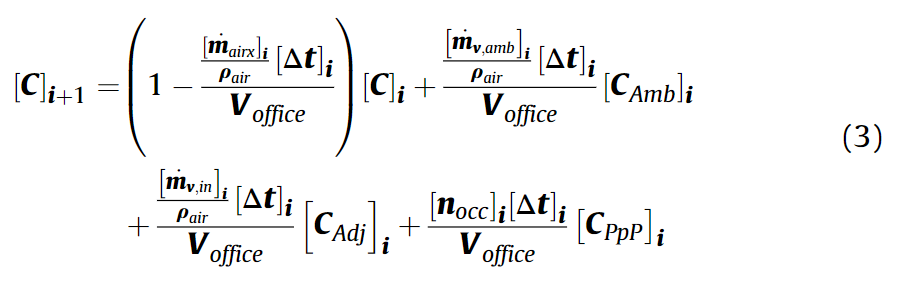
# **[Building occupancy estimation and detection: A review]**

**[A review of building occupancy measurement systems]**

# **[CO2 based occupaCction algorithm: Experimental analysis and validation for office and residential buildings] regression, optimize unknown variables in the equation**

难点：

the main issue of occupancy estimation and detection using CO 2 concentrations is that the estimation results are always with a time delay from the real building occupancy due to the slow spread of CO 2 in environments.



Limitation:

Some input are not measured: C\_{amb}, C\_{Adj}. CO2 level in the ambient air, of the adjacent room: variation of the outdoor CO2concentration in a range between 300 ppm and 500 ppm.

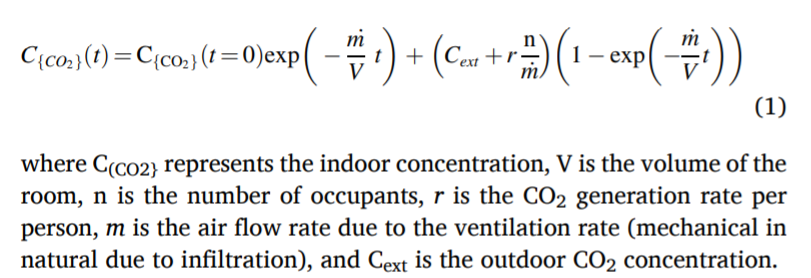
dm/dt through windows and doors, depend on: dTemp, wind, shape

C\_{people} varies

# **[Measurement of CO2 concentration for occupancy estimation in educational buildings with energy efficiency purposes] regression by differnt variables, dCO2/dt ~ V/n best**

Outdoor Co2 level: 250-600 ppm, standard: 400 ppm

Indoor: 1000 ppm is poor, max 1500 ppm in European Standards



**[Predicting occupancy counts using physical and statistical CO2-based modeling methodologies]**

**Compare different data-driven and physical methods.**

The main factors to achieve a well performing dynamic physical model are the **assumptions of a well-mixed indoor space**, correct use of CO2 generation rates and accurate measurements of CO2 concentrations at select measurement points as well as ventilation rate

MPC side:

### [[All you need to know about model predictive control for buildings](https://www.sciencedirect.com/science/article/pii/S1367578820300584)] 2020 **review**

However currently, the state-of-the-art occupancy behavior models (e.g. obFMU [Hong, Sun, Chen, Taylor-Lange, & Yan, 2016](https://www.sciencedirect.com/science/article/pii/S1367578820300584" \l "bib0203) or StROBe [Baetens & Saelens, 2016](https://www.sciencedirect.com/science/article/pii/S1367578820300584" \l "bib0042)) are computationally too expensive to be included in MPC. Therefore, less computationally demanding approaches are typically adopted in the context of MPC, for example models based on heuristics (e.g. anticipated schedules) or machine learning.

**[Modeling and estimation of the humans’ effect on the CO2 dynamics inside a conference room][37]**

partial differential equation-ordinary differential equation (PDE-ODE) algorithm to model CO 2 concentrations in a conference room for oc- cupancy estimation

**[Occupancy detection via environmental sensing]**

applied the same algorithm in [37] for occupancy estimation using CO 2 sensors

Occupancy estimation through environmental monitoring is a promising approach, as parameters such as indoor CO2 concentration are indicative of the presence of humans, which are the main source of variations; in addition, it can leverage existing sensing infrastructures without introducing significant privacy risks.

