constant reserve (S1)
Goal: to check the overall behavior of the building aggregation and the capability of responding to the LFC signal under the constant reserve provision assumption.
Description: in this set of tests, the optimization problem runs with the constant reserve provision assumption (constant amount for each day). The simulation is performed once without any call signal and a second time with real LFC signal (Table 7.6).

Table 7.6: Simulation environment: validation test with constant reserve (S1)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Setting</th>
<th>Parameter</th>
<th>Setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soften constraints</td>
<td>no</td>
<td>Profit rate</td>
<td>110%</td>
</tr>
<tr>
<td>Penalty coefficient</td>
<td>Lv1: 100’000</td>
<td>Real-time simulation</td>
<td>before: zero call signal</td>
</tr>
<tr>
<td></td>
<td>Lv2: 100’000</td>
<td>Constant reserve asmp.</td>
<td>after: LFC signal</td>
</tr>
</tbody>
</table>

With varying reserve provision

Case Study 7.7. Validation test with varying reserve (S1)
Goal: to check the overall behavior of the building aggregation and the capability of responding to the LFC signal without the constant reserve provision assumption.
Description: in this set of tests, the optimization problem runs without the constant reserve provision assumption (varying amount for every time step). The other settings keep the same as that of previous test. The simulation is performed once without any call signal and a second time with real LFC signal (Table 7.7).
7.4. IRA AGGREGATION VALIDATION (S5)

7.4.1 Validation

This section concerns the validation of a small building aggregation of three identical S5 samples. Note that, different from the validation test environment, the soft constraint and varying reserve provision are necessary for type S5. This is due to the fact that TABS has slow dynamics such that the building need to heat up so early with full capacity to meet with the tight temperature constraints during working hour.

Case Study 7.9. Validation test with varying reserve (S5)

Goal: to check the overall behavior of the building aggregation and the capability of responding to the LFC signal without the constant reserve provision assumption.

Description: in this set of tests, the optimization problem runs once without any call signal and a second time with real LFC signal (Table 7.9). Note that to increase the flexibility, the soft constraints are considered.
Table 7.9: Simulation environment: validation test (S5)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Setting</th>
<th>Parameter</th>
<th>Setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soften constraints</td>
<td>yes</td>
<td>Profit rate</td>
<td>110%</td>
</tr>
<tr>
<td>Penalty coefficient</td>
<td>Lv1: 100'000</td>
<td>Real-time simulation</td>
<td>before: zero call signal</td>
</tr>
<tr>
<td></td>
<td>Lv2: 100'000</td>
<td></td>
<td>after: LFC signal</td>
</tr>
<tr>
<td>Constant reserve asmp.</td>
<td>no</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Chapter 8

Results and Discussions

In this chapter, the detailed control behavior and thermal behavior of each building will be shown. For all the plots in this thesis, the following rules will be obeyed:

(1) If there is a plot without unit, it means the power/reserve in the plot is represented in % of the full capacity of corresponding actuator.
(2) If a building group contains identical building samples, then the plots of all the buildings will be shown in the text if they don’t have identical behavior.

8.1 VAV model validation

8.1.1 Step Response Test

Recall Figure 7.1, the output response will reach a saturation value $v_2$ after the settling time $t_3 - t_1$. In the following plots of step responses, we assume a zero initial output value ($v_1 = 0$) and zero initial time ($t = 0$). Thus the value read on x-axis is the settling time and the value read on y-axis is the output response (value deviation).

HM model

Result Description 8.1. In Figure 8.1, the system settling time is 650 seconds ($\approx 11$ min) and the stable value is $-0.14^\circ C$. This means the fan control command increases every $1\%$, the building temperature will decrease $0.14^\circ C$ in approximately 11 minutes.

Discussion 8.1. In model HM, the unit response gives a saturation value of $-0.14^\circ C$ which is not that large. However, recall that the model is a linear system so that the room temperature decrement is proportional to the increment of fan control command. Besides, the supply temperature is assumed to be constant ($13^\circ C$) all the time, then the controller could choose to lower room temperature quicker by setting larger value or full capacity of fan control command. For instance, if the fan control command is increased by $10\%$, then the room temperature will decrease by $1.4^\circ C$ in 11 minutes.

