大连理工大学

Mechanism and Technology Application of Non-Uniform Environment Creation in Large Public Buildings

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Part 1

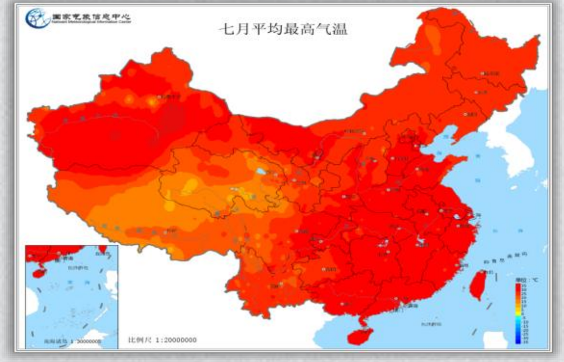
Introduction

- Research Background
- Research Status at Home and Abroad
- Research Contents

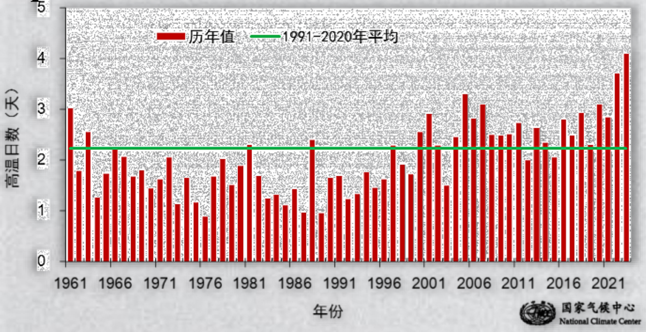
Research Background

Extreme Climate

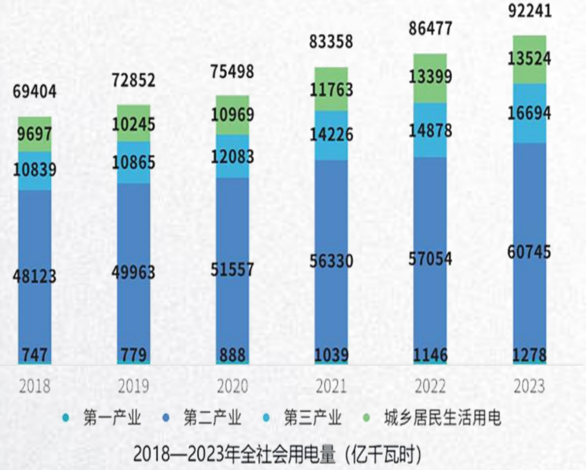
Climate warming continues. Summer temperatures rise annually, overloading power grids



In 2024, 4 national-scale heatwaves occurred. Power shortages in many provinces exceeded 1 trillion kWh



On July 4, 2025, national electricity demand reached a record high. AC accounted for 37% of total power use.



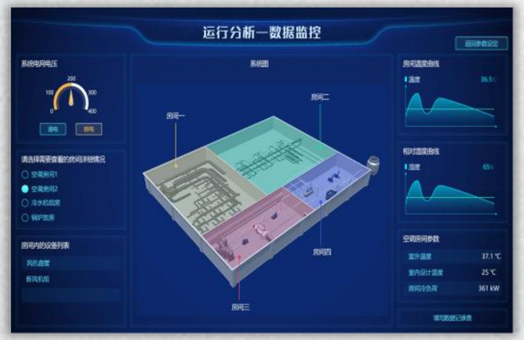
From 2018–2023, electricity consumption kept increasing

Building energy demand must be urgently reduced!

Research Background

Supply-Demand Imbalance

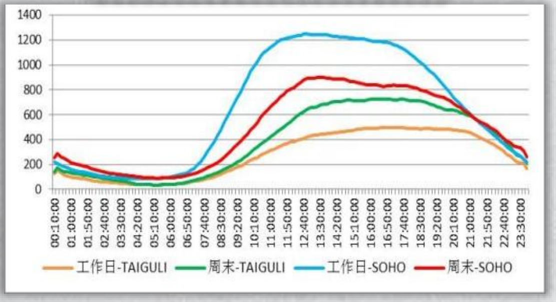
Mismatch Between Traditional HVAC Systems and Actual Needs



Full-area air supply in large spaces leads to spatial mismatch

Constant operation of HVAC systems causes temporal

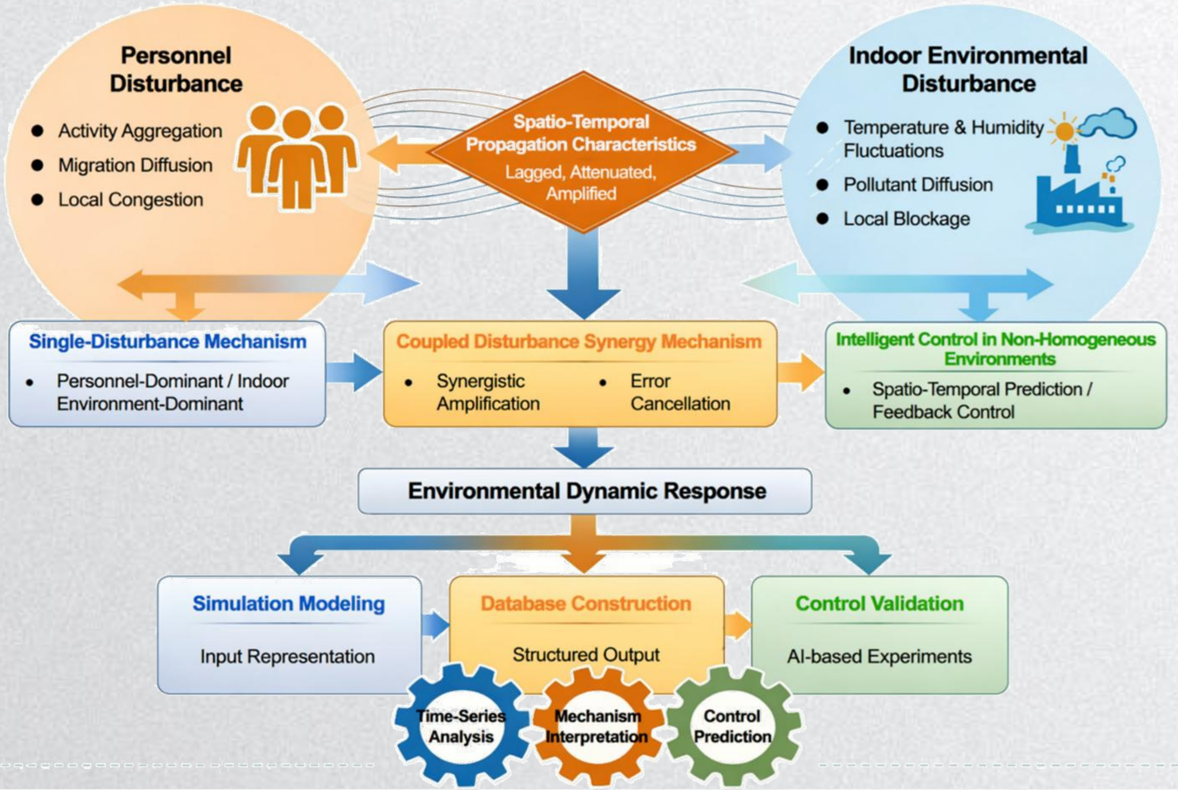
- **Traditional methods overlook real-time demand**
- **End-point thermal transfer is not fully analyzed**
- **Urgent need for a human-centered theory considering partial time and partial space!**



Research Background

Challenges and Limitations

Limitations of Traditional Sensing and Control Under Dynamic Environmental Demands

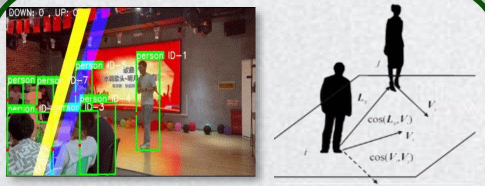


Breakthrough Points

1. Occupant information acquisition
2. Movement behavior modeling
3. Pollutant dispersion mechanism
4. Rapid environmental recognition

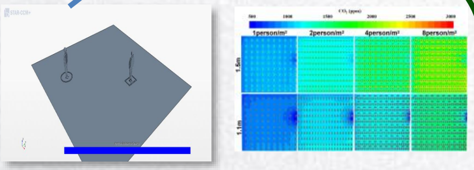
Research Contents

Technical Framework & Implementation

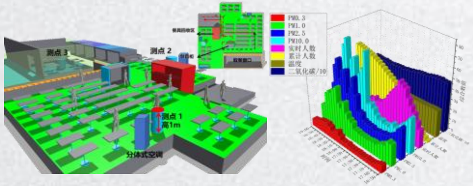


Information Input: Based on computer vision (YOLO), real-time occupant detection is conducted, and a movement model is built.

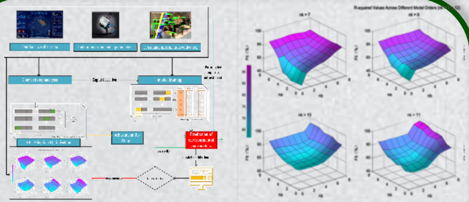
Spatial Layer



CFD simulations and real-world validation are used to explore how occupant movement affects the environment under different scenarios.



Multi-round field measurements in densely populated scenes are performed to explore correlations between occupant distribution and environmental changes.



A data-driven prediction model is developed to realize rapid forecasting and optimization of environmental parameters.

Temporal Layer

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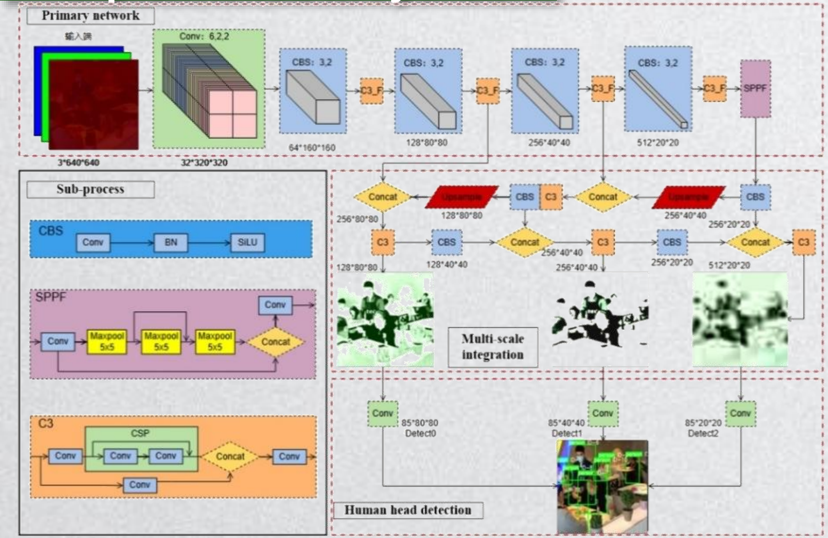
Part 2