Existing approaches, nevertheless, often require an **extended training phase** when data of ground truth occupancy are collected through surveys or camera recordings, which tends to limit its deployment.

Another major drawback, especially for CO2-based systems, is the **delay** of detection as a result of the relatively long time (**10–15 min**) it takes for the effect of human presence to build up to the detection threshold [10].

!!!!!!!!!!!!!!!

**[Occupancy behavior based model predictive control for building indoor climate—A critical review] 2016; review, CO2, MPC**

### **[[A critical review of field implementations of occupant-centric building controls](https://www.sciencedirect.com/science/article/pii/S036013231930561X?casa_token=CM6vry1E7wUAAAAA:QFpCEVnGBmog3bIWQZtiSkLDv8ZWEl8exHHArfZDC7rLkp9EChlmuJWCZfzu9Y8zLUshK1M8qnlR)]**

However, there are relatively few studies in which OCC is implemented in real buildings.

42 papers Jan 2019: actual implementation of OCC in real building environment MPC:7

one reason:reluctance of facility managers, might limit the potential OCC approaches because it might cause malfunctions.

OCC approach requires: sensory data from both occupants and building systems, and the active utilization of this data to control.

Actual people counting: problem

Complexity increases! (Building model, Occ est and pred model)

**[Practical implementation and evaluation of model predictive control for an office building in Brussels]2017; MPC; experiments**

Grey box model by linear regression

**internal power (normalize it to occupancy)**

**prediction: weekly persistence**

State estimation by the Grey-Box Buildings toolbox

**[Performance comparison of occupancy count estimation and prediction with common versus dedicated sensors for building model predictive control ] 2017; CO2, 没有使用MPC; Compare estimation and prediction by common sensors and camera**

Grey box model . Only estimate occ, use it to do prediction

Occ estimation: Grey box model or camera

Occ prediction: Decision tree and Random forest regression methods with 1-month long training dataset (from estimation)

estimation of occupant counts from the common sensors(like CO2): data mining and machine learning,a physical model of the indoor environment

major limitation of the data-driven: a long-term monitoring is needed and it is difficult to take into account factors like interzonal airflow and outdoor air supply rate

model-based approach,system identification: using least squares methods, evolutionary algorithms (该篇),Monte Carlo methods, Kalman filters (该篇, 只对occupancy), direct inversion method

**[Importance of occupancy information for building climate control]**

Compare MPC of:

1 Prediction by Prediction standard occ profile

1 + close light when no occ (detected by sensor)

1 + close light and ventilation when no occ (detected by sensor)

Perfect prediction of occ

Occ: a constant or 0

The realization was assumed to differ from the schedule in terms of additional vacancies, i.e. vacancies （office情况，请假与否）

Energy savings from: increasing occ prediction

对比Energy savings: adjusting lighting and ventilation by instantaneous occ sensor save most of energy, perfect occ prediction does not lead to significant savings (就office的vacancy频率而言。prediction 与real相差变大才大起来)

[Model-based controllers for indoor climate control in office buildings– **Complexity and performance evaluation**] controller 可能有问题， prediction没有 （上面那篇说精度不重要，所以它直接去掉了prediction）, internal gain分开考虑却没仔细描述怎么modeling. 为了对比有人时energy saving，不用set-back的relax

Low complex model-based control: not lose to much performance

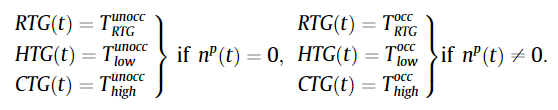
Internal disturbance: similar performance improvement -> because highly correlated

Occ: high, meeting room; low, office room

**[Occupancy-based zone-climate control for energy-efficient buildings: Complexity vs. performance]**

Baseline: 类似dead-band, fixed schedule 考虑了occ，但没有测量

Measured Occupancy Based Setback:

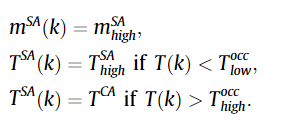


没人就relax setpoint, 代价是会violate constraints more easily

MPC 1: measure occ(k), occ\_pred\_{i|k} = occ(k)

MPC 2: measure occ(k), predict the perfect occ\_pred\_{i|k}

When infeasible: use the maximal input



Occ: 1 person

In the absence of predictions of occ, MPC can only do what a well-designed feedback controller will also do, that is: set back the zone temp when it is unoccupied, but not too much so that it can be changed quickly when occ changes.

