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SinBerBEST | Singapore-Berkeley Building Efficiency
and Sustainability in the Tropics

Thrust Two: Multi-level Control

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Outline

- Background
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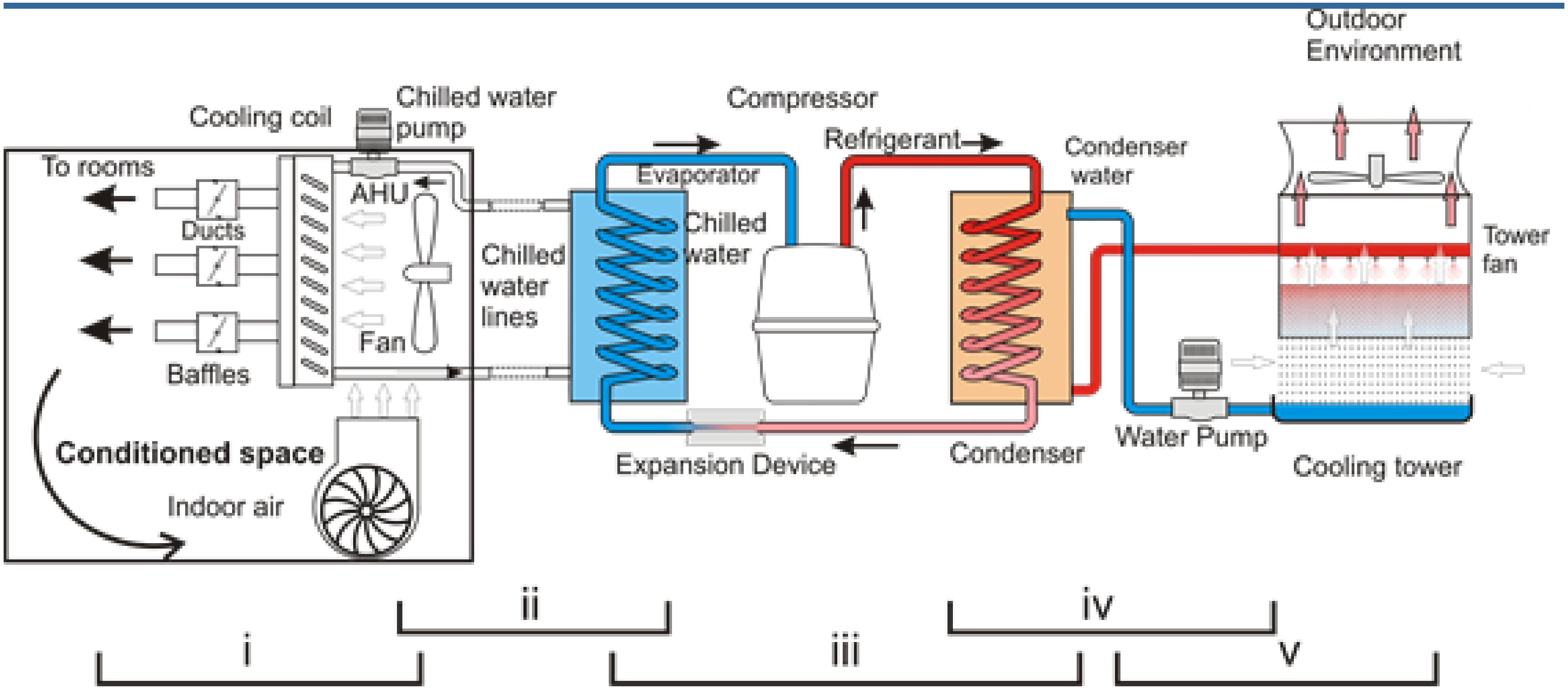
  - Cooperative Control of Air Distribution
  - Scheduling of Non-preemptive Precooling Processes for an In-building Air Distribution System
- Conclusion

Background

Typical Building HVAC System



Five function loops

i) Indoor air loop

ii) Chilled water loop

iii) Refrigerant loop

iv) Condenser water loop

v) Outdoor air loop

Typical Energy Distribution by A/C Elements

The approximate distribution is:

- Chillers: 55%,
- Fans: 35%,
- Pumps: 5%
- Cooling towers: 5%,

Energy consumption very high because of:

- Over-sizing of systems
- Inaccurate or incorrectly located sensors
- Control systems unable to respond to changing conditions, and varying levels of cooling needed in different parts of the air conditioned space.
- Inaccurate modelling of the air circulating in large buildings.
- The tender processes in the purchase of HVAC systems and control based purely on cost and footprint.
- Lack of solutions for local conditions

Motivations and Challenges

Motivations:

- BCA's Green Mark program: electricity consumption in building HVAC system accounts for more than 52% of total electric energy generated in Singapore;
- Optimization and control of HVAC systems can save up to 17% energy

Challenges:

- Two ends open, very complex, different design for different buildings;
- Existing models are far too complex to be used for control and optimization;
- Interactions among HVAC subsystems are hardly understood and modeled;
- The large number of parameters that determine building conditions change continually, prohibiting accurate state estimation and prediction

Reducing energy consumption of A/C

Identified by Techprimer, areas of research which have a significant energy saving potential are:

- Cooling technologies, such as renewable energy and waste heat cooling;
- Desiccant dehumidification;
- Optimization and control systems based on sensor network platforms;
- Innovative air ventilation schemes

Thrust 2: Control

Mission Statement

Develop innovative energy-efficient air-conditioning technologies, information-driven control and optimization technologies, and resource management technologies for tropical buildings to save 50% of energy compared with the current state-of-the-art technology.

Proposed Research Projects of Trust 2

- Active chilled beam systems for tropic buildings
- Renewable energy cooling systems for tropic buildings
- Total dynamic model for control and optimization
- Dynamic control and optimization
- Distributed cooperative multi-level control
- Resource management

Progress in Research

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Active Chilled Beam Based HVAC Systems

Cai Wenjian, NTU

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Motivation

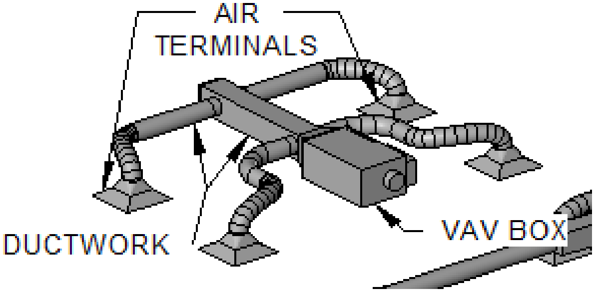
ACB can achieve **25%−30%**** energy savings in cooling compared with **VAV** systems widely adopted in Singapore.