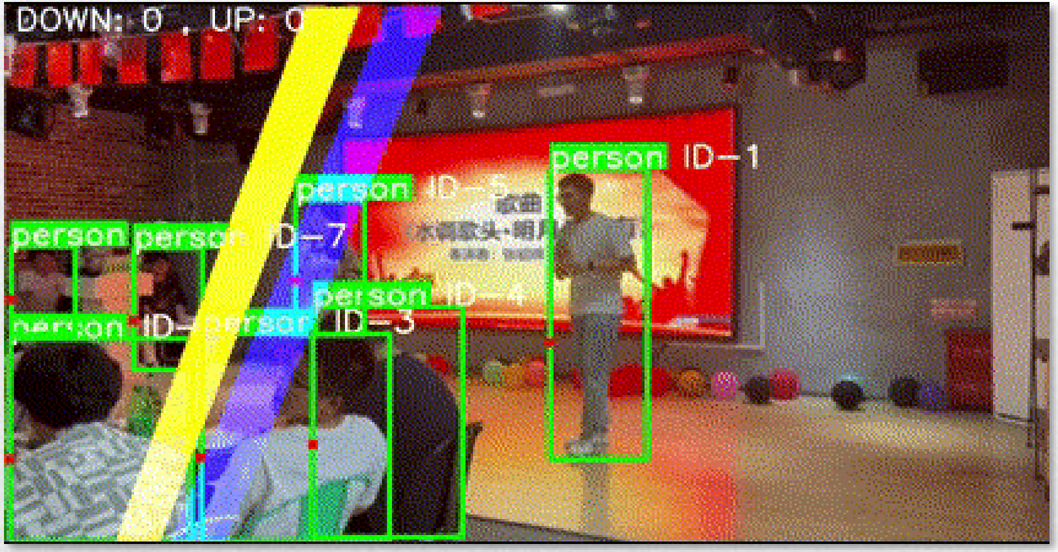
Dynamic Perception and Movement Modeling of Occupants

- Dynamic information acquisition in densely populated spaces
- Movement modeling — Social Force Model
- Movement prediction CFD coupled simulation

Dynamic Information Acquisition in Crowded Spaces

YOLO-based Detection Implemented in Python

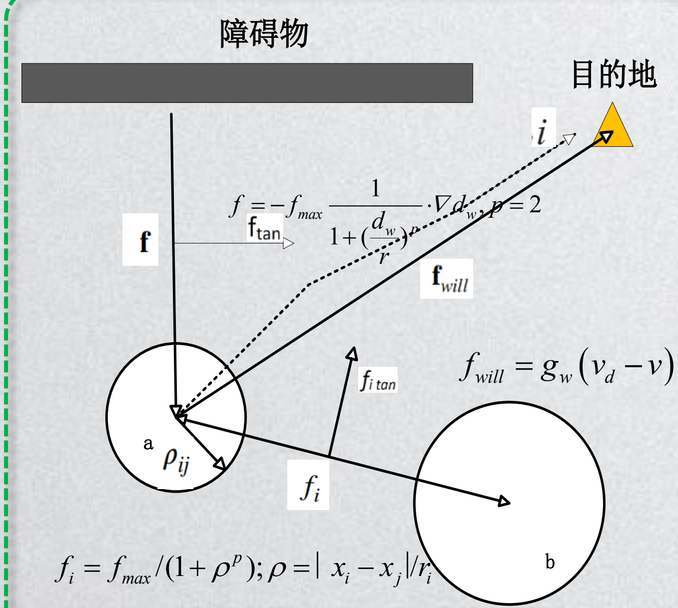





```
Fusing layers...
Model Summary: 290 layers, 21172173 parameters, 0 gradients, 48.9 GFLOPs
类别: person | id: 3 | 上行撞线 | 上行撞线总数: 1 | 上行id列表: [3]
类别: person | id: 9 | 上行撞线 | 上行撞线总数: 2 | 上行id列表: [9]
类别: person | id: 3 | 下行撞线 | 下行撞线总数: 1 | 下行id列表: [3, 11]
类别: person | id: 11 | 下行撞线 | 下行撞线总数: 2 | 下行id列表: [11]
类别: person | id: 11 | 上行撞线 | 上行撞线总数: 3 | 上行id列表: [11]
类别: person | id: 11 | 下行撞线 | 下行撞线总数: 3 | 下行id列表: [11]
类别: person | id: 3 | 上行撞线 | 上行撞线总数: 4 | 上行id列表: [3, 11]
类别: person | id: 11 | 上行撞线 | 上行撞线总数: 5 | 上行id列表: [11]
类别: person | id: 2 | 上行撞线 | 上行撞线总数: 6 | 上行id列表: [2]
类别: person | id: 2 | 下行撞线 | 下行撞线总数: 4 | 下行id列表: [11, 2]
```

This method is well-suited for complex and dynamic human flow environments, providing accurate input data for subsequent environmental prediction models.

Occupant Movement Modeling — Social Force Model



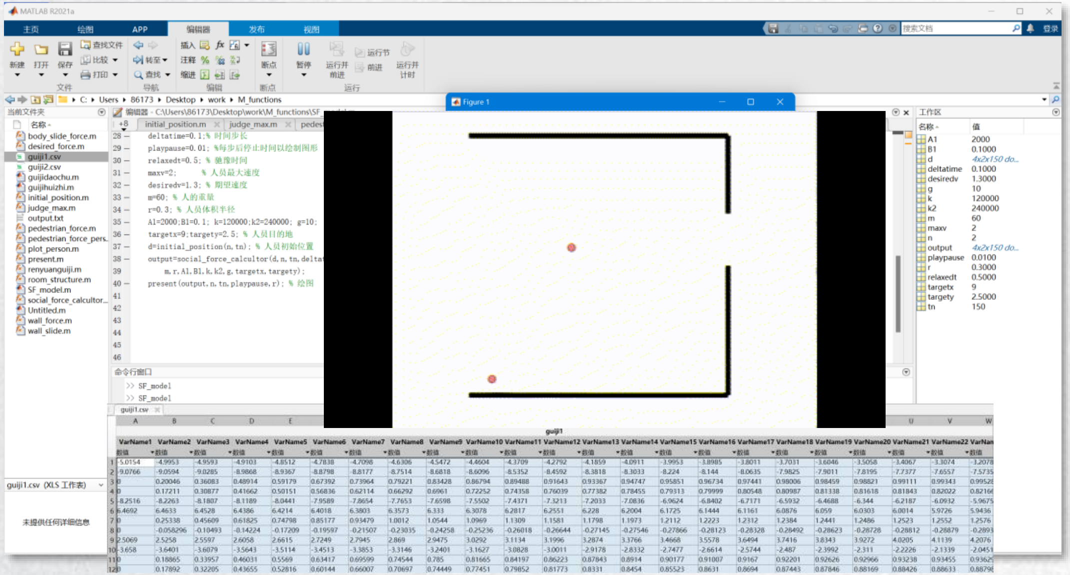
Model Logic

The model is built on three core forces:

Self-driving force (toward goal)

Repulsive force

Contact force (from physical interaction)



Simulation & Export in MATLAB

Supports multi-agent trajectory simulation

Exports trajectory data, including position and directional speed

Enables coupled simulation with other platforms (e.g., CFD)

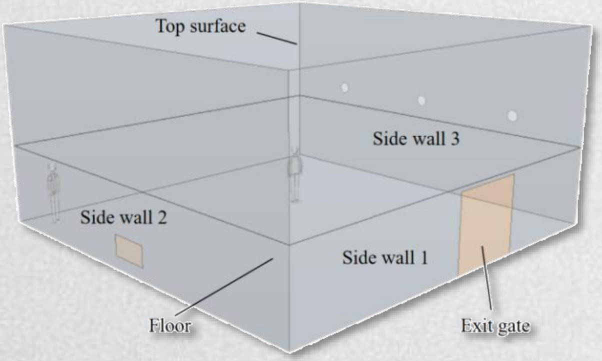
Part 3

Impact of Occupant Movement on Key Environmental Parameters

- Simulation Setup and Validation
- Analysis of Environmental Parameters
- Impact and Interaction of Human Flow on the Environment

Simulation Setup and Validation

Geometry Model Setup

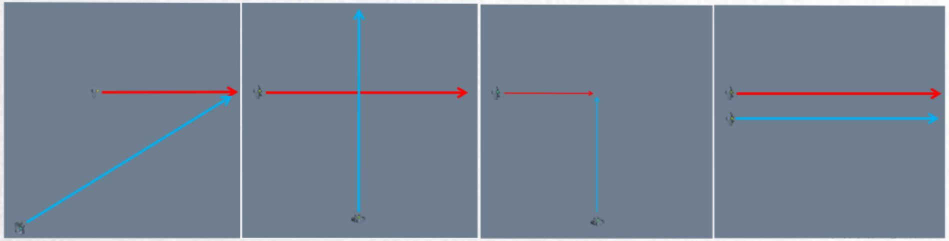


Model: Side-supply, bottom-return room

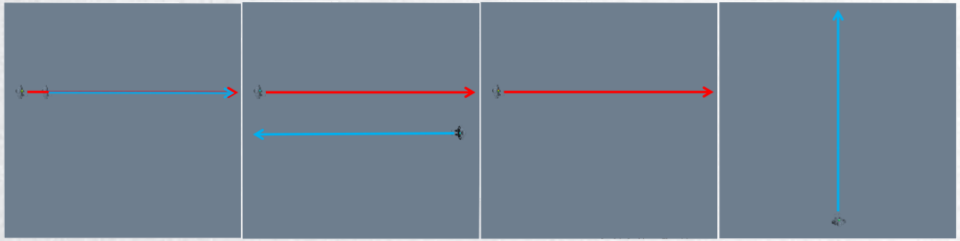
Room size: 10 m × 10 m × 5 m (L × W × H)

Supply vent: 3 m above floor

Return vent: 800 mm × 500 mm single-layer louver, 0.3 m above floor



d) Physical Model and Pedestrian Flow Path Map (Scenarios 1–4)



e) Physical Model and Pedestrian Flow Path Map (scenarios 5–8)

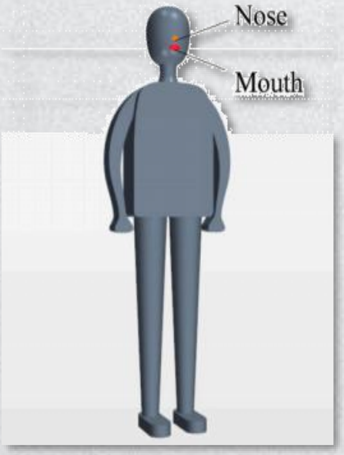
Eight Typical Movement Scenarios

Complex motion scenarios are decomposed into 8 typical types

Focus is placed on the first 3, with the remaining 5 used for comparative analysis

Simulation Setup and Validation

Boundary Type	Parameter Settings
Supply vent	Velocity inlet, 4 m/s, 18°C, CO_2: 0.04%
Return vent	Pressure outlet
Pedestrian nose	2~2 m/s velocity, 36°C, CO_2: 5%
Pedestrian speed	1 m/s (constant), movement force not modeled
Pedestrian surface	Wall boundary, 100.2 W/m² heat flux
Other walls	Adiabatic no-slip surface
Initial condition	26°C, CO_2: 0.05%
Aerosol particles	Diameter: 1 μm, Temp: 36°C, exhaled at 5000 particles/s
CO_2	Diffusivity: 1.64E–5, Schmidt number: 0.94