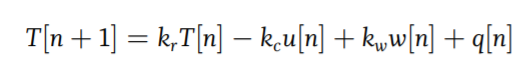
提升energy saving of perfect prediction: 本文只考虑 medium sized office with a small design occ(1-5 people), ASHRAE规定没人也要最低通风速度。如果人多了省得多了 （如果没有这个min要求，就算这么点人，也能40% 变80%， 所以人多了， prediction 很重要）

MPC需要获得更多的利益 - self-triggered

**[Reducing Transient and Steady State Electricity Consumption in HVAC Using Learning-Based Model-Predictive Control] use temperature model to estimate occ**

In this method the heat generated in the room is estimated based on the room model,AC Input and room temperature, to measure people activities in the room. 30% energy saving.

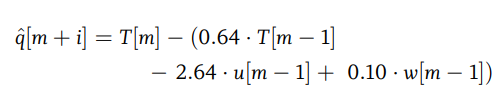
Single stage heat pumps: most common, motors with one fixed speed.



Know T, u, w, not know q, semiparametric regression of partially linear models



At time m, q\_prediction is estimated from the physical model:



[CO2 sensors for occupancy estimations: Potential in building automation applications] simulation MPC, CO2 estimate occ (direct dynamic approach)

delay of CO2 sensor

###

Common setups

HVAC system: RC model

MPC: nonlinear

Occ: measurement, physical model, grey box model; prediction, machine learning methods, statistical methods (Markov model,Adaptive Gaussian Process, Hidden Markov Model, Episode Discovery and Semi-Markov Model)

Compare: baseline, fixed schedule; rule-based with occ mea; mpc with occ mea; mpc with occ pred

Burden: modeling, prediction

Specific but common case: class and meeting room, lots of students, PIR and motion sensors are useless

Points in the paper of applied energy:

1. Innovation: whether used in buildings, what is not considered
2. Details: experimental setup; different process and steps
3. Analysis: performance, energy savings, violation

Human heat:

Tarik El-Shemmeri [2] defined typical heat emission from the people with respect to activity. He assumed that an adult man spreads 80 W when sleeping and 570 W when doing heavy work, respectively.

According to the ASHRAE Handbook – Fundamentals [55], the total cooling load associated with a person with moderately active office work is 132 W, of which 59 W (44%) correspond to latent heat.

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Building

Burden: modeling

Physical-based models: several month; machine-learning-based model: days?

Highlights:

1. MPC and some novel improvement
2. Multi-objective optimization (energy, comfort by PMV)

more comprehensive thermal comfort indices: Predicted Mean Voted (PMV) [2,15,37,38] , or dynamic thermal sensation [7,8] , rather than using air temperature alone as the control parameter.

1. Modeling
2. Paper focus, novel points: e.g.,

Common points

* 1. Long time exp, analysis (previous: short time, or simulation)
  2. Real exp in a specific HVAC structure
  3. building models with solid prediction accuracy (e.g. data-driven models)
  4. multi-objective: energy and comfort indices

Special points

1. Self-adaptive ML modeling
2. Robust MPC
3. Demonstrate on/off actuators for high-performance MPC
4. MPC integrates weather and occupancy (number and duration)

## [1] almost first weather prediction, (1)

[3] (2) radiant floor systems (3)

[5] (4) (PMV) (2) DOAS-assisted SSLC system

[6] (1) and 1.

[12] 4. compare basic RBC, RBC and MPC with occ, complex MPC does not increase performance a lot

## [Energy and Buildings](https://www.sciencedirect.com/science/journal/03787788" \o "Go to Energy and Buildings on ScienceDirect)

[2] (4) percentage [of occupants] dissatis-fied (PPD);use occ comfort feedback to tune comfort satisfaction; 51 days

[4] (2) active chilled beam

[8] include internal heat gains: plug power, occupancy

[9] (4). different costs and exps (detail PMV and PPD); 3.