HMD model

Result Description 8.2. Figure 8.2(1), (2) show the impact of internal gains to the room temperature. In Figure 8.2(1), the system settling time is approximately 650 seconds ($\approx 11$ min).
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Figure 8.1: Model HM step response: the impact of fan control command unit increment (%) to room temperature

Figure 8.2: Model HMD step response: (1) the impact of outside temperature unit increment (°C) to room temperature (2) the impact of internal gain (W) unit increment to room temperature
8.1. VAV MODEL VALIDATION

Figure 8.3: Model HMDC step response: (1) the impact of chiller power unit increment (kW) to room temperature (2) the impact of chiller power unit increment (kW) to supply air temperature

min) and the stable value is 0.03°C. This means when the outside temperature increases every 1°C, the building temperature will increase 0.03°C in approximately 11 minutes. In Figure 8.2 (2), the system settling time is approximately 650 seconds (≈ 11 min) and the stable value is 1.5 × 10⁻⁴°C. This means the internal increases every 1W, the building temperature will increase 1.5 × 10⁻⁴°C in approximately 11 minutes.

Discussion 8.2. In model HMD, it seems that the internal gain increment would have little influence on room temperature. However in real life a person produces up to 100W internal gains during normal daily activities (e.g.: sitting, walking). Thus a building with 200 people inside at the same time will have an internal gain of 20’000 W which will increase room temperature by 3°C in 11 minutes. Thus, the internal gain actually has large impact to the building climate (room temperature).

HMDC model

Result Description 8.3. In Figure 8.3 (1), the system settling time is approximately 2.2 × 10⁴ seconds (≈ 6.1 hr) and the stable value is -20°C. This means that if the chiller power increases every 1kW, the building temperature will decrease 20°C in approximately 6.11 hours. In Figure 8.3 (2), the system settling time is approximately 2.9 × 10⁴ seconds (≈ 8 hr) and the stable value is -21°C. This means the chiller power increases every 1kW, the supply air temperature will decrease 21°C in approximately 8 hours. However, the supply air temperature could decrease 13.1°C within 3.6 × 10³ seconds (1 hr).

Discussion 8.3. Different to model HM and HMD, the supply air temperature of model HMDC can be changed by chiller power consumption. The step response results show that it will take a long time to cool down the supply air as well as the whole building. Assuming a indoor temperature of 26°C, then an increment of chiller power by 1kW will make the supply air decrease to 13°C within an hour and to 5°C after 8 hours while at the same time the room temperature will decrease to 6°C.
8.1.2 Signal Tracking Test

**Result Description 8.4.** Figure 8.4 illustrates the tracking behavior as well as the corresponding thermal behavior of model HM in a 24 hour simulation horizon. In each plot, the tendency of the control sequence or related states are shown along with the simulation horizon. In Figure 8.4a, one can see that the value of the power sequence coincides with target signal perfectly in every time step (1 hour). In Figure 8.4b is the control behavior (fan control command) chosen by MPC to have target power. Figure 8.4c shows the corresponding reaction of the mass flow under such fan control command. The trend of room temperature is shown in Figure 8.4d. It easy to see that all three states keep the same trend as the control sequence. Moreover, the temperature is always within the comfort range.

**Discussion 8.4.** First of all, the power sequence of model HM is able to perfectly track the target signal in an hourly time step simulation. Recall the definition of the target signal
8.2 IRA AGGREGATION VALIDATION (S1)

8.2.1 Impact of Soft Constraints

Remark 8.1. Penalty coefficient. In this thesis, the value of the penalty cost \( H_p \) is chosen to equal 100'000. This value is high enough to guarantee the robustness and energy efficiency of the problem while on the other hand is low enough to let the controller exceed the bound when it’s necessary. Figure C.2 shows a simple sensitivity analysis towards the penalty coefficient value. One can see that the lower is the penalty coefficient, the more amount of reserve could be provided at the cost of violating the comfort range. Though with a lower
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Figure 8.6: Level 1 result: Reserve allocation

(a) without soft constraint

(b) with soft constraint

Figure 8.7: Profit Rate
penalty coefficient, the reserve amount almost doubles, the comfort range should be respected in a higher priority.