Challenges of ACB in tropical regions

- Difficulty in handling humidity/condensation
- High latent cooling load associated with Dedicated Outdoor Air System (DOAS)

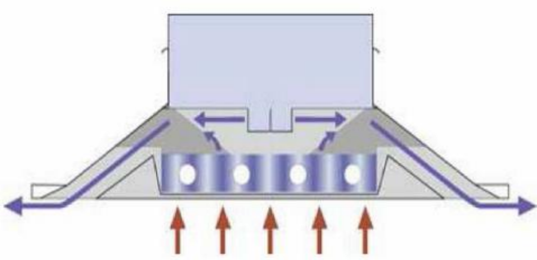
Solutions

- Design ACB to handle both sensible and latent load;
- Minimize latent cooling load in primary air supply;
- Optimize chilled water supply system;
- Advanced optimization and control;
- Verify performance through Lab and real site tests.



Typical All–Air VAV system

Conventional ACB



Air Profile

Research work done

1. Investigation ACB Design and Operation
2. Primary Air System Development
3. Chilled Water System Development
4. Enhancement of Energy Management, Control and Optimization System (EMOCS)
5. Testers and Energy Simulations

Nozzles and Nozzle Tester

Nozzle tester

Different Nozzles

ACB and ACB Tester

ACB Tester

First Prototype of ACB

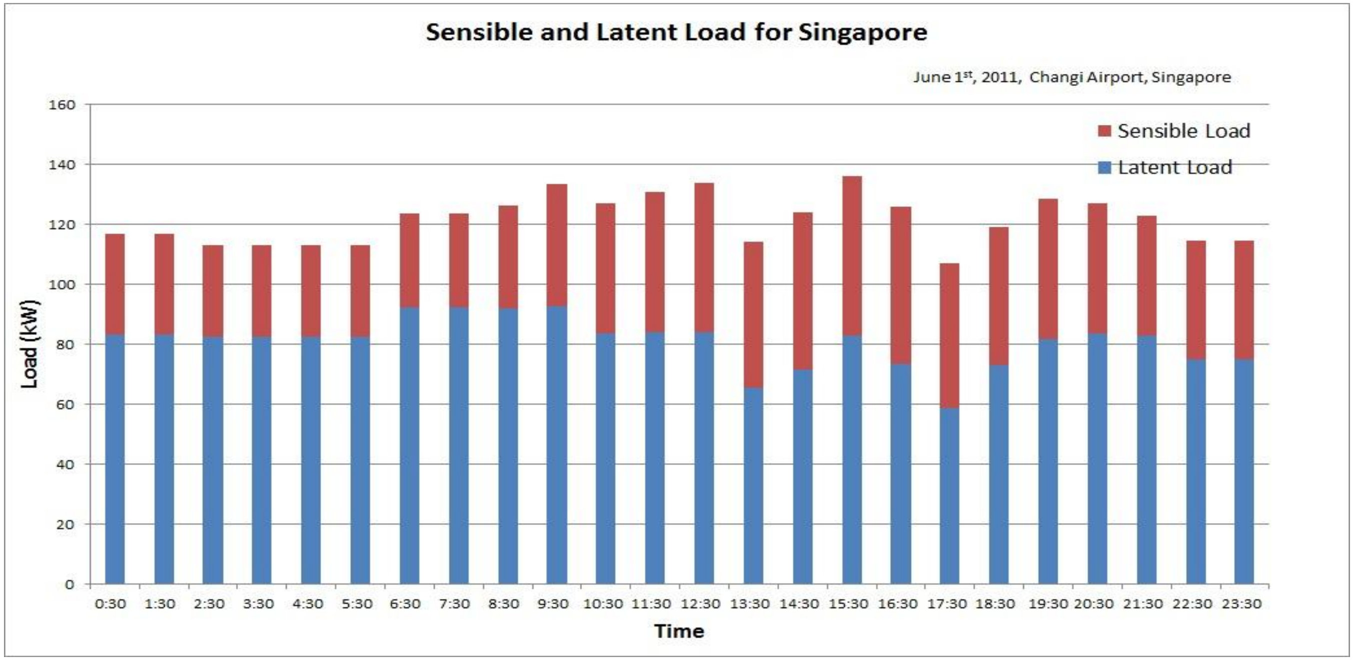
Future Work

1. Design both horizontal and vertical configurations and test their performance;
2. Develop control algorithms for ACB control and condensate handling;
3. Build a testing Lab;
4. Two collaborations with outside entities.

