Application-oriented input design for room occupancy estimation algorithms

Afrooz Ebadat *Damiano Varagnolo* Giulio Bottegal
Bo Wahlberg Karl H. Johansson

KTH VETENSKAP OCH KONST
LULEÅ UNIVERSITY OF TECHNOLOGY
TU/e Technische Universiteit Eindhoven University of Technology

The paper in a nutshell

Application-oriented *input design*

for room occupancy estimation algorithms

Why occupancy estimation?

Roadmap

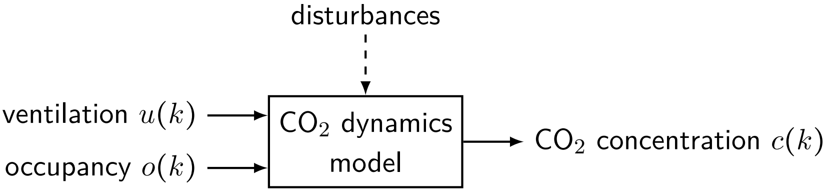
1. how do we estimate occupancy levels?
2. how do we identify the system?
3. how confident are we in the occupancy estimates?
4. can we operate the HVAC so to increase the final confidence on the estimates?
5. what do we get, in practice?

How do we estimate occupancy levels?

Main idea:

first, identify the dynamics

second, invert the estimation problem



Grey box modelling of the CO_2 dynamics

(Ebadat et al., Multi-room occupancy estimation through adaptive gray-box models, CDC 2015)

Physics-based continuous-time model assuming:

- well-mixed air
- mass conservation

$$v\frac{dc(t)}{dt} = \left(\dot{Q}^{\text{vent,sup}} + \dot{Q}^{\text{leak,in}}\right)c^{\text{ext}} - \left(\dot{Q}^{\text{vent,exh}} + \dot{Q}^{\text{leak,out}}\right)c(t) + go(t) \tag{1}$$

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Discretizing and collecting the unknown parameters:

$$\begin{cases} c(k) = \dfrac{\theta_1}{1+\theta_3 u(k)}c(k-1) + \dfrac{\theta_2}{1+\theta_3 u(k)}o(k) \\ y(k) = c(k) + e(k) \end{cases} \tag{2}$$

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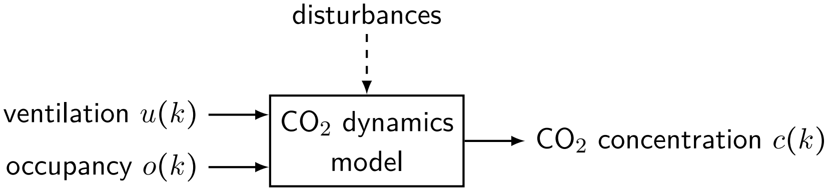
MVU predictor:

$$\widehat{c}(k\,;\,\boldsymbol{\theta}, \boldsymbol{o}) = \phi\left(k, \boldsymbol{o}, \boldsymbol{u}, \boldsymbol{y}, \boldsymbol{\theta}\right) \tag{3}$$

PEM identification of the CO_2 dynamics

Available information:

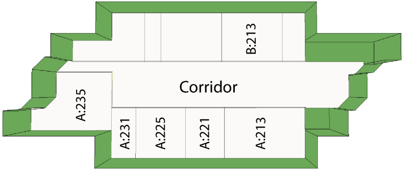
- $o(k)$
- $y(k)$
- $u(k)$

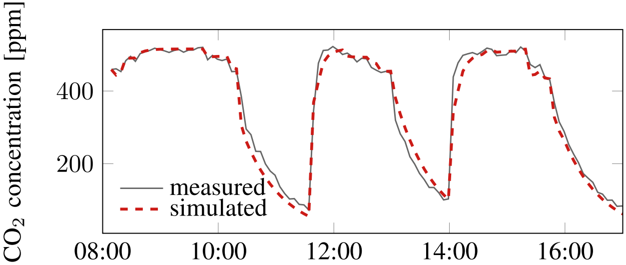


$$\widehat{\boldsymbol{\theta}}_N = \arg\min_{\theta \in \Theta} \sum_k \Big(y(k) - \widehat{c}(k; \boldsymbol{\theta}, \boldsymbol{o}) \Big)^2 \qquad (4)$$

How good is this model?