**Result Description 8.6.** Figure 8.6 shows a comparison of the reserve split before and after applying the soft constraints while the prediction is performed for 48 hours. The three colors represent the reserve amount assigned to each building by the aggregator and the total area of the three colors are the total reserve amount of the whole aggregation. For both of the cases, the total possible reserves for the two days are 0.68MW and 0.09MW.

Recall that the buildings are of the same type, settings and initial conditions in these tests. In the case *without* soft constraint (Figure 8.6a), the MPC generally chose to heat up the building and provide reserve in turns among the three buildings. In day I, before working hour starts, almost half of the reserve is assigned to BD3 while BD1 and BD2 are heating up in turns. During the working hours, three buildings are assigned with similar proportion between 06:00-10:00 and then BD1 provides less proportion gradually. BD2 hardly contributes from 16:00-24:00. For day II, BD1 contributes most almost whole day. However, in the case *with* soft constraint (Figure 8.6b), the buildings have the same behavior (reserve proportion) throughout the whole horizon.

**Discussion 8.6.** Applying the soft constraint won’t help to enhance reserve provision, but the application could let the aggregation members behave in a more independent way while the control targets of the same settings tend to behave same. This is because when there is no soft constraint, all the buildings have to keep the hard constraint of temperature so that the MPC chose to heat each building in turns. Under such circumstance, adding/removing an aggregation member could influence the overall reserve scheduling largely. Thus for decentralized control, the soft constraint is such a design to guarantee the lowest interruption between all the control targets.

### 8.2.2 Sensitivity towards Profit Rate

**Result Description 8.7.** In Figure 8.7, when the profit rate is lower than 100%, the system can hardly provide any reserve ($\leq 0.5\text{kW}$). When the profit rate equals to 100%, the system start to provide a small amount of reserve in day I ($\geq 41\text{kW}$). Moreover, when the profit rate is larger than 100%, it becomes also possible to provide reserve in day II ($\geq 35\text{kW}$). Increasing the profit rate in the range 100-120% drastically increases the reserve amount. Further profit rate increases affect the reserve amount only marginally.

**Discussion 8.7.** The system has a marginal profit rate to provide reserve, which means the building aggregation need enough economic incentive to provide reserve. Such feature sets a lower limit to the bidding price. To encourage such kind of ancillary service to enter the market, new conditions and schemes are required to give enough economic incentive to the end-users. In the end a profit rate of 110% has been chosen in this thesis to have a reasonable amount of reserve while keep the building running in an energy-efficient way.

In an aggregation of same buildings (type S1), no matter applying the soft constraints or not, the reserve provision is proportional to the building number (Figure C.3). According to current criteria of secondary frequency control (Appendix A), a minimum amount of $\pm 5\text{MW}$...
should be guaranteed. Thus, to reach this requirement, a building group of at least 30 buildings (type S1) is necessary. However, for future development, the group size could also adapt to the change in market rules.

8.2.3 Validation

With constant reserve provision

Result Description 8.8. First of all, Figure 8.8 shows the results of the reserve determination phase (Level 1) and the scheduling is performed for 48 hours. Figure 8.8a shows the total power consumption schedules (including both lighting and heating) of the building group. The light blue line in the middle is the optimal control sequence which guarantees the reserve provision while the red and blue curves are the power schedule when providing maximum positive/negative reserves. The distance between the nominal line and the red/blue line, which is the reserve, keeps the same throughout day I and day II. With the constant amount assumption, the system would have an approximately ±0.75MW reserve for day I and ±0.1MW reserve for day II. The total power consumption reaches a high peak just before the working hour and a relative lower peak before the end of working hour. Figure 8.8b shows the reserve split among the aggregation members. Again, the buildings heat up and provide reserves in turns.

Then comparisons of the centralized open-loop control (Level 1) and the decentralized closed-loop control (Level 2) of three buildings are shown in Figure 8.9, 8.10, 8.11. For Level 1 of each building, the control sequence of the actuator which provides reserve is plotted in a 48-hour horizon as well as the temperature (Figure 8.9a, 8.10a, 8.11a). For Level 2, the correspond control sequence and temperature are plotted in a 24-hour horizon (Figure 8.9b, 8.10b, 8.11b). For all the plots, a pair of envelopes is added to illustrate the extreme case of providing maximum positive/negative reserves.