Liquid Desiccant Dehumidification System

Needs for Dehumidification

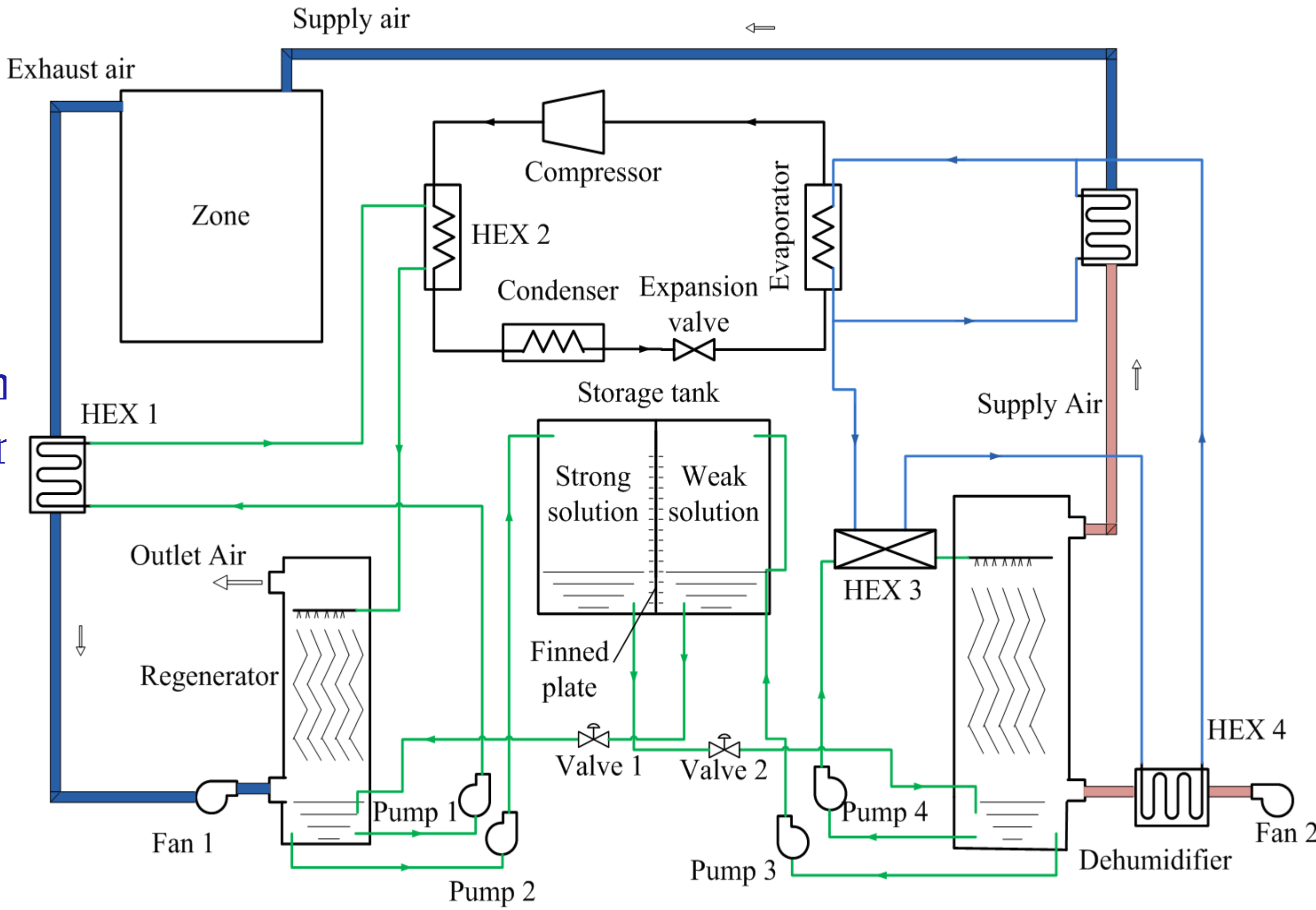
- Lower humidity levels in occupied spaces
- Reduced condensation on cooling coils, drain pans and duct work.
- Downsizing of HVAC equipment & ductwork.
- Separating the moisture and sensible loads to effectively handle increased outside air.



Most of the load in fresh air comes from moisture, the total sensible heat load is much smaller. Even with fresh air is cool, it must be dehumidified

New LDDS Concept

- Flexible configuration
  - Solar
  - Waste heat recovery
  - Double heat pump
- Waste heat recovery from exhaust air of regenerator
- Batch operation of the dehumidifier through temperature and flow control
- Advanced optimization and Control system