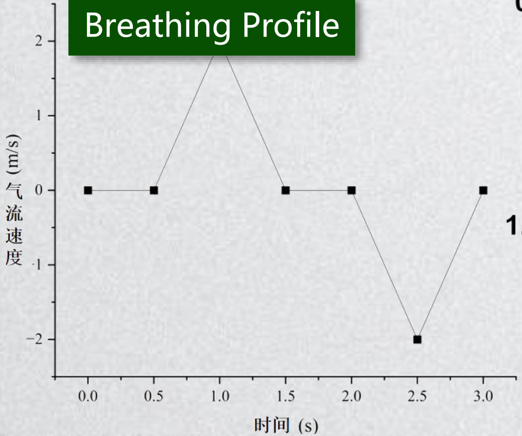
Human Model

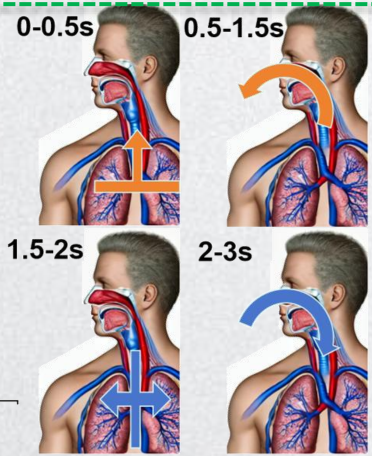
Upright posture, height: 1.7 m

Nose: two circles, radius 0.005 m

Mouth: elliptical, axes 0.03 m and 0.02 m

Breathing Profile





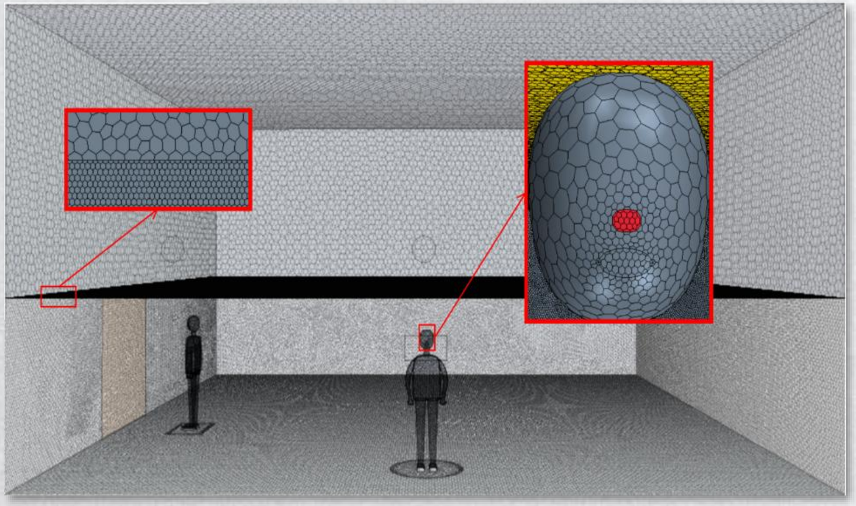
Simulated realistic pulsed breathing

3s cycle: each inhale exhale ranges 0–2 m/s, gradual ramp

Duration: 1s per phase + smooth transition (zero velocity in between)

Simulation Setup and Validation

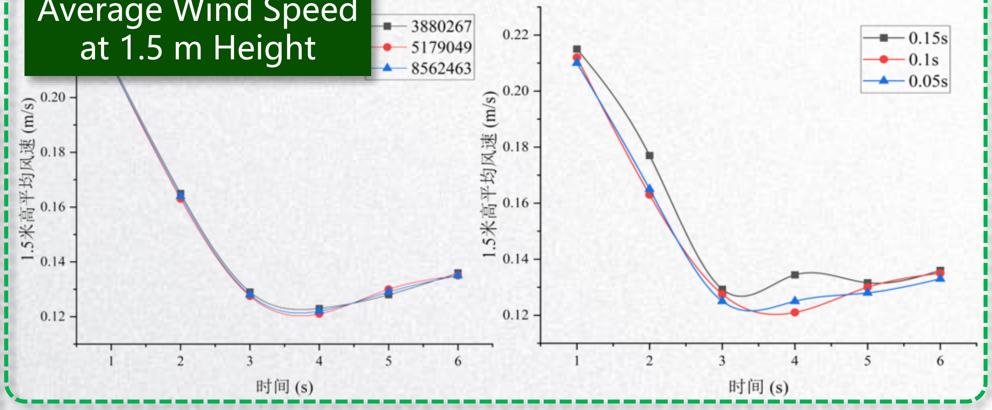
Mesh and Independence Verification



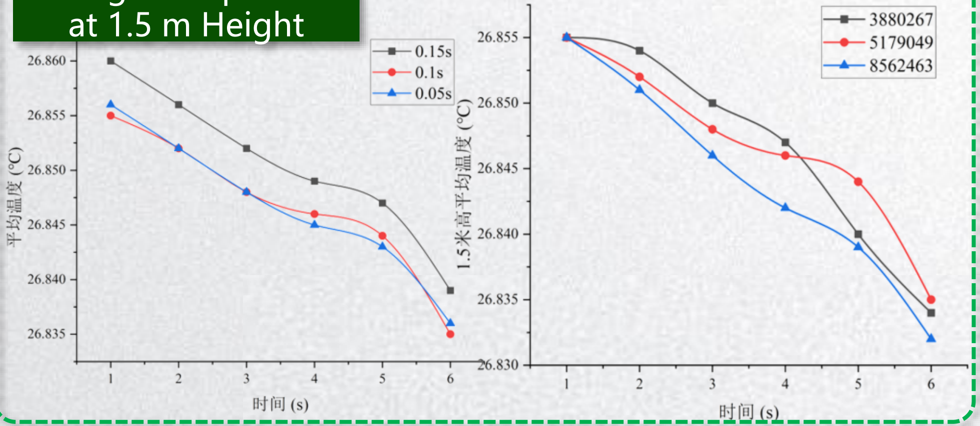
Mesh Model

All parameter errors are within 10%
Grid Convergence Index (GCI): 1.36%
Indicates that using a time step of 0.1 s and 5,179,049 cells yields reliable results

Average Wind Speed at 1.5 m Height

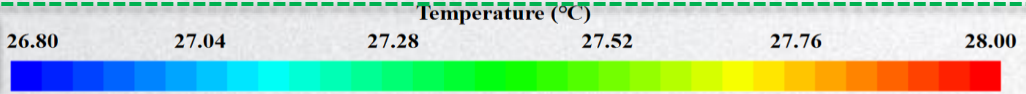


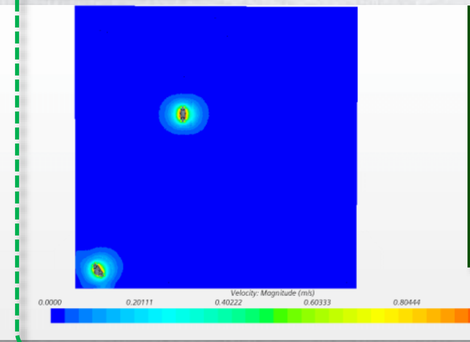
Average Temperature at 1.5 m Height



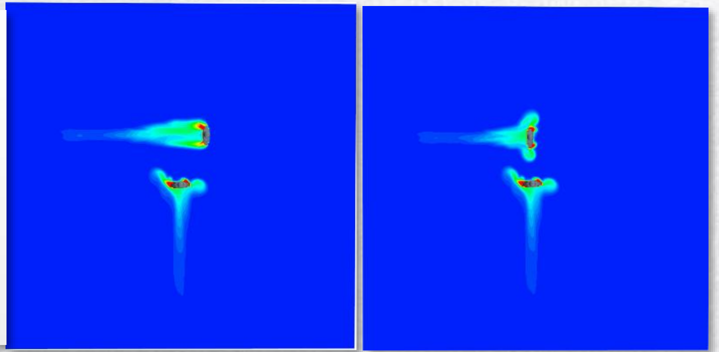
Environmental Parameter Analysis

Temper



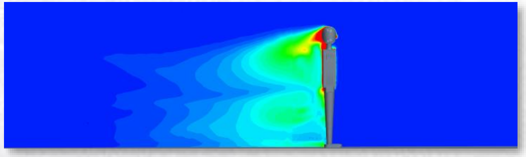


Temperature Field at 5s

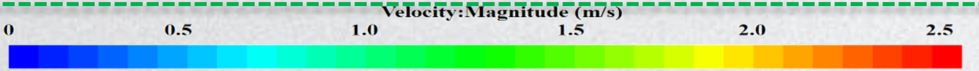


Human movement has negligible impact on overall air temperature (less than 0.01°C)

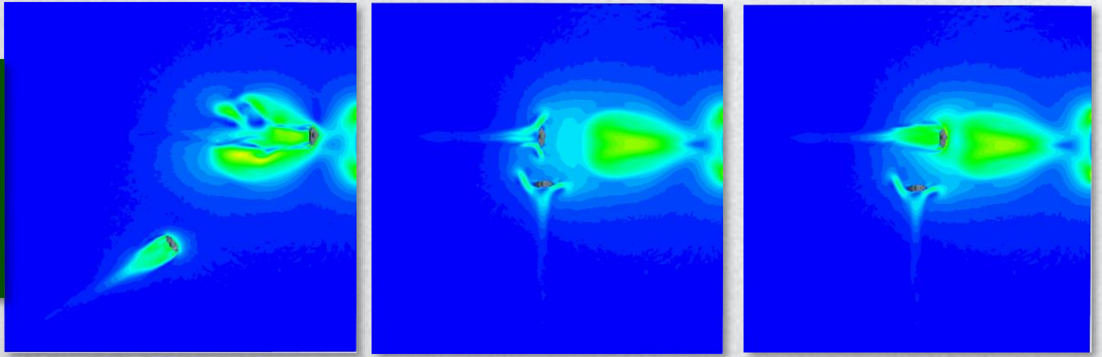
However, thermal plumes from the body raise temperatures behind the person by 0.1–0.2°C



Velocity



Velocity Field at 5s



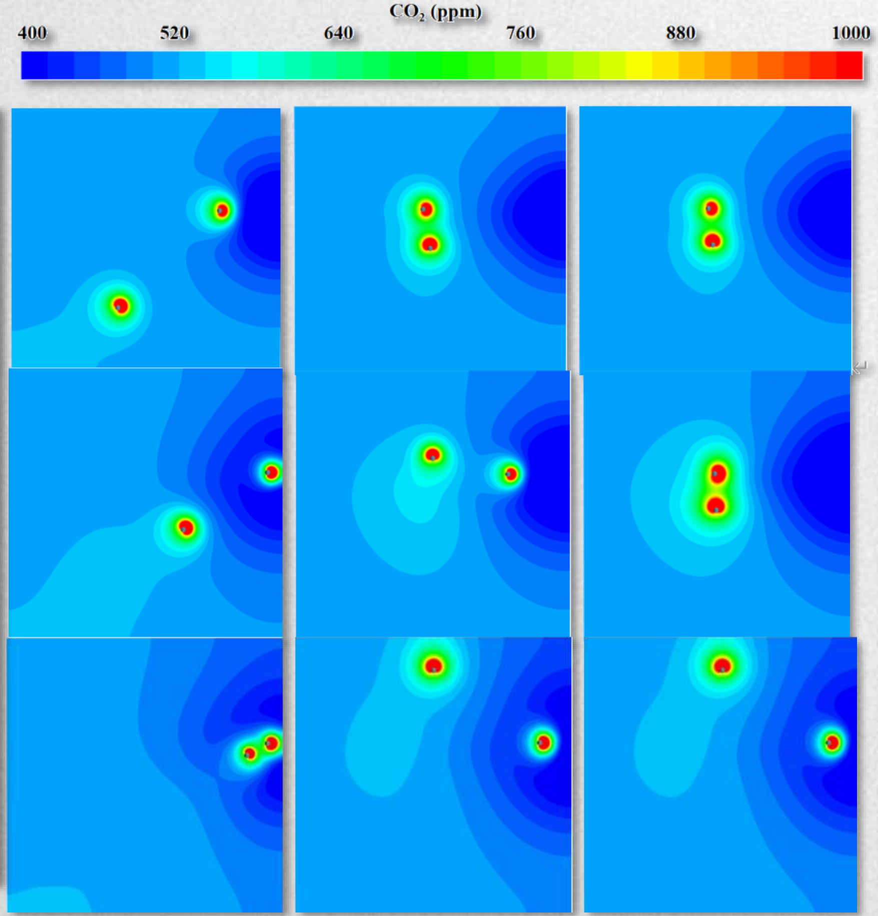
Walking creates a wake zone extending 3–4 m behind the person and 1 m to each side