With zero LFC signal, looking at the plots of heating actuator for each building, the distances between the optimal control sequence and its envelopes are not the same throughout the horizon. Comparing the two levels, the control sequences implemented in Level 2 have similar trends as the control sequences scheduled in Level 1 but have smaller values than the schedule. The temperature (including the envelopes) always follows the trend of the actuator. For both the upper and lower bounds, the comfort range is always respected. The distance between the envelopes in Level 1 gets larger along with the horizon while it keeps the same in Level 2.

Figure 8.13, 8.14, 8.15 show the simulation results of the operation with the LFC signal (Figure 8.12) and real-time control (Level 2 and Level 3). For Level 2 of each building, the control sequence of the actuator which provides reserve is plotted in a 24-hour horizon as well as the temperature\(^1\) (Figure 8.13a, 8.14a, 8.15a). For Level 3, the real-time (every 10 seconds) control sequence of the actuator is shown (Figure 8.13b, 8.14b, 8.15b). During the operation, the actuators and corresponding temperatures are able to follow the LFC signal while the system constraints are respected. For all the buildings, the control sequences implemented

\(^1\)The envelopes are the same as that in the zero LFC signal simulation.
and the corresponding state (temperature) in real-time operation never exceed the envelopes.

![Diagram](image_url)

**(a) Total power scheduling**

**(b) Reserve split**

**Figure 8.8: Validation test with constant reserve (S1): overview**

**Discussion 8.8.** First of all, we are convinced that it is feasible for an aggregation of commercial buildings to provide the secondary frequency control reserve. For the HVAC system type S1, the reserve could count up to $\pm 33.7\%$ of the total heating (radiator) capacity in a winter day. Since S1 has faster dynamics, the power schedule is largely influenced by disturbances (internal gains) and comfort range (Figure 8.8b).

The soft constraint is not used in these tests, thus the comfort range becomes a hard constraint to the optimization problem. The reason that the operation spends less power than scheduling is the application of closed-loop control, which provides feedbacks (updates states) to the controller so as to avoid enlarging the effects of extreme cases. Moreover, the control sequences of the operation will coincide with scheduling when the worst case happens (e.g., always providing negative maximal reserve). The reason why the temperature envelopes in Level 2 are not getting farther is also the closed-loop control. But the reason of non-constant distance between the optimal control sequence and the envelope is that the reserve proportion assignment is based on the reserve split schedule (Figure 8.8b).

The results of the simulation with LFC signal imply that the system could fast react to the requests without violating any constraints. Thus the hierarchical controller algorithm
proposed in this thesis is practicable to provide reserves.

Figure 8.9: Validation test with constant reserve (S1): with zero LFC signal (BD1)
8.2. IRA AGGREGATION VALIDATION (S1)

Figure 8.10: Validation test with constant reserve (S1): with zero LFC signal (BD2)

(a) Level 1: open-loop control

(b) Level 2: closed-loop control
Figure 8.11: Validation test with constant reserve (S1): with zero LFC signal (BD3)
8.2. IRA AGGREGATION VALIDATION (S1)

Figure 8.12: Real-time LFC signal

(a) Level 2: closed-loop control

(b) Level 3: real-time control

Figure 8.13: Validation test with constant reserve (S1): with LFC signal (BD1)
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(a) Level 2: closed-loop control

(b) Level 3: real-time control

Figure 8.14: Validation test with constant reserve (S1): with LFC signal (BD2)
8.2. IRA AGGREGATION VALIDATION (S1)

With varying reserve provision

Result Description 8.9. Similar to the test layouts before, the simulation results of Level 1 are shown first. Figure 8.16a is the total power consumption schedule with envelopes and Figure 8.16b is the reserve split. The power consumption reaches a peak at 06:00 and reserve drops sharply. With the varying reserve provision, each building counts for the same proportion throughout the prediction horizon. The maximum possible reserve increases up to approximately ±1.1MW during non-working hours while during working hours the reserve amount decreases to less than ±0.7MW. Moreover, the peak reserve amount counts up to half of the total heating capacity. In Table 8.1 is a comparison between with/without constant assumption on the total reserve energy of 48 hour horizon. After relaxing the constant amount assumption, the total reserve energy provision of two days increased by 58.34%.