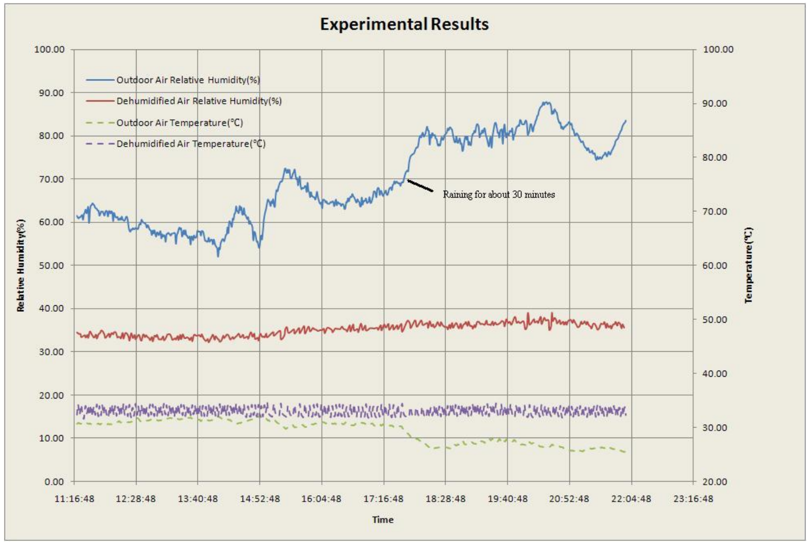


Testing Facility

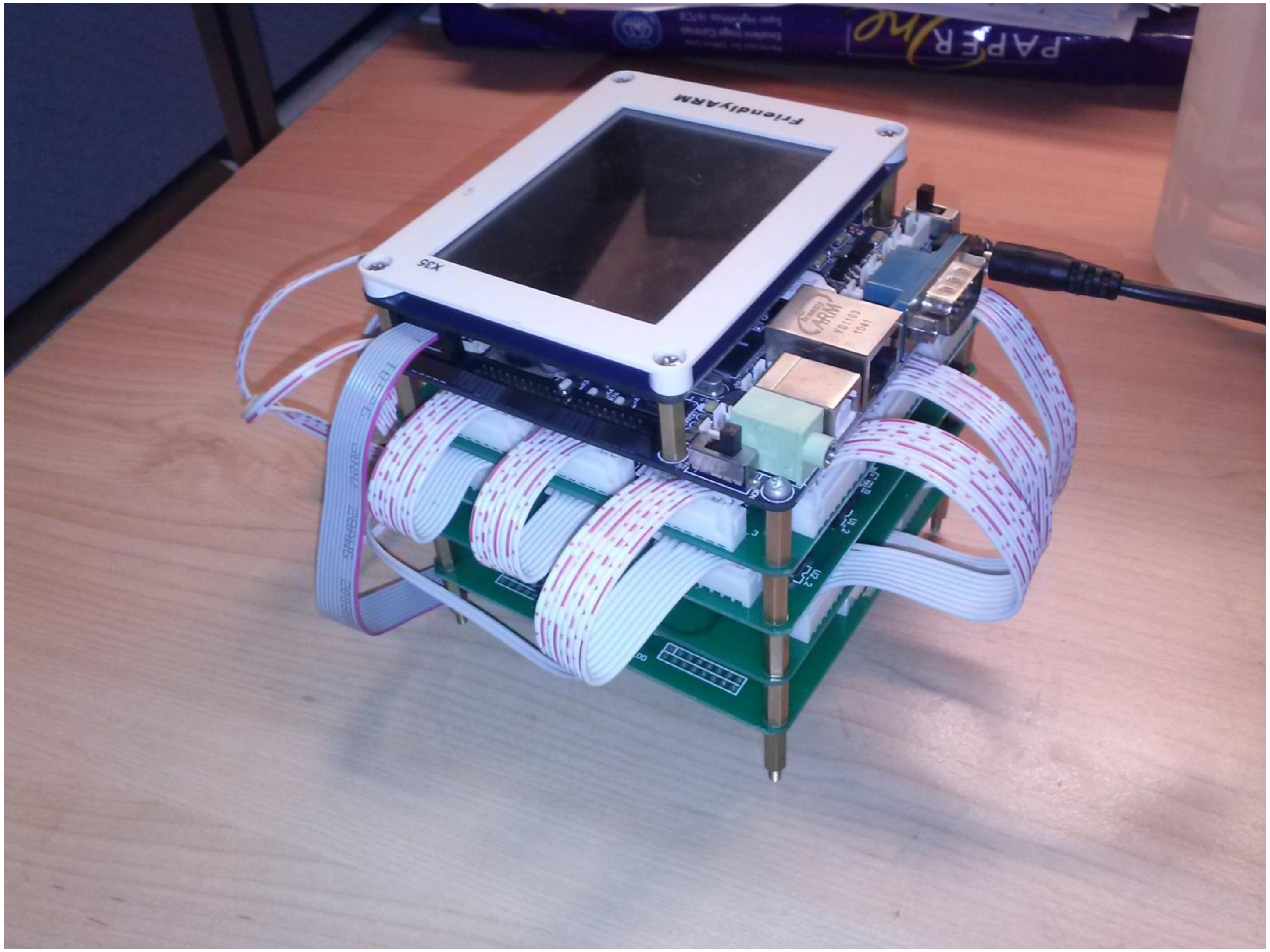
Testing conditions

Outlet air Temperature	30°C
Outlet air Humidity	30-35% R.H.
Dehumidification Temperature	25°C
Concentration of solution	35%-40%
Regeneration Temperature	60°C
Fresh air flow rate	1000 m^3/hr

Testing results



Dedicated Controller Developed



Future Work

1. Integrated system test (combined mechanical system and automation system);
2. Integration with chiller plant to test the energy performance on real building;
3. Commercialization;
4. Two collaborations with outside entities.

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Decomposition Approach for Modeling of Complex Systems

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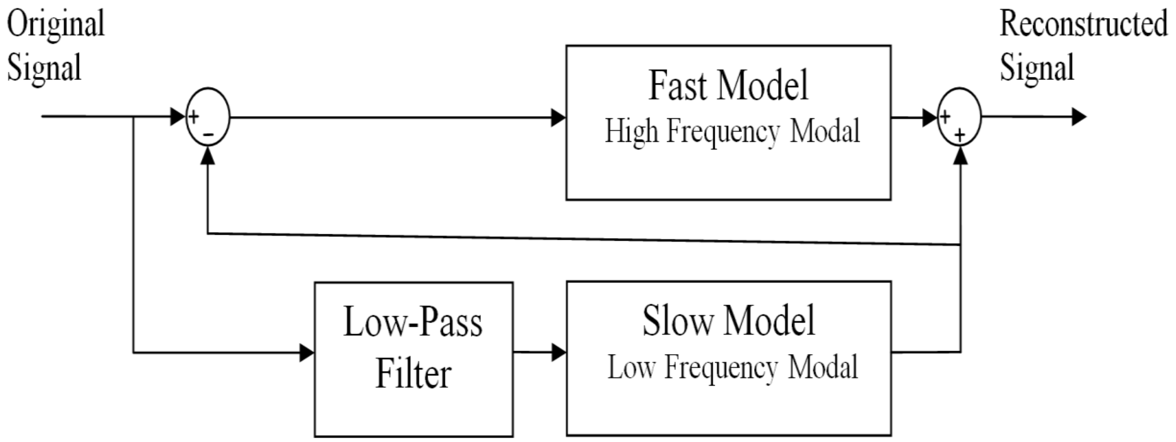
1. Introduction

- In building systems, some variables (such as flow rate) have high frequency modal, while others (such as temperature) have low frequency modal, which constitutes complexity. For multi-level optimal control for this kind of complex systems, we need to identify accurate model of them firstly.

- In this work, we present a new modeling method to get better accuracy over ordinary method.

2. Proposal Method

- Decompose the original signal into two components: fast modal and slow modal.
- Model the slow modal signal firstly.
- Then construct fast modal signal and model it.
- At last, reconstructed signals from slow model and fast model are added as the final reconstructed signal. The block diagram is as follows



3. Low Pass Filter

- Use a low-pass filter:

$$F(s) = \frac{K}{1+\tau s}, \qquad f_c = \frac{1}{2\pi\tau}.$$

where τ is time constant of filter, K is the filter pass-band gain.

- Transform continuous low pass filter into discrete form:

$$y(i) = \alpha x(i) + (1-\alpha) y(i-1), \qquad \alpha = \frac{\vartriangle T}{\vartriangle T + \tau}.$$

where $\vartriangle T$ is the sampling period of discrete system.

3. Simulation

- The original signal is composed by two linear signals:
  - Slow modal:

$$u(t) = 2.9988 \times u(t-1) - 2.9976 \times u(t-2) + 0.9988 \times u(t-3).$$

  - Fast modal:

$$u(t) = 2.6351 \times u(t-1) - 2.6363 \times u(t-2) + 0.9988 \times u(t-3) + \varepsilon(t).$$

  where the initial condition is set as $u(1)=10$, $u(2)=10$, $u(3)=10.002$. For fast modal signal, five different level white noise $\varepsilon(t)$ are added for comparison.
- Linear regression is applied as the modelling method.
- Model quality is checked based on the root mean square error (RMSE) of original signal and reconstructed signal.

	G1						G2					
	Ordinary		Decomposition		Improvement/%		Ordinary		Decomposition		Improvement/%	
	Train	Test	Train	Test	Train	Test	Train	Test	Train	Test	Train	Test
α=0.5	0.0085	0.0098	0.0009	0.0008	89.4500	91.8694	0.4299	0.4131	0.0009	0.0008	99.7908	99.8081
	0.0129	0.0201	0.0011	0.0010	91.7045	95.1508	0.4308	0.4162	0.0011	0.0010	99.7511	99.7656
	0.0615	0.0463	0.0035	0.0034	94.3748	92.5897	0.4705	0.4344	0.0035	0.0034	99.2652	99.2099
	0.1205	0.1087	0.0068	0.0067	94.3619	93.8489	0.6938	0.6023	0.0068	0.0067	99.0209	98.8902
	0.1558	0.1476	0.0333	0.0337	78.6436	77.1281	2.2341	1.2791	0.0333	0.0337	98.5107	97.3615
α=0.1	0.0085	0.0098	0.0041	0.0039	51.6061	59.9738	0.4299	0.4131	0.0041	0.0039	99.0404	99.0553
	0.0129	0.0201	0.0044	0.0044	65.6783	78.3599	0.4308	0.4162	0.0044	0.0044	98.9701	98.9540
	0.0615	0.0463	0.0055	0.0051	91.0145	89.0961	0.4705	0.4344	0.0055	0.0051	98.8263	98.8374
	0.1205	0.1087	0.0076	0.0072	93.7150	93.4115	0.6938	0.6023	0.0076	0.0072	98.9086	98.8113
	0.1558	0.1476	0.0300	0.0304	80.7685	79.4174	2.2341	1.2791	0.0300	0.0304	98.6589	97.6256
α=0.05	0.0085	0.0098	0.0064	0.0066	25.0088	32.1266	0.4299	0.4131	0.0064	0.0066	98.5131	98.3981
	0.0129	0.0201	0.0077	0.0089	40.5493	55.5807	0.4308	0.4162	0.0077	0.0089	98.2161	97.8530
	0.0615	0.0463	0.0098	0.0088	84.0669	81.0599	0.4705	0.4344	0.0098	0.0088	97.9188	97.9805
	0.1205	0.1087	0.0111	0.0102	90.7834	90.6476	0.6938	0.6023	0.0111	0.0102	98.3994	98.3126
	0.1558	0.1476	0.0307	0.0309	80.3074	79.0816	2.2341	1.2791	0.0307	0.0309	98.6267	97.5869