(Ebadat et al., Multi-room occupancy estimation through adaptive gray-box models, CDC 2015)

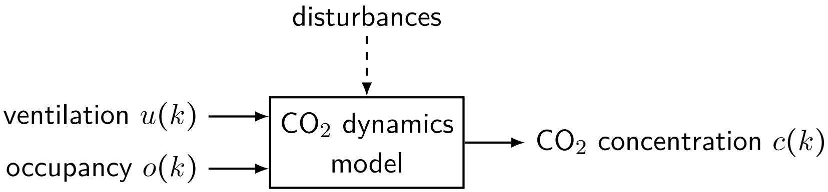




How to estimate $\boldsymbol{o}$ given $\widehat{\boldsymbol{\theta}}_N$

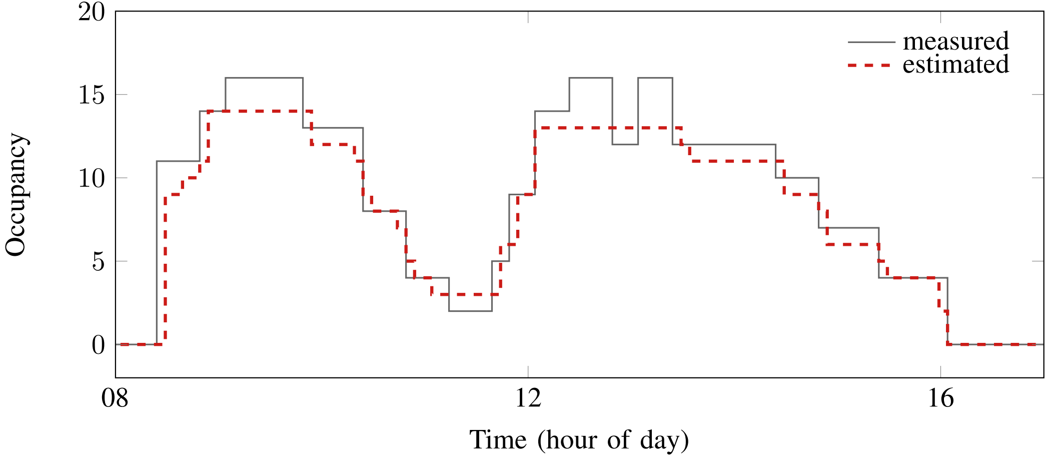
(Ebadat et al., Regularized Deconvolution-based Approaches for Estimating Room Occupancies, T-ASE 2015)

$$\widehat{\boldsymbol{o}}(\widehat{\boldsymbol{\theta}}_N) = \left[\arg\min_{\widetilde{\boldsymbol{o}}} \sum_{k=1}^{N} \left(y(k) - \widehat{c}\left(k; \widehat{\boldsymbol{\theta}}_N, \widetilde{\boldsymbol{o}}\right) \right)^2 + \lambda \left\| \Delta \widetilde{\boldsymbol{o}} \right\|_1 \right] \tag{5}$$



How good is this estimator in practice?

(Ebadat et al., Regularized Deconvolution-based Approaches for Estimating Room Occupancies, T-ASE 2015)



How good is this estimator in theory?

(this paper)

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Cost in terms of occupancy estimation:

$$V_{\text{app}}\left(\widehat{\boldsymbol{\theta}}_N, \boldsymbol{\theta}_0\right) := \mathbb{E}_{\boldsymbol{u}}\left\{\frac{1}{N}\left\|\widehat{\boldsymbol{o}}\left(\widehat{\boldsymbol{\theta}}_N\right) - \widehat{\boldsymbol{o}}(\boldsymbol{\theta}_0)\right\|_2^2\right\} \qquad \textit{(a.k.a. application function)} \qquad (6)$$

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Our requirement:

$$\widehat{\boldsymbol{\theta}}_N \in \Theta_{\text{app}}\left(\boldsymbol{\theta}_0, \gamma\right) := \left\{\boldsymbol{\theta} \;:\; V_{\mathsf{app}}(\boldsymbol{\theta}, \boldsymbol{\theta}_0) \leq \gamma^{-1}\right\} \qquad \textit{(a.k.a. application set)} \qquad (7)$$

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Problem: we actually don't know $\boldsymbol{\theta}_0$! $\Longrightarrow$ substitute it with an initial guess $\widehat{\boldsymbol{\theta}}_0$

(even better, do things recursively)

Our requirement, rephrased

$$\widehat{\boldsymbol{\theta}}_N \in \Theta_{\mathrm{app}}\left(\widehat{\boldsymbol{\theta}}_0, \gamma\right) := \left\{\boldsymbol{\theta} \ : \ V_{\mathsf{app}}\left(\boldsymbol{\theta}, \widehat{\boldsymbol{\theta}}_0\right) \leq \gamma^{-1}\right\} \tag{8}$$

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Problem: how do we compute $V_{\mathsf{app}}\left(\boldsymbol{\theta}, \widehat{\boldsymbol{\theta}}_0\right)$?