Due to the fact that the buildings behave identically in this test, only the plots of BD1 are shown (Figure 8.17, 8.18) and the results of BD2 and BD3 are attached in Appendix D. With a time-invariant reserve allocation, it is easier to observe that the distance between the
temperature envelopes in Level 1 gets larger along with the horizon while the distance keeps the same in Level 2 (Figure 8.17).

Table 8.1: Impact of daily reserve bids (Unit: MWh)

<table>
<thead>
<tr>
<th>Type</th>
<th>Reserve amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>32.89</td>
</tr>
<tr>
<td>Varying</td>
<td>52.08</td>
</tr>
</tbody>
</table>

**Discussion 8.9.** For the reserve provision, such drop is mainly caused by comfort range setbacks, and so as the peak power. Comparing Figure 8.8b with Figure 8.16b, the constant assumption application actually cuts the reserve amount during non-working hours down to the daily minimum amount. When there is no constant constraint, the reserve potential could be exploit thoroughly (±50%) so that the identical building members tend to behave identically. But when there is a constant assumption, a heating strategy has to be chosen to maximize the total reserve out of economic incentive.

However, in current design, the time step is 15-minute interval while current reserve market is cleared weekly. Thus, to encourage such kind of ancillary service to enter the market, new conditions and schemes to carry out multi-amount short-term reserve bidding are necessary for the ancillary service market especially the tendering procedures.

Figure 8.16: Validation test with varying reserve (S1): overview
8.2. IRA AGGREGATION VALIDATION (S1)

Figure 8.17: Validation test with varying reserve (S1): with zero LFC signal (BD1)

(a) Level 1: open-loop control

(b) Level 2: closed-loop control
8.2.4 Reserve Determination of 16-building Aggregation

**Result Description 8.10.** Figure 8.19 shows the overall power consumption schedule and reserve split of the full S1 population. With the varying reserve provision, each building is behaving identically. The peak total reserve provision of the 16-building aggregation is approximately 3.5MW and the minimal value is approximately 0.8MW (Figure 8.19b). However, from Figure 8.19a, one can see that the nominal power consumption during non-working hours stays high (about \( \approx 3.5\text{MW} \)) and gets higher between 06:00-18:00.

Moreover, the width of each color represents the reserve amount of each building, the wider is one color, the more reserve is provided by this building. Among the population, the buildings which provide larger proportion are BD9, BD10, BD13 and BD14. The corresponding building type of them are: \{sa,h,wh,ih\}, \{sa,h,wh,il\}, \{sa,l,wh,ih\} and \{sa,l,wh,il\}. The buildings which provide small proportion are BD3, BD4, BD7 and BD8. The corresponding building type of them are: \{pa,h,wl,ih\}, \{pa,h,wl,il\}, \{pa,l,wl,ih\} and \{pa,l,wl,il\}. 

Figure 8.18: Validation test with varying reserve (S1): with LFC signal (BD1)
8.2. IRA AGGREGATION VALIDATION (S1)

![Graph](image)

(a) Total power scheduling

![Graph](image)

(b) Reserve split

Figure 8.19: Validation test with constant reserve: 16-building aggregation

Discussion 8.10. Here comes up with an issue that the more reserve the aggregation is able to provide, the more energy will be used during non-working hours. This energy is consumed to let the aggregation ready to provide downwards reserve at anytime. In other words, even if there is no LFC signal received in one day, the aggregation will still need to consume an amount of $R \times 24\text{hr}$ electrical energy to get itself ready. A good controller is not necessary to provide the most reserve, but a trade-off between being environmental-friendly or providing more reserve should be dealt with properly.

Back to the observation of individual building contribution, within the buildings of most contributes the common features are \{sa, wh\} which represent a Swiss average house with a high window area fraction. Similarly, the buildings of less contributes share the features \{pa, wl\} which represent a passive house with a low window area fraction. This mainly due to the fact that a Swiss average house is usually a less efficient one. The heat loss through the building envelope and windows will already keep the radiator on in a winter day. The controller is just rearrange the consumption to become reserves.
8.3 IRA Aggregation Validation (S5)

8.3.1 Validation

**Result Description 8.11.** The simulation results of Level 1 are shown first, Figure 8.20a is the total power consumption schedule with envelopes and Figure 8.20b is the reserve split. With the varying reserve provision, the controller chose to heat up by TABS at full capacity in day I from midnight until 4 p.m., then the power consumption drops and a steady reserve amount of $\pm 1.1\text{MW} \ (\leq 50\%)$ is maintained until the end of day II. The power consumption goes higher during the working hour of day II.