G1: The order of linear model in ordinary method is 3
G2: The order of linear model in ordinary method is 6
α: The smoothing factor of corresponding low pass filter
Ordinary: Root mean square error of output from ordinary modeling
Decomposition: Root mean square error of output from decomposition modeling
Improvement: Decomposition modeling improvement in percentage compared with ordinary modeling

Future work

- Currently, the cutoff frequency is set manually. This work is very time-consuming and dull. A method for tuning cutoff frequency of low-pass filter adaptively is under improvement and will be applied to this new method in further study.
- The decomposition approach can be extended to more than two model case.
- Develop multi-level optimal control based on such models and plant architecture

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Cooperative Control of Air Distribution

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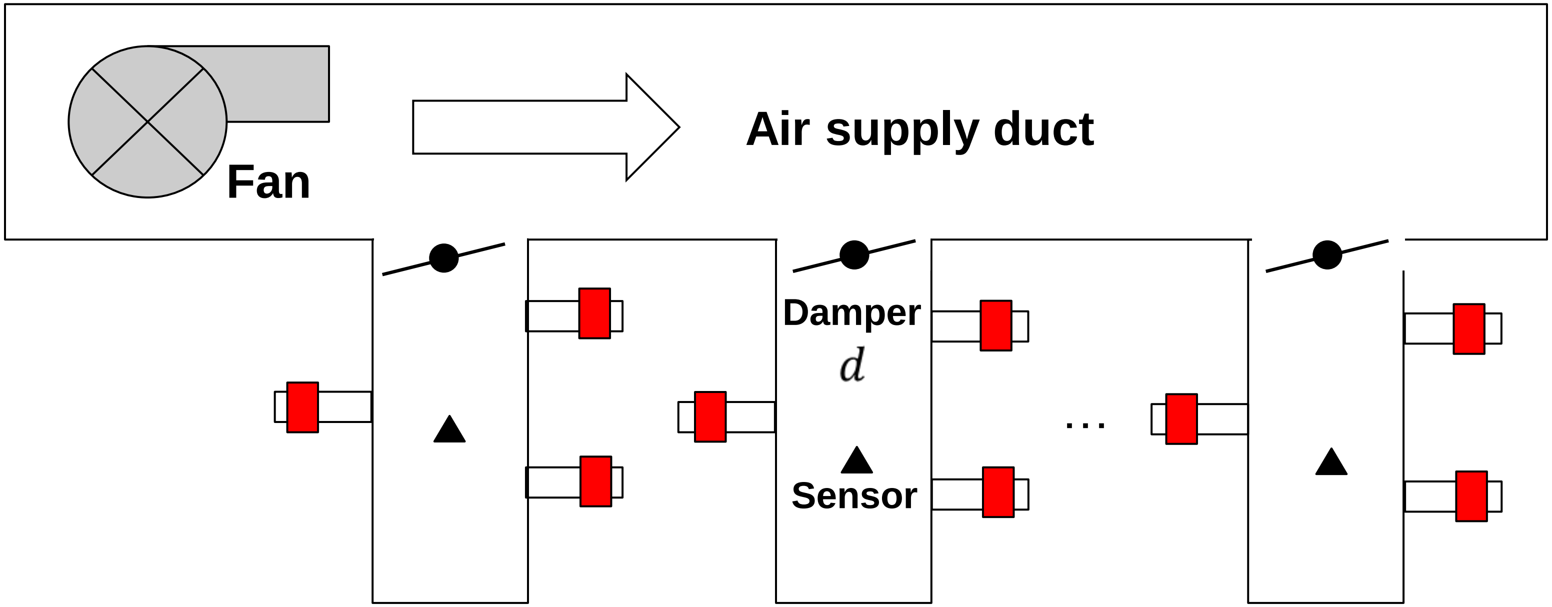


🟥 VAV box

Motivation

- The cool air is sent to air supply duct driven by a fan and then distributed to each zone through variable air volume (VAV) box.
- VAV is conventionally controlled based on PID.
- When the damper of one VAV changes, the air pressure of the supply duct is affected which essentially affects the pressure at the inlet of each zone. The air pressure conversely affects the air flow rate which leads to changes on the other VAVs.

Motivation

- The power consumption of fan is proportional to the cube of air flow rate. A fluctuating air flow rate causes more energy consumption.
- A distributed cooperative control strategy can be introduced to reduce this air flow fluctuation.

Objective

- Adjust the pressure control dampers in a cooperative manner such that the air flow rate is smooth when the environment is changing.
- The pressure at each branch is equal to a desired value.
- Adjust the VAV box so that the temperature at each zone converges to a comfort level.

Challenges

- No universal air pressure model exists.
- The air pressure and air flow rate are coupled. When adjusting VAV box, the air pressure is affected which conversely affects the air flow rate.
- The dampers for pressure control are coupled.

Approach

- Two level control

✓ Temperature control (lower level)

Based on temperature measured by the sensors in the zone to control VAV box and supply cool air flow.

✓ Pressure Control (high level)

Consensus based cooperative control is applied to the damper based on pressure information of neighbor branches.