With a 0.1 m/s threshold, the wake extends 3.2 m

Maximum wake velocity: 1.87 m/s

After stopping, airflow recovers in 3–4 seconds

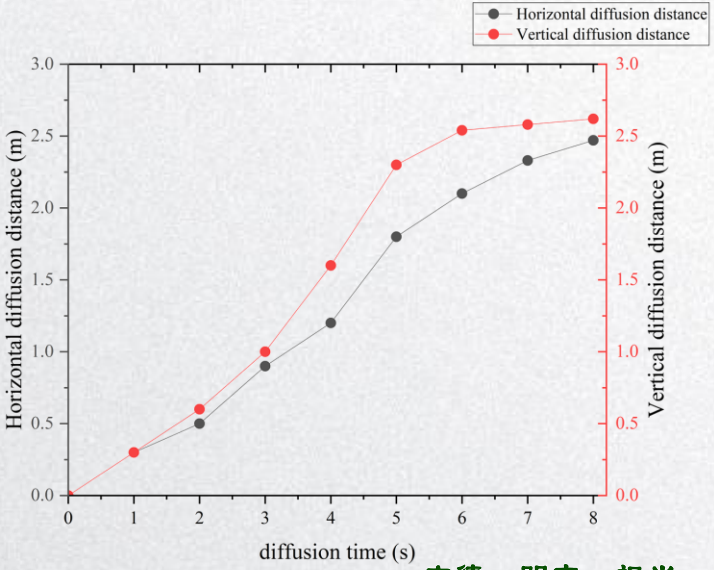
Environmental Parameter Analysis



Left map: CO_2 distribution at 4 / 7 / 10 seconds

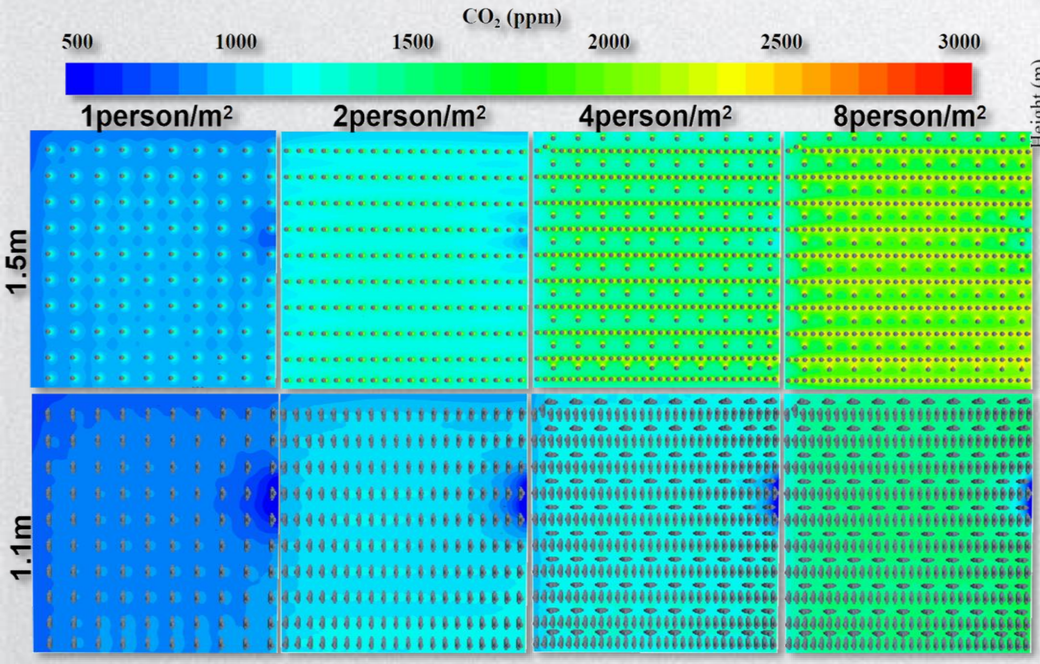
CO_2

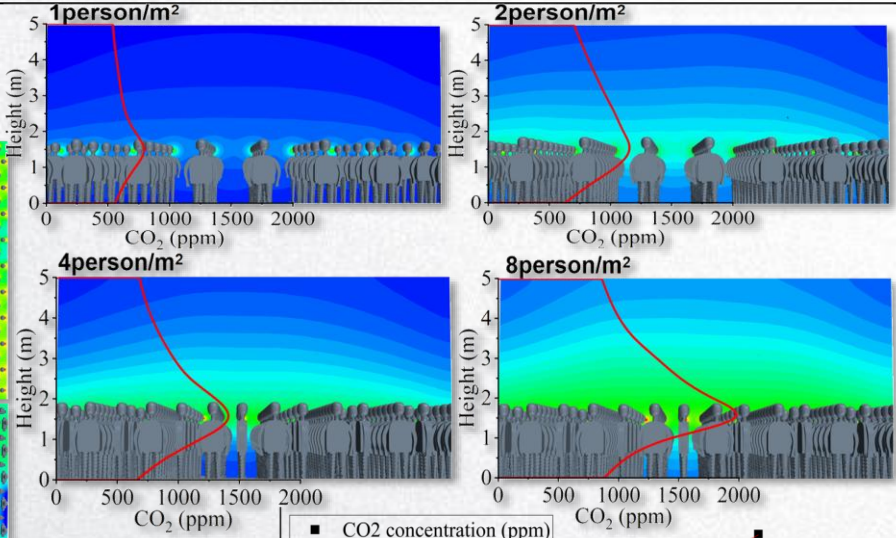
Within 10 seconds, a single pedestrian produces a teardrop-shaped CO_2 plume near the breathing zone
Affected area: 20 m², concentration difference: 5–15 ppm
As the plume spreads, CO_2 gradient decreases
Horizontal diffusion is 20% faster than vertical diffusion

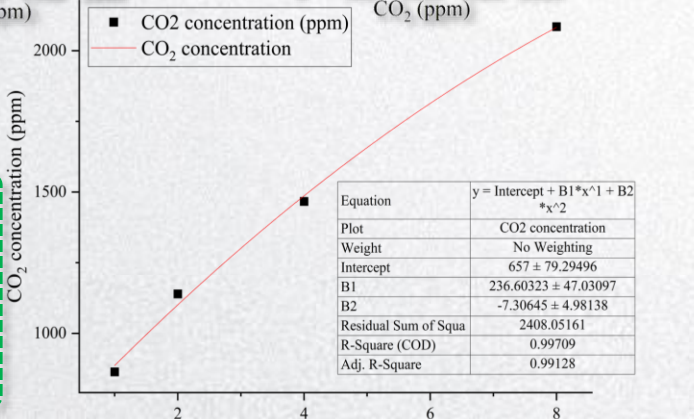


Diffusion Rate
Lateral vs Vertical CO_2

Environmental Parameter Analysis





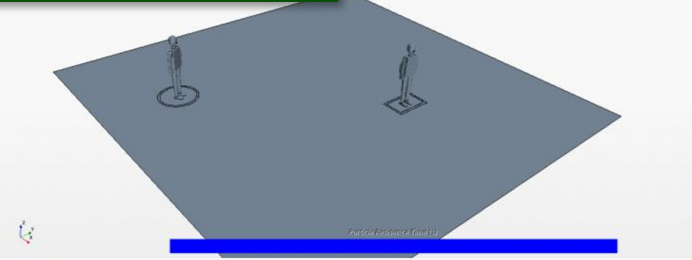


A strong correlation was found between occupant density and CO_2 concentration
Regression equation: $R^2 = 0.997$
At 1.52 persons/m², CO_2 exceeds 1000 ppm after 10 minutes
At 8 persons/m², CO_2 exceeds 2000 ppm

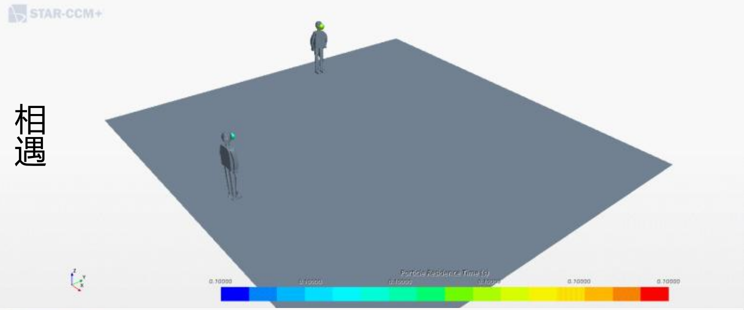
Environmental Parameter Analysis

Aerosol Particles

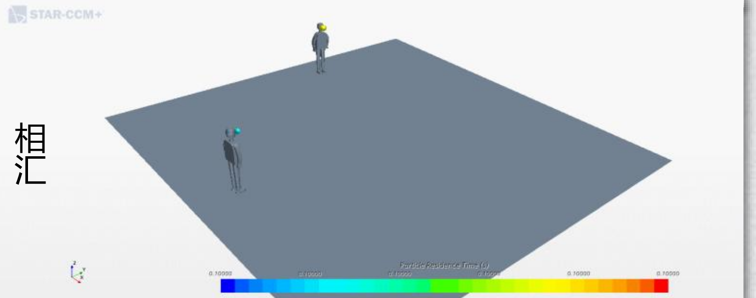
跟随

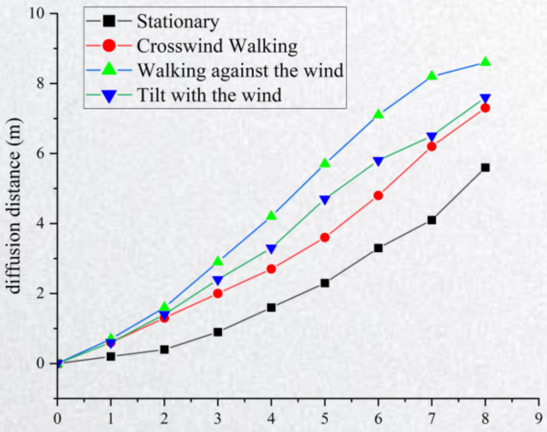


相遇

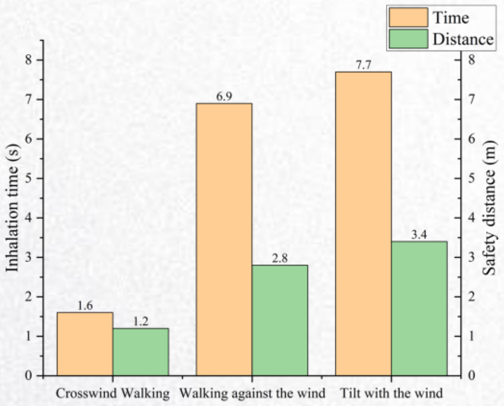


相汇





Aerosol diffusion rate over time



Inhalation Time and Distance

Aerosol dispersion speed is closely related to the relative direction between walking and airflow