Again, due to the identical behaviors, only the plots of BD1 are shown (Figure 8.21, 8.22) and the results of BD2 and BD3 are attached in Appendix E. Figure 8.21a, 8.21b and 8.22a show the simulation results of the Level 1 and Level 2 (with zero or real-time LFC signal). But during the Level 2 operation, the comfort range is not always respected during working hours. Moreover, the control sequence largely differs from the Level 1 schedule from 0:00 to 14:00, the building should start to heat from midnight according to the schedule, but in the operation, the building does not start to heat until 14:00.

**Discussion 8.11.** The building type S5 (TABS) behaves quite differently from type S1 due to its large time constant. The system needs to heat up so early (from 0:00) to meet with the tight temperature constraints during the working hour. This is also why the system can hardly provide any reserve with constant assumption. Also, due to the combination of slow dynamics and closed-loop control, the temperature envelopes in Level 2 are overlapping (Figure 8.21b, 8.22a), which means even a LFC signal is responded the room temperature won’t change much.

Moreover, because the prediction horizon of Level 1 is 48 hours, the controller always takes day II into consideration. As the result, the controller chose to have a long heating period in day I to warm up the building so that day II is able to provide steady reserves by take the advantage of the slower dynamics. Under such circumstances, when the simulation horizon move on to the beginning of next day with the new initial values (final state of last day, $\approx 20^\circ\text{C}$), the controller will again choose to have a long heating period in day I and so on so forth. Then the actual time of providing reserve will be really short (less than 8 hours) for building S5.

Now we come to the observation that the power schedule of Level 1 and the nominal real-time schedule of Level 2 are not the same. The temperature envelopes show that the scheduling (Level 1) is a feasible solution which guarantees robust while the control sequence in Level 2 does not. Such difference is actually caused by the combination of slow dynamics and soft constraints. Since it is possible to violate the constraints with the cost $H_p$, the MPC prefers not heating up from midnight but sacrifices the comfort range respecting. However, the optimization problem is infeasible without soft constraints and a penalty coefficient $H_p$ higher than 100’000 will lead to energy-inefficiency decisions such as turning on the light during the night to produce some heat. Above all, we need to deal with the trade-off between energy-efficiency and maximal reserve. Adjustments should be down to current controller design to be adapted to building type S5 and make practicable results.
8.3. IRA AGGREGATION VALIDATION (S5)

Figure 8.20: Validation test (S5): overview

(a) Total power scheduling

(b) Reserve split
CHAPTER 8. RESULTS AND DISCUSSIONS

Figure 8.21: Validation test (S5): with zero LFC signal (BD1)

(a) Level 1: open-loop control

(b) Level 2: closed-loop control
8.4 Further Work

8.4.1 VAV model

Model HM accuracy improvement  Recall Eq.5.7, 5.12 one can see that there are two terms which lead to the non-linearity of the model. In Hao’s model, methods of using perturbation form or eliminating some terms were used to linearized the dynamic system, which are considered might lose the accuracy of the model. Thus, instead of simply eliminating the bilinear (or higher order) terms, approximation has to be done to keep the dynamic system elegant. Regarding the bilinear term, it could be solved by apply Sequential Linear programming (SLP) algorithm which decompose the problem into linear ones and find the optimal solution by iterations.

Model HMDC improvements  Recall the observation in Section 8.1.1, the model HMDC behaves in way which violates our common sense. Such strange behavior might lead from improper chiller implementation (e.g.: improper assumption) or lacking of damper in the
system. Thus, it worth the efforts to investigate more study on the principle of chiller and the implementation of damper. Once the implementations are done, the system would be able to have normal heating exchange with outdoor environment. After completing the model in the right way, we are confident that the VAV model could provide at least ±20% of its fan capacity as reserves.

8.4.2 Controller Improvement

Bidding strategy In this thesis, the bidding price is actually manually set to a constant while the value is gain by sensitivity analysis. However, in reality the bidding strategy is much more complicated. The bidding price will change with marginal cost which is largely influenced by disturbances and system constraints. The market will also allow multi-stage bidding in which different price are assigned to different amount. Thus the controller is complete only when having an optimal bidding strategy.