Temperature Model

- Temperature model of zone

$$\dot{T}_i(t) = \dot{m}_i(t) K_{1,i}(l - T_i(t)) + K_{2,i}(s_i - T_i(t))$$

- T_i, l and s_i are temperatures of zone i, supply air and heat sources;

$$\dot{m}_i(t) = u_i(t)\sqrt{\frac{2p_i(t)}{\rho}}$$

is the mass flow rate, u_i is the VAV damper open area, p_i is the air pressure of branch i, ρ is the air density;

- $K_{1,i}$ and $K_{2,i}$ are constants.

Pressure Model

- Pressure model of branch i

$$\sqrt{p_i(t)} = f_i(d_1(t),\cdots,d_n(t),u_i(t),P_{fan},t)$$

P_{fan} is pressure difference generated by the supply fan, d_j is the damper open area, f_i is a nonlinear function satisfying

$$\frac{\partial f_i}{\partial d_i} > 0, \quad \frac{\partial f_i}{\partial d_j} < 0, \quad -F < \frac{\partial f_i}{\partial u_i} < 0, \quad \sum_{k=1}^{n} \frac{\partial f_i}{\partial d_k} > 0$$

Objective

- Design u_i such that the temperature T_i converges to a comfortable value T_0.
- Design d_i so that the pressure at each branch is equal to p_0.
- **Challenges**

- The two models are coupled. u_i not only affects T_i, but also affects pressure p_i.
- p_i conversely affects T_i.
- p_i is affected by other dampers d_j.

Cooperative Controller

- The control input of u_i and d_i are

$$\dot{d}_i(t) = \alpha\left[\sum_{k\in\mathcal{N}_i}\left(\sqrt{P_k(t)} - \sqrt{P_i(t)}\right) + \beta\left(\sqrt{P_0} - \sqrt{P_i(t)}\right)\right]$$

$$\dot{u}_i(t) = \gamma(T_i(t) - T_0)$$

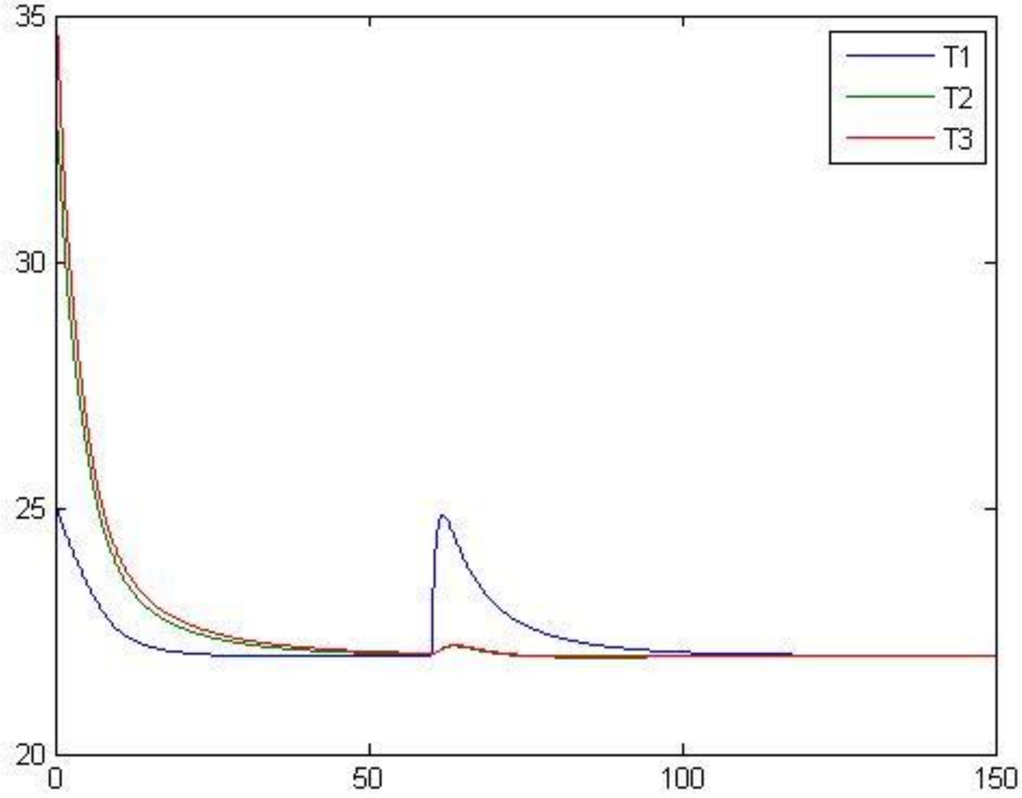
- α, β and γ are positive constants.
- There exists a closed set B such that when $p_i(0) - p_0$, $T_i(0) - T_0$ and $u_i(0) - \bar{u}$ are in B,

$$\lim_{t\to\infty}(p_i(t) - p_0) = 0, \quad \lim_{t\to\infty}(T_i(t) - T_0) = 0$$

where $\bar{u}$ is the steady control input.