Upwind walking leads to the fastest spread, much faster than in a static case

After 6s, upwind walking can spread up to 3.2 m, while shape boundary expansion slows down afterward

Safe distance ranges from 1.2 m to 3.4 m

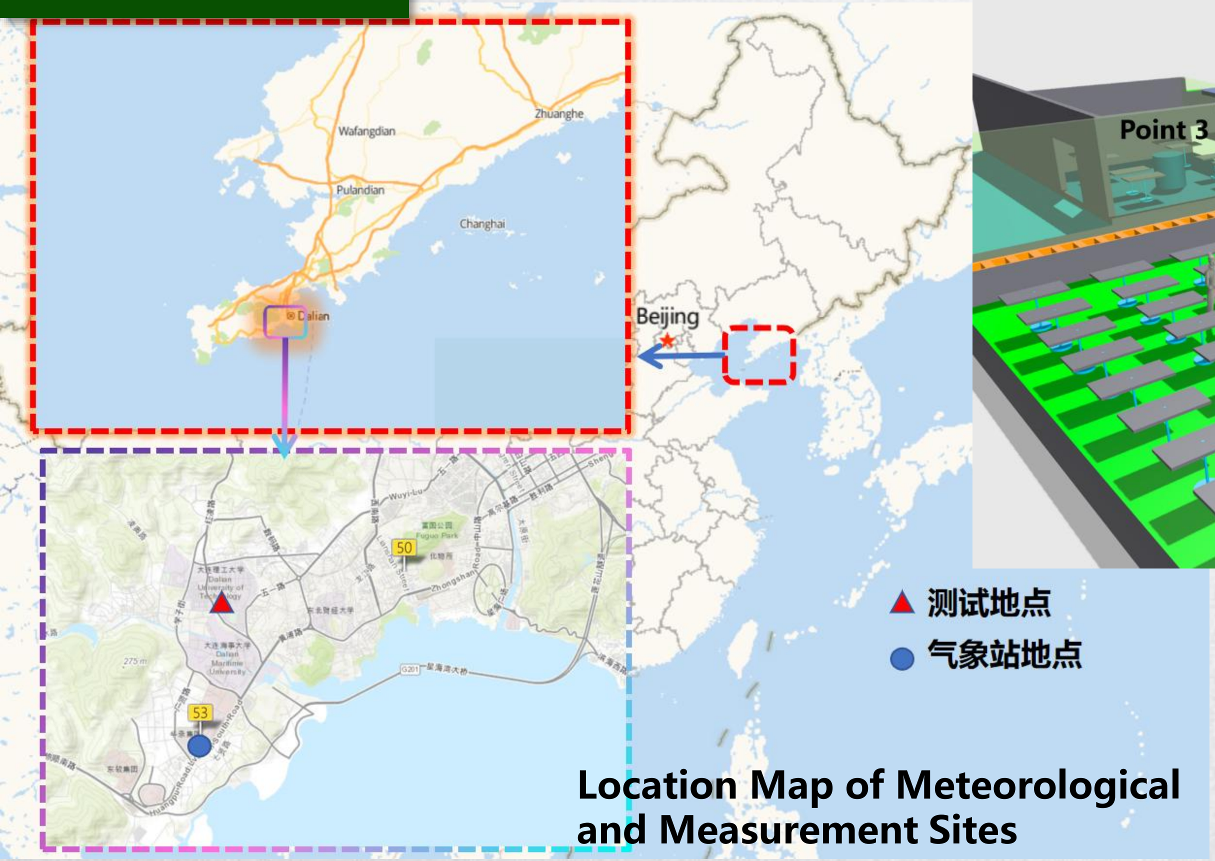
Part 4

Data-Driven Model on Air Quality Prediction in Large Spaces

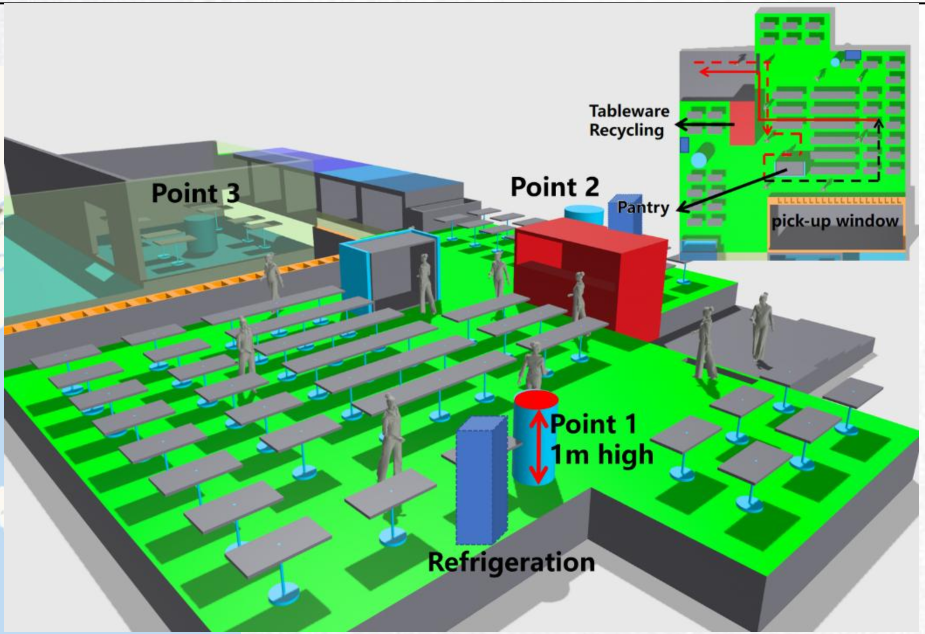
- Selection of Prediction Methods
- Environment Prediction Using the ARX Model
- Comparison and Optimization of Prediction Results

Field Measurement Plan

Data Collection



Location Map of Meteorological and Measurement Sites



Layout of Functional Zones

The restaurant's outdoor environmental data comes from local real-time weather stations.

Field Measurement Plan

Nov & Dec 2022: Lingxi Library

Sep 2023, Nov 2023, Jun 2024: Qinyuan

Lingxi Library Measurements

Dates: Nov 30 & Dec 11, 2022

Locations: Rooms 502 & 401

Measured items:Temperature, Humidity, PM10, PM2.5, PM1.0, PM0.3, CO_2, Air Velocity, Occupant Count, and Bioaerosol

Qinyuan Canteen Measurements

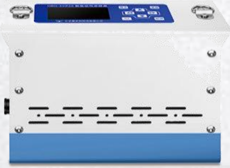
Dates:Sep 23, 24, 27, 2023 (16:50–18:50)

Nov 22, 2023 & Jun 21, 2024 (17:00–19:00)

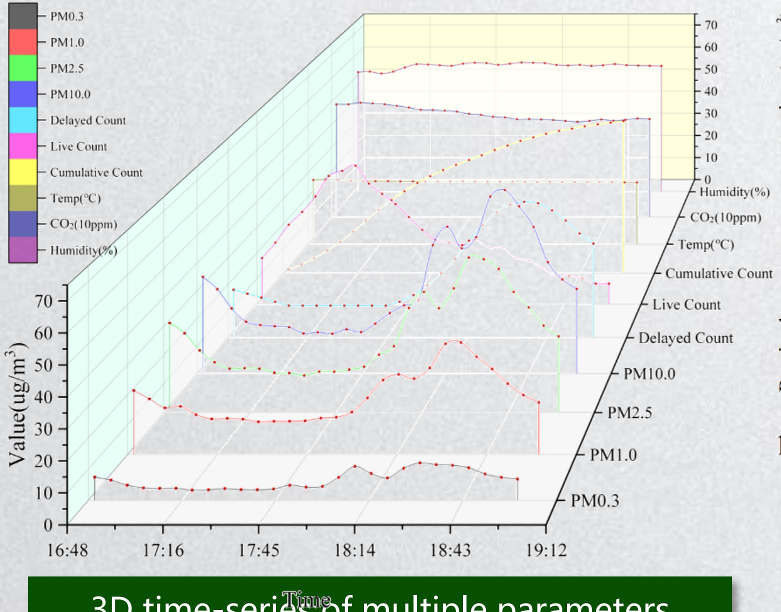
Location: 2nd Floor, Qinyuan Canteen

Measured items:

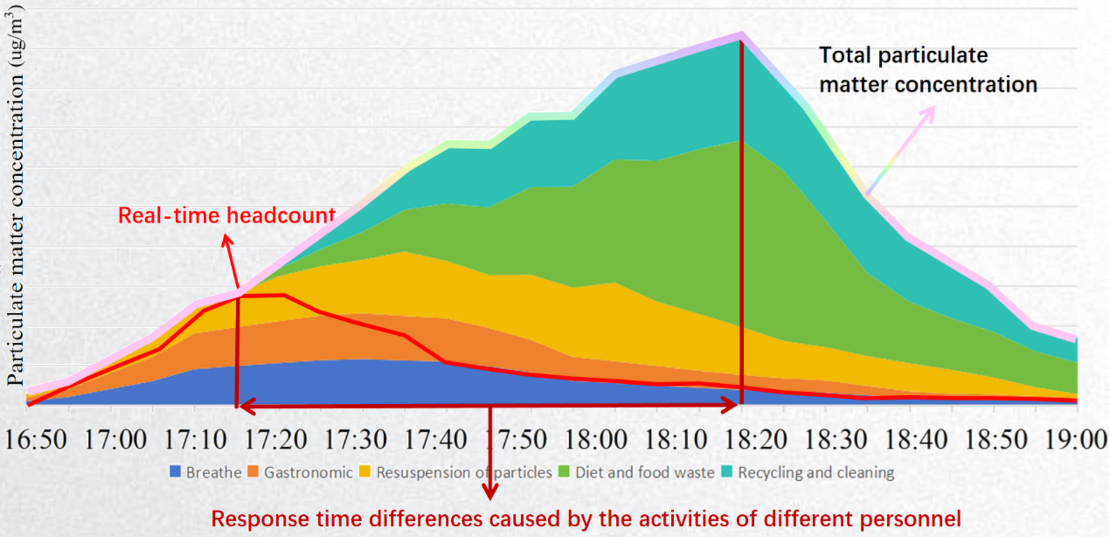
Temperature, Humidity, PM10, PM2.5, PM1.0, Nanoparticle Size Composition, CO_2, Air Velocity, Occupant Count