8.4.3 Further Exploration

Varying electrical price In this thesis, the electrical price is assumed to be constant throughout the whole horizon but in reality, the retail price differs during day and night, working days and weekends. The implementation of varying electrical price will definitely influence controller decision largely, for instance, heating up more during cheap hours.

Statistical study on LFC signal The statistical study of LFC signal will bring us more facts/knowledges of the secondary control reserve. Recall the Figure 8.12, the values of real LFC signal mostly lay between [-50%,50%] and the signal might have some inter-relation to other factors (e.g.: weather forecast). Thus, the statistical study can help to have a better prediction of LFC signal so that more potential reserve could might be exploited.

Symmetric assumption In this thesis, only the impacts of daily reserve bids assumption have been explored while the symmetric assumption is always kept. For future work, it is interesting to relax this assumption to see the reserve potential of such kind of ancillary service. With the constant amount assumption, there are four possible combinations: symmetric and constant bid, asymmetric and constant bid, symmetric and varying bid, asymmetric and varying bid. Combing with the statistical study of LFC signal, the results will be helpful to further ancillary service market development. Such kinds of services will largely increase the flexibility of the ancillary services as will as the complexity of the market.
Chapter 9

Conclusions

In this thesis, first, a HVAC model with VAV boxes in state-space form is rebuilt. Based on the this model, two extension models are developed to consider disturbances and chiller in the dynamics. Investigations are done to validate the models. Second, a group of commercial buildings (IRA HVAC system) are aggregated in MATLAB. Then based on the building aggregation, a controller aiming at exploring secondary reserve provision potential is developed. A day-ahead centralized reserve determination phase, a decentralized MPC-based scheduling phase and a decentralized real-time proportional controller are included in the algorithm. Numerical simulations are performed in MATLAB to test the applicability of the proposed method.

The results of model investigations show that it is possible to apply MPC to the VAV model while the model has a potential of providing ±20% of its total supply fan capacity (±6.6kW) as the reserve. However, the model is missing a damper to realize heating exchange with outdoor environment. Further studies are necessary to complete and validate the VAV model.

From the sensitivity analysis of controller design parameters, we discover that the soft constraints can enlarge the feasible set of the optimization problems and lower the independence between group members. Moreover, only a profit rate \( \geq 100\% \) (availability price = 2-retail electrical price) could trigger the building groups to provide reserve while an improper high profit rate \( \geq 150\% \) will lead to energy-inefficient decisions.

Numerical simulations are also performed to explore the reserve potential. Simulation results of IRA building aggregation (type S1) show that, under the daily reserve bids (constant amount everyday) assumption, the commercial building aggregation is able to provide ±33.7% of its total heating capacity as the secondary control reserve. Without such assumption, the peak reserve provision could reach ±50% of its total heating capacity.

Real-time simulation with LFC data provided by Swissgrid proves the practicability of current design. Moreover, a simulation based on full S1 population implies that a Swiss average house with a high window area fraction tends to provide more reserve while a passive house with a low window area fraction tends to provide less.

Numerical simulations are also performed to type S5. So far, soft constraints and vary-
ing reserve assumption are necessary in the simulation to promise the feasibility. It is also discovered that a HVAC system with slower heating dynamics (TABS) activates heating early (zero reserve before 4 p.m.) and then provides a steadily reserve for the rest of the day. Further studies are required to adapt current design to type S5 to have better results.

In summary, though being the large energy consumers, the commercial buildings (IRA) also have large potential in secondary frequency reserve provision. There are still many features could be explored in future studies. In addition, considering the study results, new conditions and regulation schemes need to be developed to encourage the participation of proposed design into the ancillary service market and to carry out multi-amount short-term reserve bidding.
Appendix A