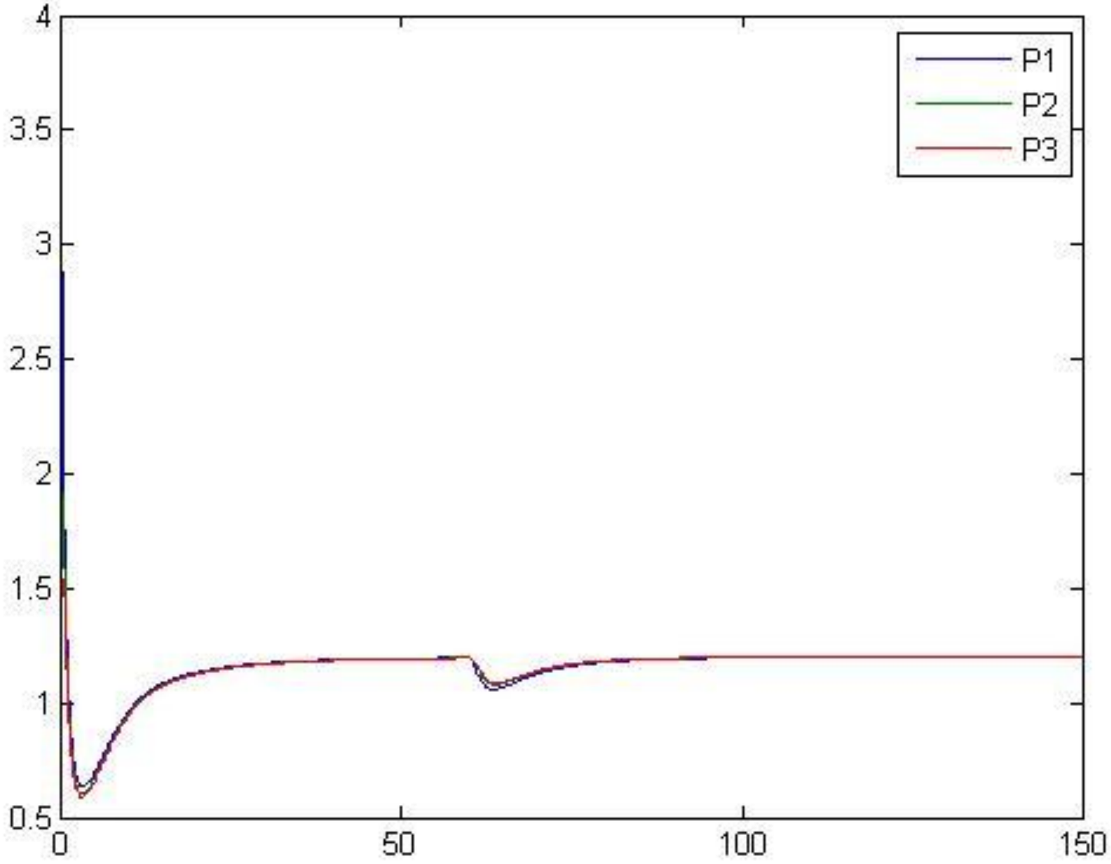
Simulation

- Three zones are considered. A heat source is introduced at 60. The set point is $22^{o}C$



Simulation

- The pressure changes correspondingly at 60.



Future Work

Active chilled beam (ACB) system based room temperature distribution control

- Consider the trade off between the number of ACBs and the tolerance of temperature distribution deviation. Design the best locations of the ACBs.
- Cooperatively control multiple ACB systems to in a room to meet the cooling demand of each zone based on human activity models.

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Scheduling of Non-preemptive Precooling Processes for an In-building Air Distribution System

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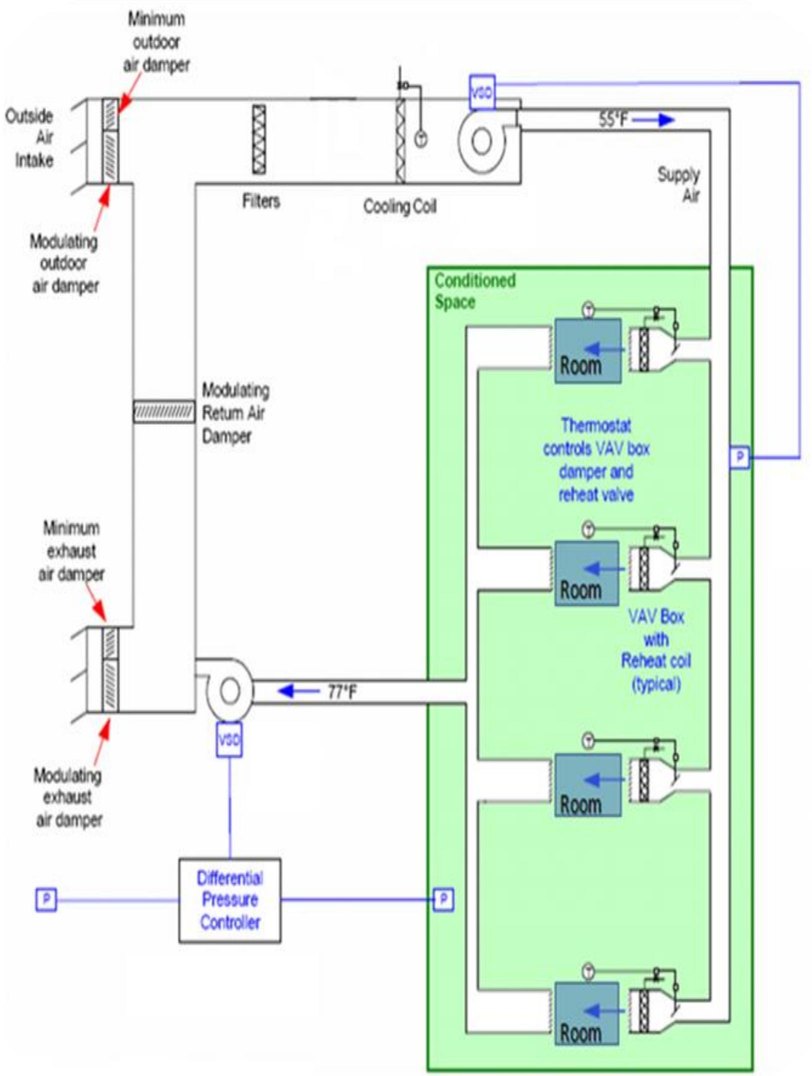
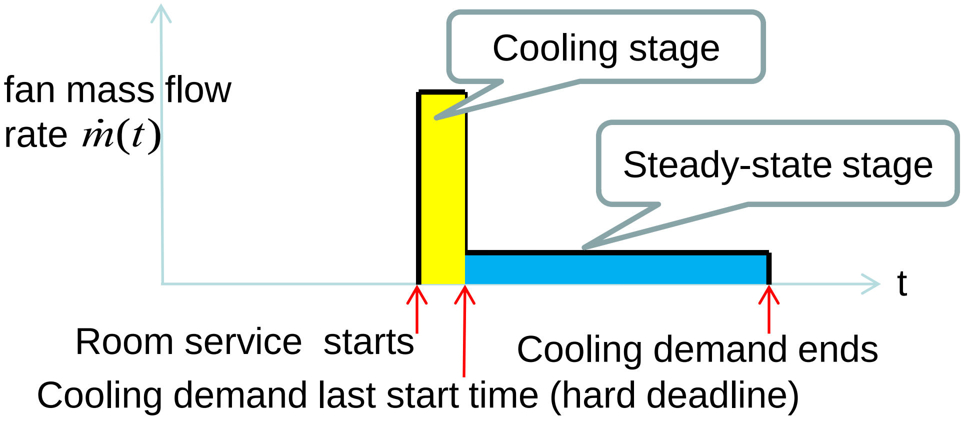
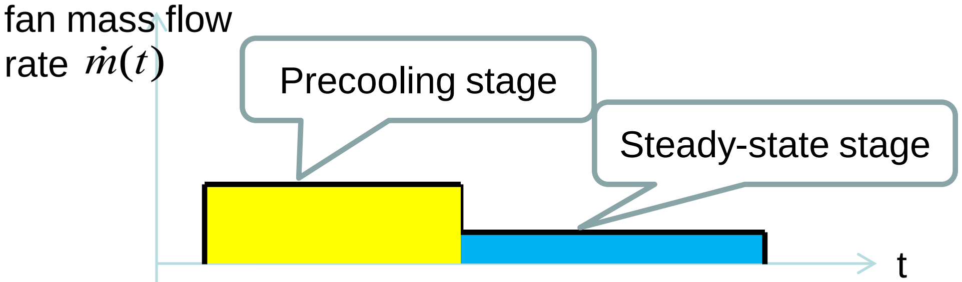
Motivation



- Air distribution = 30% of HVAC energy budget
- Cooling air distribution energy allocation:





- Elongated precooling processes saves energy
- Many room services offer more energy saving!
- It is a planning problem, not a control problem
- Need to compute set points for control
- Exploit nonlinearity of fan power function!