Data Analysis



3D time-series of multiple parameters

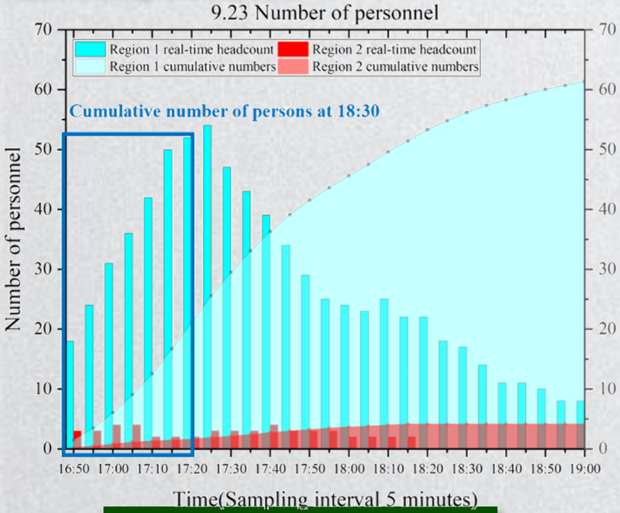


Sources contributing to particle concentration

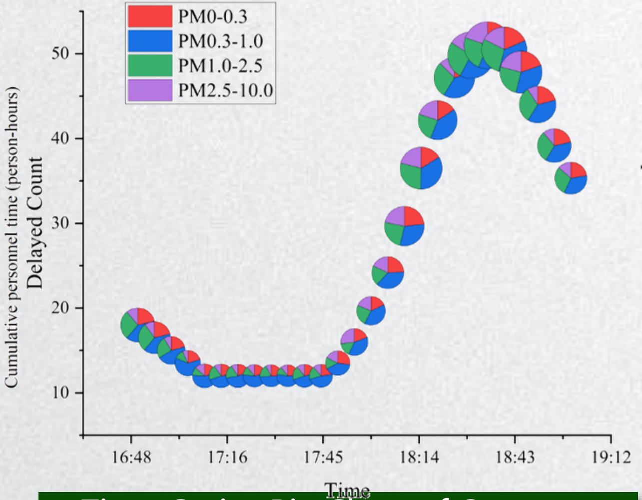
There is a time lag between the peak in occupant count and the peak in particle concentration.
Possible Causes：
1.Different human activities have different response times
2.Time required for particle dispersion(Sensor location may not coincide with human activity location)
3.Human flow patterns (Actions like door opening enhance indoor–outdoor air exchange and airflow disturbance)

Data Analysis – Estimating Time Lag

Determination of lag time

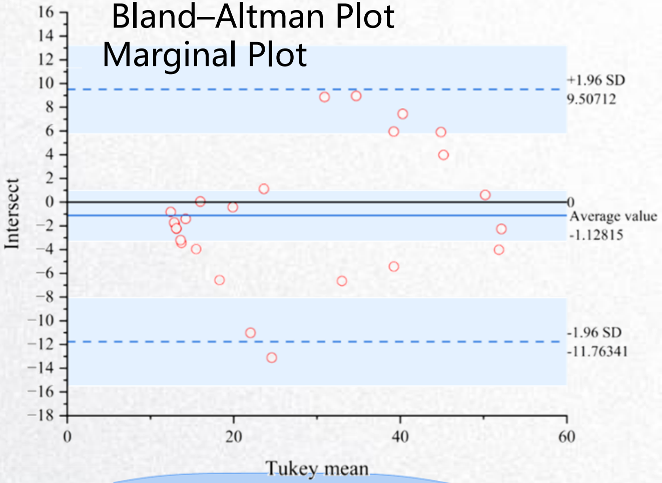


Estimation of Time Lag

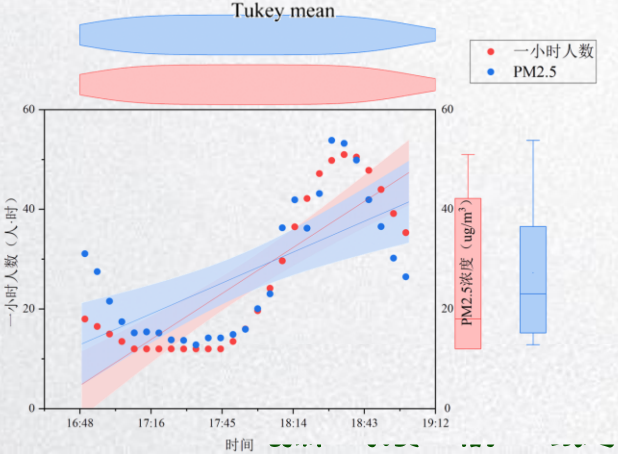


Time-Series Pie Chart of Occupant Count vs Particle Concentration

Bland–Altman Plot



Marginal Plot

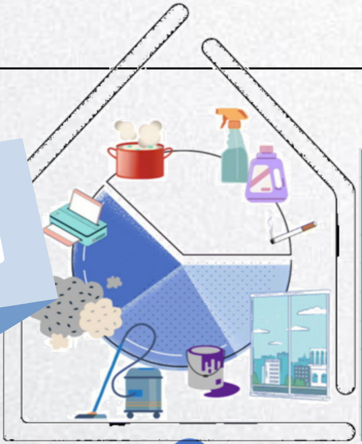


Due to the lag between occupant count and pollutant concentration, a "cumulative dwell count" is introduced for better correlation and prediction of pollutant levels
Most values fall within the 95% confidence interval, indicating strong agreement in trend

Selection of Prediction Methods

Feasibility Analysis

- **Human activity intensity is positively correlated with particle concentration**
- **Over 80% of particles originate indoors**
- **Kitchen emissions significantly affect VOCs in the dining area, but have limited impact on CO_2 and particulates**
- **In densely occupied canteens, humans are the primary pollution source**



Ordinary building

Source group	Contribution to PM2.5
building materials & furniture	5-25%
combustion-related	2-61%
cooking	3-38%
resuspension	2-35%
consumer products	3-37%
indoor generated secondary ' pollutants	<10-45%
outdoor sources	10-90%

Crowded restaurants

Source group		Contribution to PM
Personnel density related	Breathing and coughing	65-95%
	gastronomic	
	Resuspension of particles	
	Diet and food waste	
	Smoking	
	Recycling and cleaning	
Other	Outdoor sources	10-40%
	Indoor Plant Soil	5-15%
	Kitchen Infiltration	20-60%

Although humans are not the only direct source of pollution, their direct or indirect contribution to pollution accounts for 65–95%, making environmental prediction based on occupancy both feasible and effective

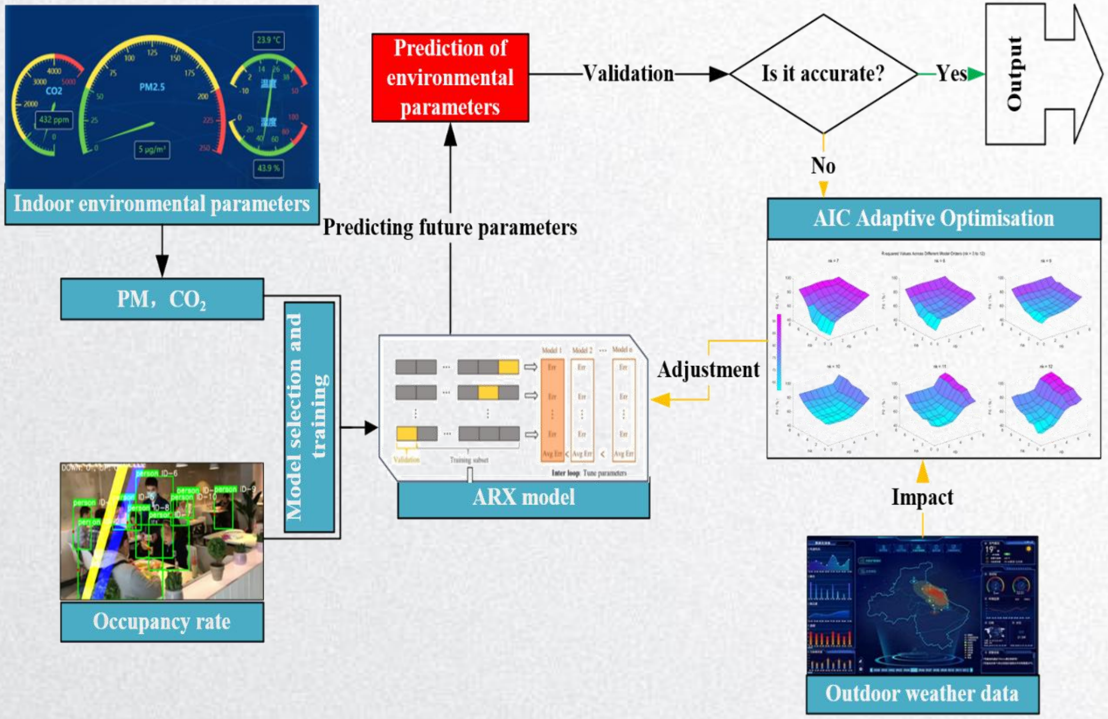
Environmental Prediction Method Based on ARX Model

ARX Model

After comparing multiple models and conducting preliminary analysis, the ARX model was selected.
It considers hidden influencing factors in indoor environments, and is trained using historical data to avoid the impact of incomplete direct variables.

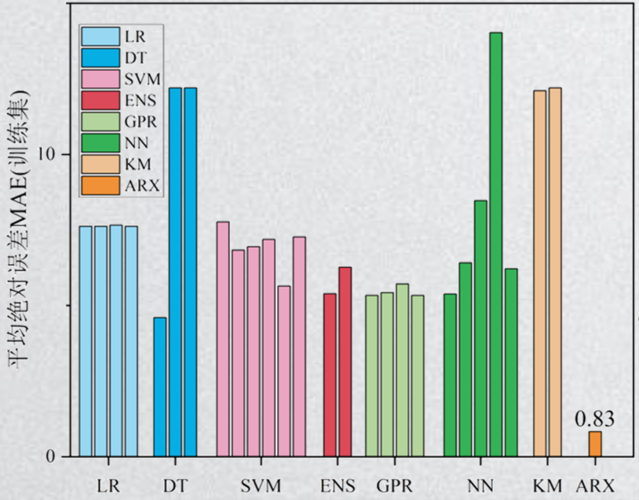
$$C(t)=\sum_{i=1}^{n_a} a_i C(t-i)+\sum_{j=0}^{n_b} b_j P(t-n_k)+e(t)$$

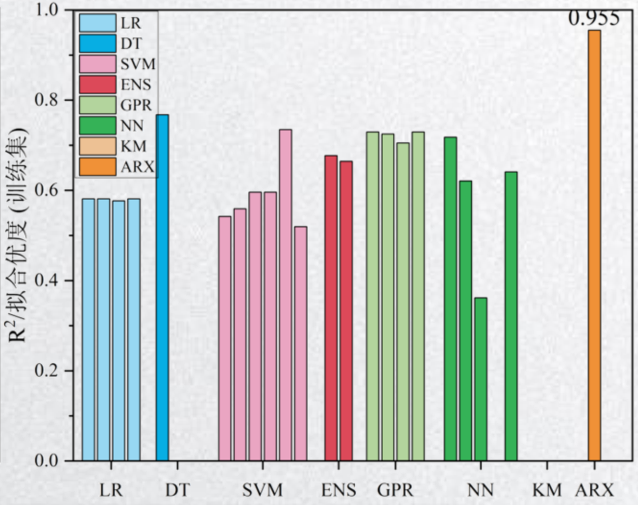
Requires relatively little data
Offers fast prediction speed (suitable for real-time prediction; computation speed is in seconds)
Avoids missing variables through modeling hidden relationships