Others

1. (2) 5-zone AHU control
2. 4.
3. 4. use temp to estimate occ

[14] (3): linear model for CO2 and temp

1. Real experiments: communications and work flow, very detail
2. Performance analysis : energy saving%, compared method

[1] Similar buildings B1 B2 cross comparison: 1 week B1 RBC, B2 MPC, 2nd week exchange;

Heating degree days (HDD): estimate energy needed (e.g. mean(y\_ref-wea\_temp)) andsimilar average outside temperature w

[3] compare MPC simulation, exp, and baseline simulation, same disturbances for the weather and internal heat gain

[5] energy and comfort: assume same schedule

[6] RBC, MPC with physical model or ML model

[7] 4-day RBC, 1day MPC, similar ambient temperature patterns, internal heat gain (maybe 1 year ago)

[8] RBC and MPC,normalize data by HDD; x: cost/HDD y: discomfort (PPD predicted percentage of dissatisfied); x: HDD, y: daily cost

[9]MPC with different costs: thermal comfort, energy consumption

most similar weather conditions, same number of people (5)

[10] RBC and MPC

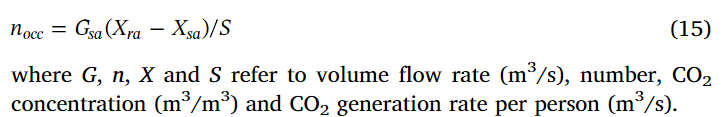
[12] RBC with or without occ,MPC with occ, 18 days; complexity MPC only increase a little. Reason: small room, setback of MPC very small, prediction： hold occ(k), wea(k)

[13] one day RBC, MPC

[14] 4-day RBC, MPC

OCC

[3] constant prediction: occ 65W, equipment: 50W, fixed occ schedule

[5]prediction: constant

[7]5 zones, 650.3-m2,Bidirectional people counters (PIR sensor 因为office room ); forecasts for weather and zone thermal loads.

The zone thermal loads are forecasted using on-line occupancy sensor data and occupancy models generated using historical data

[8] 2 floors, each 480m2, each 40-70 people Internal power (normalize it to occupancy); prediction: weekly persistence

[9] same number of people (5)

[10] 7-zone 67.5m2, max 12 people. MPC integrates weather and occupancy (number and duration). 100 indoor environmental sensors (temp,co2, humidity, light,motion, acoustics, power of electrical plug, HVAC and lights),

Estimate occ by Hidden Markov Mode, build prediction model by Semi-Markov Model

1. = [2] 3-floor 3322m2 and 3-floor 1808m2 office buildings; do not estimate occ number; occupancy use computer to feedback their comfort feeling
2. PIR (once detect occ, assume max people inside), a small office 20 m2, prediction: hold occ(k), wea(k)
3. Lab room: 60m2, Use temp estimate occ, prediction: hold occ(k)

[14] 80m2 PIR prediction: historical scenarios

[101] office 4 people [102]=[5] lecture hall 255m^2, 240 seats

PIR: 3+1 small rooms

Known:2+2

Temp:1

CO2: 2

Environ:1

Power:1

## [Experimental analysis of model predictive control for an energy efficient building heating system](https://www.sciencedirect.com/science/article/pii/S0306261911001668" \t "https://reader.elsevier.com/reader/sd/pii/_blank)

1. [Trial results from a model predictive control and optimisation system for commercial building HVAC](https://www.sciencedirect.com/science/article/pii/S0378778813008542" \t "https://reader.elsevier.com/reader/sd/pii/_blank)
2. [A model predictive control strategy to optimize the performance of radiant floor heating and cooling systems in office buildings](https://www.sciencedirect.com/science/article/pii/S0306261919306191" \t "https://reader.elsevier.com/reader/sd/pii/_blank)
3. Experimental study of a model predictive control system for active chilled beam (ACB) air-conditioning system
4. Experimental study of model predictive control for an air-conditioning system with dedicated outdoor air system
5. Model predictive control with adaptive machine-learning-based model for building energy efficiency and comfort optimization
6. Implementation of model predictive control for an HVAC system in a mid-size commercial building (HVAC&R Research)
7. Practical implementation and evaluation of model predictive control for an office building in Brussels
8. A comparison of thermal comfort predictive control strategies
9. A real-time model predictive control for building heating and cooling systems based on the occupancy behavior pattern detection and local weather forecasting
10. Trial results from a model predictive control and optimisation system for commercial building HVAC = [2]
11. [Experimental study of occupancy-based control of HVAC zones](https://www.sciencedirect.com/science/article/pii/S0306261914012331" \t "https://reader.elsevier.com/reader/sd/pii/_blank)
12. Reducing Transient and Steady State Electricity Consumption in HVAC Using Learning-Based Model-Predictive Control
13. Implementation of a scenario-based mpc for hvac systems: an experimental case study
14. Experimental study of a model predictive control system for active chilled beam (ACB) air-conditioning system

[102]=[5]

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