System Setup and Assumptions

- Room cooling demands known from Building Operating System using occupancy sensing and forecasting:

$$\{T_{s,i},\ t_i^{d},\ t_i^{de}\ |\ i = 1, \ldots, n\}$$

$T_{s,i}$ = the desirable temperature for room i
t_i^{d} = cooling demand starting time for room i
t_i^{de} = cooling demand ending time for room i

- Non-preemptive cooling strategy with piecewise constant mass flow rate for each room is chosen to simplify planning problem
  - High-volume air flow for transient operation
  - Low-volume air flow for steady-state operation
- Cooling load for each room is known and time invariant (will be relaxed in the future)
- Maximum mass flow rates of each room and the fan are known
- Air mixing in each room is assumed to be instantaneous (will be relaxed in the future)

General Planning Problem Formulation

Minimize:

$$J = \int_0^T \left(\sum_{i=1}^n I_i^b(t, t_i^b,\ t_i^e)\dot{m}_{i,1} + I_i^e(t, t_i^e,\ t_i^{de})\dot{m}_{i,2} \right)^3 dt$$

where

$$I_i^b(t, t_i^b, t_i^e) = \{1 \text{ if } \ t_i^b \le t < t_i^e, 0 \text{ else}\}$$

$$I_i^e(t, t_i^e, t_i^{de}) = \{1 \text{ if } \ t_i^e \le t < t_i^{de}, 0 \text{ else}\}$$

Subject to:

- max room flow rate
- max fan flow rate
- steady-state thermal balance

- Difficult optimization problem!
- Sub-optimal solutions can be found using
  - Nested partition methods with random sampling
  - Lagrangian dual methods with differentiable approximations

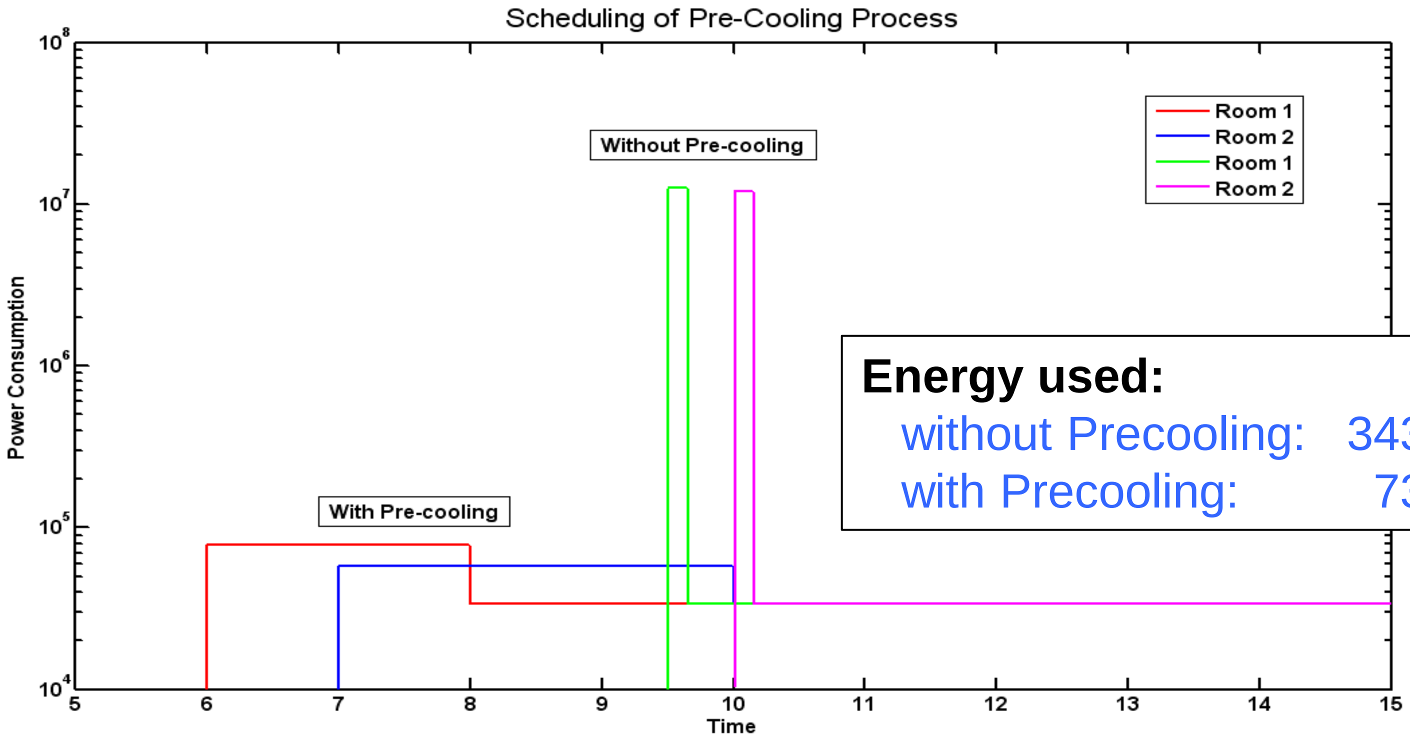
Simulation Results for 2 Rooms

Simulation data:

M_i = 10 kg T_c = 4°C $T_{r,i}$ = 27°C

T_e = 30°C Q_i = 40 kg/hour

Variables	Room 1	Room 2
$T_{s,i}$	22°C	23°C
t^d (hours)	09:40	10:10



Energy used:

without Precooling: 3432140 J

with Precooling: 734000 J

Scheduled non-preemptive precooling → 78.61% energy saving !

Future work

- Develop efficient methods to solve planning problem
- Incorporate air-mixing dynamics
- Introduce preemptive precooling processes with piecewise constant mass flow rates
- Investigate precooling process with arbitrary mass flow rate functions to unifies preemptive and non-preemptive cases in a general planning problem
- Explore impact of uncertainty from cooling demand forecasts

Thank you