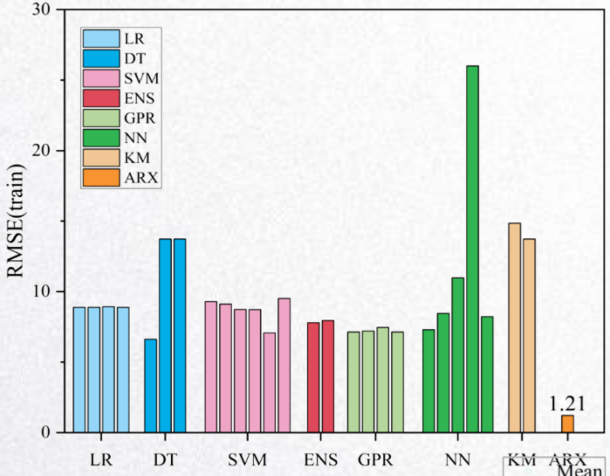


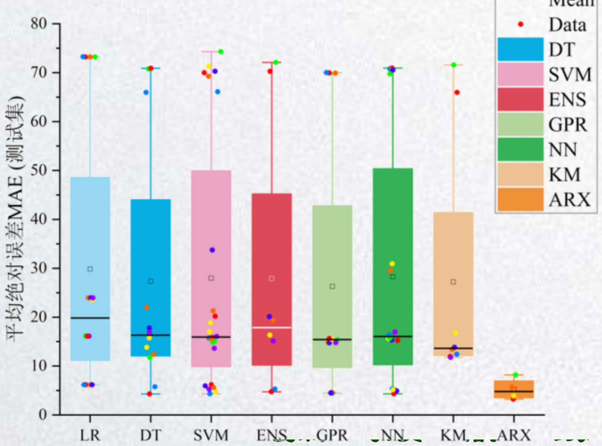
Environmental Prediction Flowchart

Prediction Results Comparison and Optimization







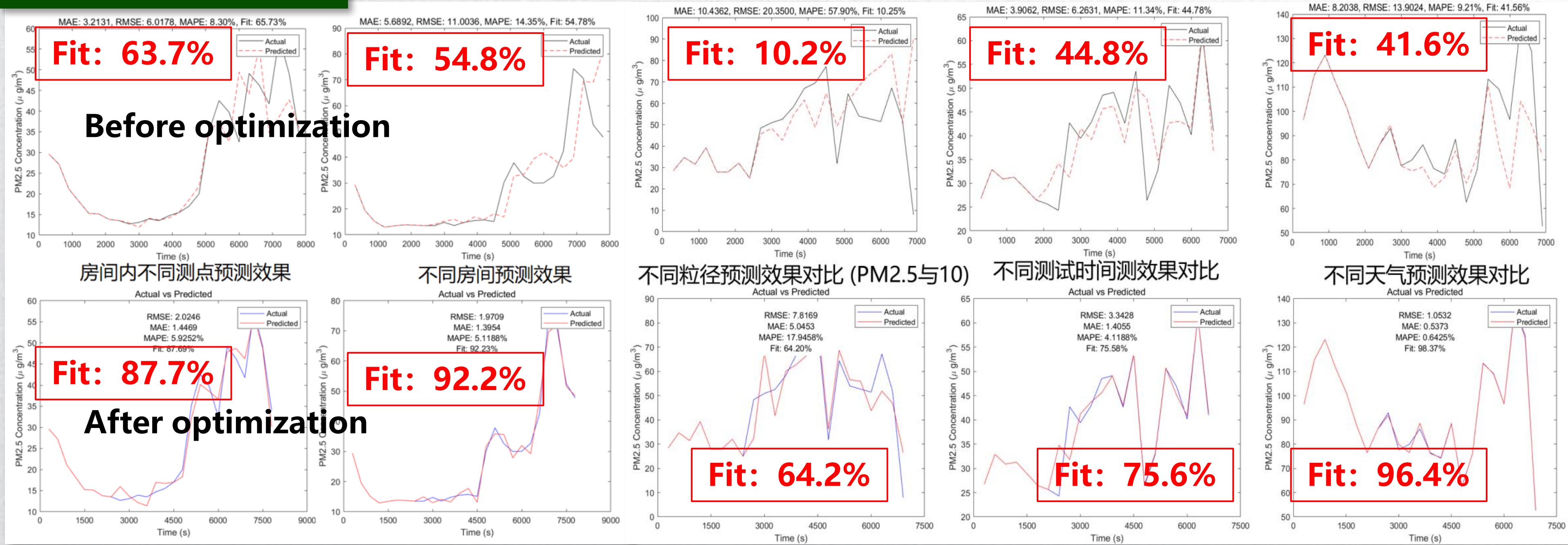


Model Performance Comparison Using RMSE, MAE, and R²

The ARX model outperformed all other models across three key metrics.
It yielded the lowest prediction error:MAE = 0.83 μg/m³
RMSE = 1.21 μg/m³   R² (Fit Accuracy) = 0.955
herefore, the ARX model is best suited for environmental prediction in densely populated dining areas

Comparison and Optimization of Prediction Results

Optimization results



The optimized ARX model was tested across various scenarios.

This demonstrates the stability and applicability of the ARX model after parameter optimization.

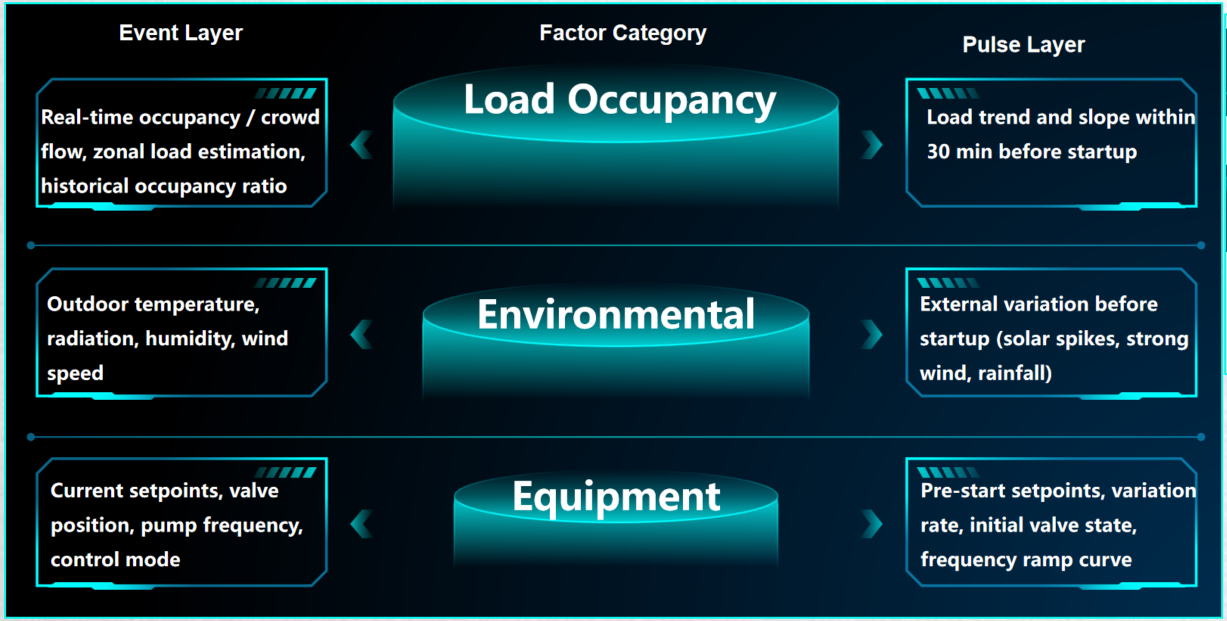
Part 5

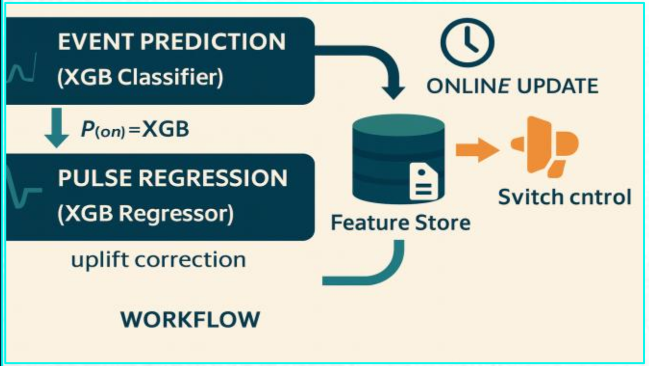
Energy Consumption Prediction and Optimization of Air Conditioning System

- Correlation
- Core Technology
- From Model to Application

Core Technology

Core Technology 1 Event–Pulse Dual-Layer Modeling for High-Accuracy and High-Speed Prediction





Model size: 7 MB, memory usage: <128 MB

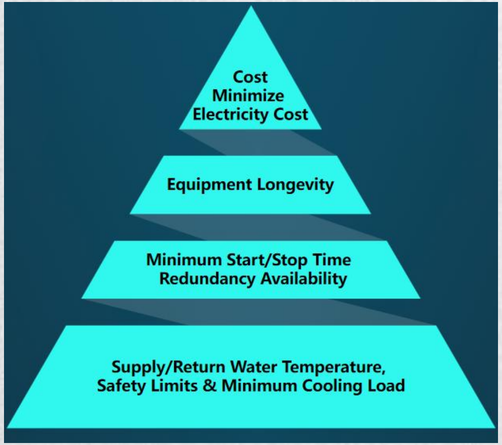
Lightweight and real-time

Event–Pulse Dual-Layer Model

Separates start/stop events and pulse power curves for independent modeling (XGB classification + regression + uplift correction).

Core Technology

Core Technology2 Hybrid Multi-Layer Coordinated Control Strategy



Upper Layer: On/Off scheduling (MILP)

Lower Layer: Continuous MPC + Surrogate Acceleration + Cost-Aware Sensing

01 Hard-constraint protection

02 Soft-constraint optimization

03 Layered structure

04 Accelerated computation

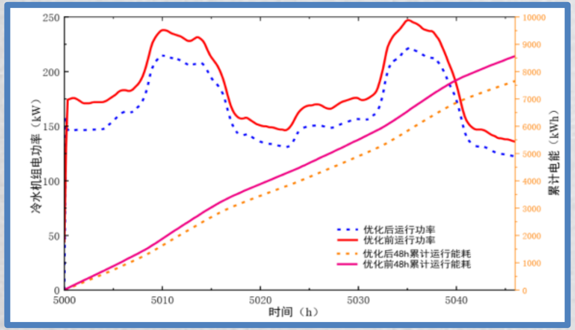
05 Robust and practical implementation

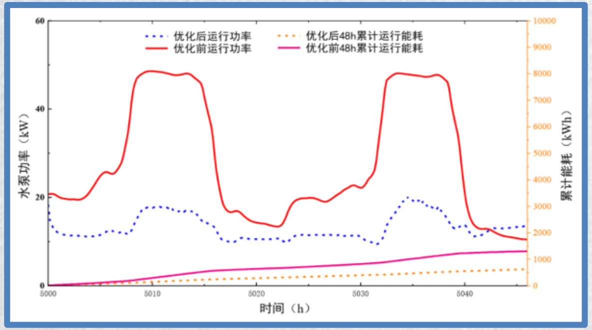
→ comfort, energy saving, economy, and equipment lifespan