Frequency Control

2.1 General principles

<table>
<thead>
<tr>
<th>Bidders</th>
<th>Generating unit portfolio («pool») or individual generating units.</th>
</tr>
</thead>
</table>
| Conditions for participation | • Only companies that have concluded a framework agreement with Swissgrid may submit bids.  
• The requirement for concluding a framework agreement is successful prequalification by Swissgrid or, for French providers of primary control power (PCP), the contracts required by RTE for provision of PCP for Switzerland.  
• The bidder is not compensated for costs incurred as a result of prequalification. |
| Tender periods | • Primary and secondary control: weekly  
• Tertiary control: weekly and daily |
| Framework conditions of the bids | • Every market participant may submit an unlimited number of bids.  
• A specific minimum size in MW is prescribed for each product. |
| Bid structure | • In order to be able to correctly assess the minimum production of the generating units in the bids, a bid may comprise several volume/price combinations depending on the product (incrementally at different prices per MW) (multi-level bid).  
• A bid cannot be split, i.e. bids cannot be partially awarded.  
• The price is given per MW in Swiss francs [CHF/MW]. |
| Selection criterion | The procurement costs are minimised based on the bid prices for power provision. |
| Pool | The bidder is responsible for coordination in the pool of generating units. |
| Power provision | • Continuous provision of the contracted control power.  
• Criterion: 100 % availability of the pool's capacity.  
• The location of the provision can be chosen freely from within the pool and amended until the start of the relevant 15-minute period – see «Requirements for RPS data» [1]. |
| Monitoring and checks | On request, high-resolution, precise measurement data must be provided to Swissgrid by the operator – see «Requirements for monitoring data» [2]. |
| Supply from abroad | Due to technical and organisational restrictions, initially only the supply of primary control from France is possible. As soon as the technical and organisational requirements have been met for individual control energy products, this restriction will be lifted. |
| Publication | Anonymous publication of the bids. |
| Completion of tender | In accordance with the tender calendar at www.swissgrid.ch. |

Figure A.1: Frequency control principles [20]
2.3 Secondary control

<table>
<thead>
<tr>
<th>Volume</th>
<th>±400 MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Product</td>
<td>Symmetrical control power bands</td>
</tr>
</tbody>
</table>
| Bid structure   | • Minimum output windows of ±5 MW  
|                 | • Multiple volume/price combinations per bid are permitted (multi-level bids), each incrementally ±1 MW at different prices |
| Tender period   | Weekly, 00:00 Monday – 24:00 Sunday |
| Request         | Proportional to bidder’s contracted capacity |
| Remuneration of capacity | Bid price for procured secondary control power |
| Remuneration of energy | Hourly spot price on SwissIX ±20 % incl. cap/floor weekly base according to control signal averaged over a period of 15 minutes |
| Energy settlement | According to post scheduling, obtained from control signal averaged over a period of 15 minutes (in 0.1 MWh) |
| Link            | Control signal to bidder |
| Demand forecast | Studies by Swissgrid |

Figure A.2: Secondary control principles [20]
Appendix B

Ancillary Service Interface

Figure B.1: Prequalification and framework agreement [21]
Figure B.2: Tendering process and contract award [21]
Appendix C

Signals and Plots

Figure C.1: Random tracking signal

Figure C.2: Penalty coefficient
Figure C.3: Building number vs. reserve amount
Appendix D
IRA aggregation (S1)

(a) Level 1: open-loop control

(b) Level 2: closed-loop control

Figure D.1: Validation test with varying reserve (S1): with zero LFC signal (BD2)
(a) Level 1: open-loop control

(b) Level 2: closed-loop control

Figure D.2: Validation test with varying reserve (S1): with zero LFC signal (BD3)
(a) Level 2: closed-loop control

(b) Level 3: real-time control

Figure D.3: Validation test with varying reserve (S1): with LFC signal (BD2)
(a) Level 2: closed-loop control

(b) Level 3: real-time control

Figure D.4: Validation test with varying reserve (S1): with LFC signal (BD3)
Appendix E

IRA aggregation (S5)

Figure E.1: Validation test (S5): with zero LFC signal (BD2)
Figure E.2: Validation test (S5): with zero LFC signal (BD3)

(a) Level 1: open-loop control

(b) Level 2: closed-loop control
(a) Level 2: closed-loop control

(b) Level 3: real-time control

Figure E.3: Validation test (S5): with LFC signal (BD2)
APPENDIX E. IRA AGGREGATION (S5)

(a) Level 2: closed-loop control

(b) Level 3: real-time control

Figure E.4: Validation test (S5): with LFC signal (BD3)
Bibliography