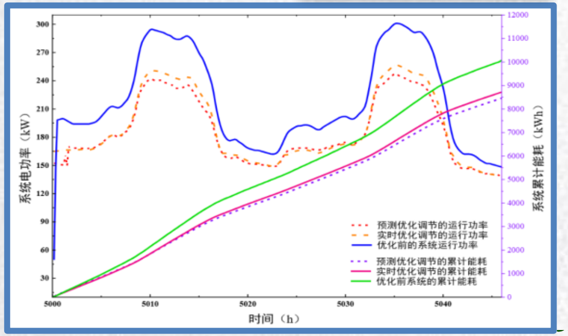
Total energy saving: 8–33% over 7 days

Peak power reduction: 5–8%

efficiency

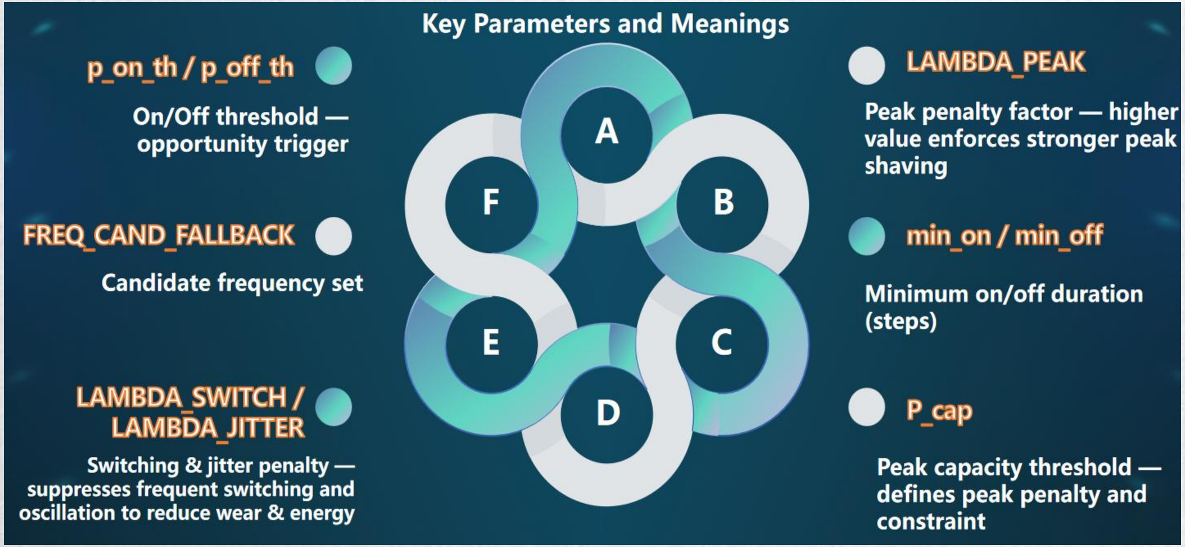






Core Technology

Core Technology 3 — Full-Chain Equipment Analysis and Rolling MPC Optimization Framework



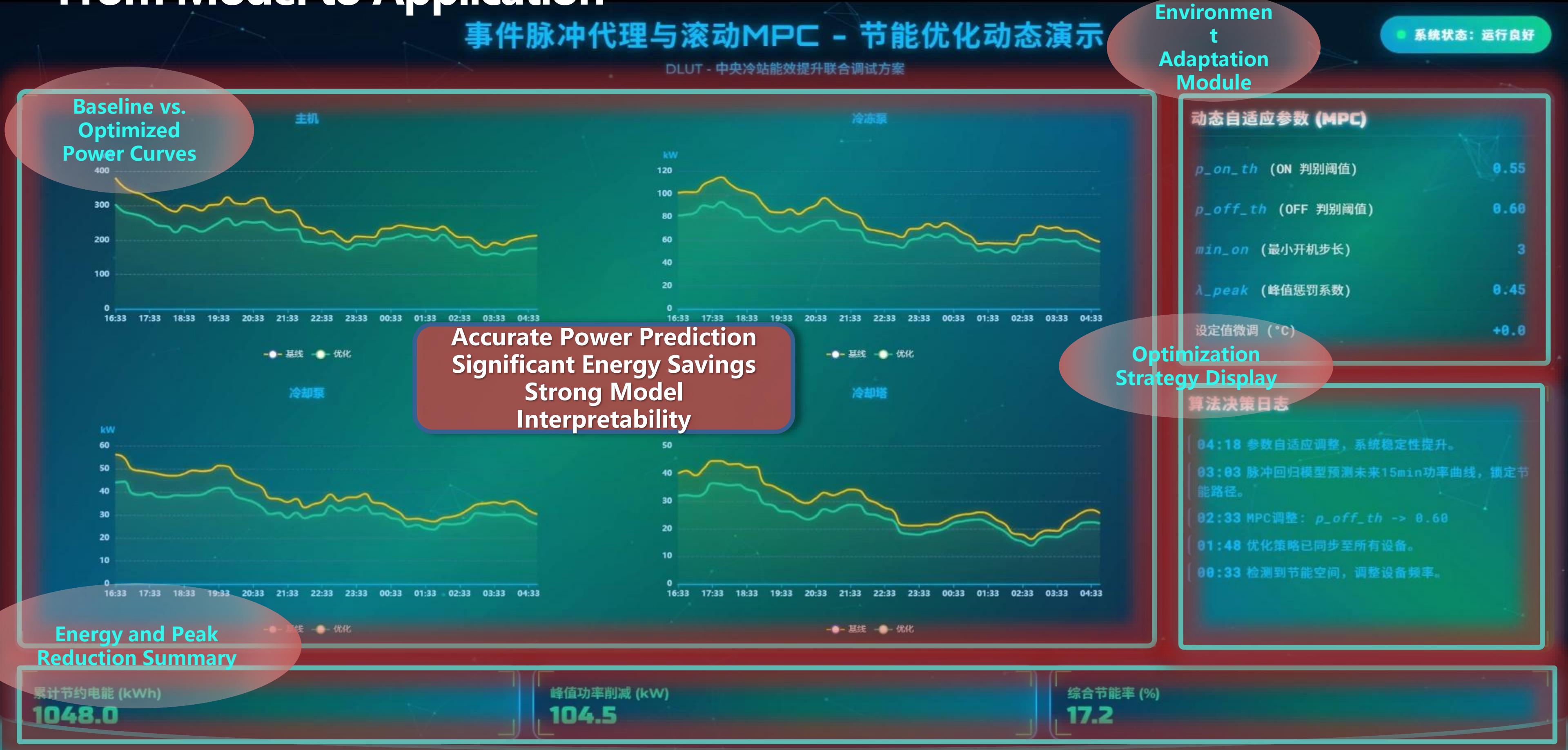
Full-Chain Equipment Analysis with Rolling MPC

Build analytical power models for pumps and towers;

automatically recalibrate parameters using historical data.

- **Equipment classification and adaptive parameter settings**
- **Peak and limit adjustments**
- **Automatic state switching and penalty coordination for compatibility**

From Model to Application

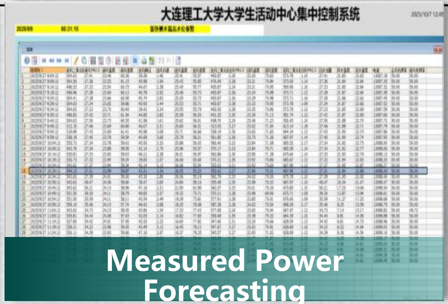


Compatible with mainstream building energy management protocols (BMS); easily integrates into existing systems,

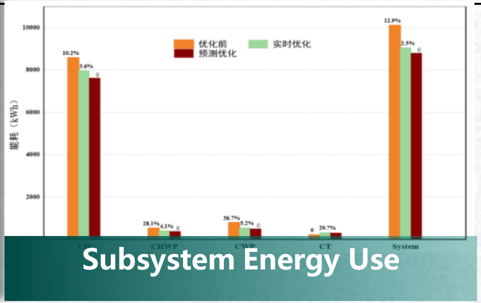
Deployment Time: 2–3 days

From Model to Application

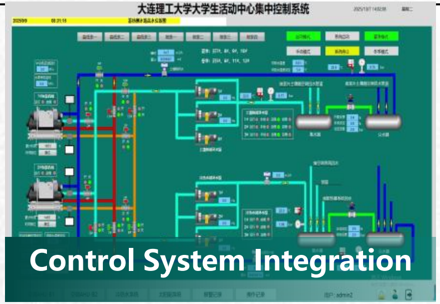

Dalian University of Technology Student Activity Center



Measured Power Forecasting



Subsystem Energy Use



Control System Integration

	Prediction Accuracy Improvement	Engineering-Level Fast Response	Operational Energy Optimization	Compatibility and Scene Adaptability
Key Metric	MAE	Response delay	Energy saving	Model deployment
Industry	45-186kW	4-30s	Daily energy saving3-6%	24-72h
Pilot	34kW	<1s	12%	<3h
	More reliable	Control speed	Peak power reduction up to 20 %	Broad applicability

Part 6

Research Conclusions and Outlook

- Conclusion
- Innovations
- Outlook

Conclusion

Impact of Human Activity

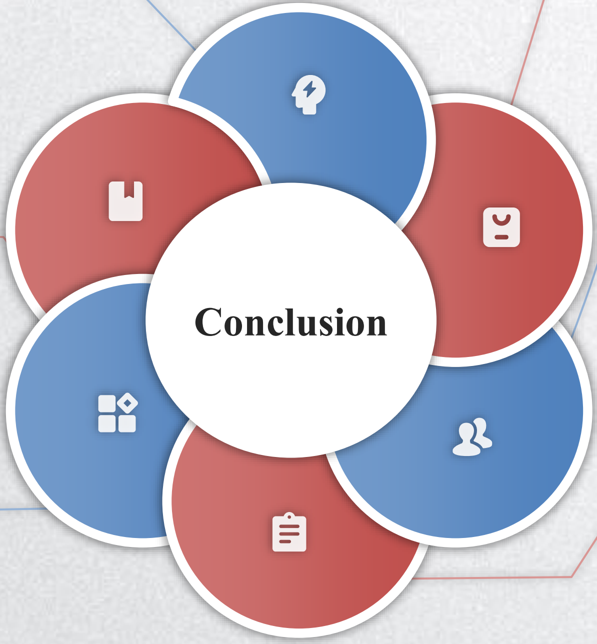
Movement and breathing cause local warming, but little impact on overall temperature; airflow recovers in 3–4 s.

CO_2 Dispersion

High occupant density raises CO_2 levels; 1.52 person/m² for 10 min can exceed limits.

Aerosol Spread

Aerosol transmission is related to wind direction.Follows wind direction faster upwind spread. Safe distance: 4 m, vertical max: 2.87 m.



Dining Space Impact

PM and CO_2 levels vary greatly with occupancy. Pollutants can linger up to 90 min.

Model Accuracy

ARX model has best PM2.5 prediction (R^2 = 0.9549), fast and stable.

Adaptive Optimization

AIC-based ARX model improves accuracy by 25%+, with better adaptability.

Innovations

For densely populated environments,YOLO + CFD + data-driven approach for fast online prediction in dense environments

Real-time Data Acquisition

OLO-based method collects real-time human data; builds social force model to support continuous environmental prediction.

1

2

Human Turbulence & Risk Modeling

Defines turbulence strength, safe distance, and empirical risk formulas based on human movement in dense spaces.

Innovations

Adaptive ARX Optimization

Proposes AIC-based adaptive tuning to address parameter sensitivity and improve model generalization and accuracy.

4

3

Time-lag Correlation Modeling

Integrates multiple data sources and considers human behavior delay, building a multidimensional feature system.

Outlook

Future Outlook

More Accurate Predictions

- Coupling of Indoor and Outdoor Environments
- Multi-scale Occupant Prediction
- Data-Physics Integration

Faster Predictions

- Database Construction
- Multi-Method Integration
- Higher Level of Automation

Thank you for listening

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- Dalian University of Technology