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$$\widehat{\boldsymbol{\theta}}_N \in \Theta_{\mathrm{app}}\left(\widehat{\boldsymbol{\theta}}_0, \gamma\right) \quad \rightsquigarrow \quad \lambda_{\mathsf{min}}\left(\widetilde{V}^{-1/2} I_F^N\left(\widehat{\boldsymbol{\theta}}_0\right) \widetilde{V}^{-1/2}\right) \geq 1 \tag{9}$$

with

$$\widetilde{V} := \frac{\gamma \chi^2_\alpha(n_{\boldsymbol{\theta}})}{2} \nabla^2 V_{\mathsf{app}}\left(\widehat{\boldsymbol{\theta}}_0, \widehat{\boldsymbol{\theta}}_0\right) \qquad I_F^N\left(\widehat{\boldsymbol{\theta}}_0\right) := \frac{1}{\sigma_e^2} \sum_{k=1}^{N} \nabla \psi\left(k, \widehat{\boldsymbol{\theta}}_0\right)^T \nabla \psi\left(k, \widehat{\boldsymbol{\theta}}_0\right) \tag{10}$$

The application-oriented input design problem – in words

$$\begin{aligned} \underset{\boldsymbol{u}}{\text{minimize}} \quad & \text{experimental cost} \\ \text{subject to} \quad & \widehat{\boldsymbol{\theta}}_N \in \Theta_{\text{app}}(\widehat{\boldsymbol{\theta}}_0, \gamma) \\ & \boldsymbol{u} \in \text{input constraints} \\ & \boldsymbol{y} \in \text{output constraints} \end{aligned} \tag{11}$$

The application-oriented input design problem – in practice

input constraints

final goal of occupancy estimation

$=$ optimize the performance of controllers

$=$ save energy

$\Longrightarrow$ use a low-energy ventilation signal during the identification experiment

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contradiction with the excitation requirements!

Trade-off $=$ constraint

$$\|\boldsymbol{u}\|_2^2 \leq (1+\beta)\|\boldsymbol{u}^*\|_2^2 \tag{12}$$

with

$$\begin{aligned} \boldsymbol{u}^* = \quad & \arg\min && \|\boldsymbol{u}\|_2^2 \\ & \text{subject to} && \boldsymbol{u} \in \text{hard input constraints} \\ & && \boldsymbol{y} \in \text{output constraints} \end{aligned} \tag{13}$$

The application-oriented input design problem – in practice

output constraints

$$\mathbb{P}\{y(k) \leq y_{\mathsf{max}}\} \geq p_y \quad \text{for every } k \tag{14}$$

The application-oriented input design problem – in practice

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Computation through exhaustive search:

$$\mathbb{P}\{y(k) \leq y_{\text{max}}\} = \frac{\sum_{k=1}^{t+N_u} \mathbb{1}\left(y_{\text{max}} - y(k)\right)}{t + N_u} \tag{15}$$

The application-oriented input design problem – final formulation

$$
\begin{aligned}
\underset{\boldsymbol{u},N}{\text{minimize}} \quad & N \\
\text{subject to} \quad & \lambda_{\text{min}}\left(\widetilde{V}^{-1/2} I_F^N\left(\widehat{\boldsymbol{\theta}}_0\right)\widetilde{V}^{-1/2}\right) \geq 1 \\
& \boldsymbol{u} \in \mathcal{U} \\
& \|\Delta \boldsymbol{u}\|_0 \leq n_c \\
& \|\boldsymbol{u}\|_2^2 \leq (1+\beta)\|\boldsymbol{u}^*\|_2^2 \\
& \mathbb{P}\{\boldsymbol{y} \leq y_{\text{max}}\} \geq p_y
\end{aligned}
\tag{16}
$$

Numerical results – setup

need: know the groundtruth

(and thus the $\boldsymbol{\theta}_0$ *generating the data)*

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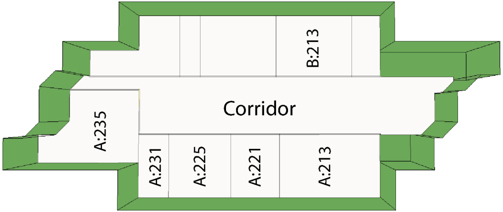
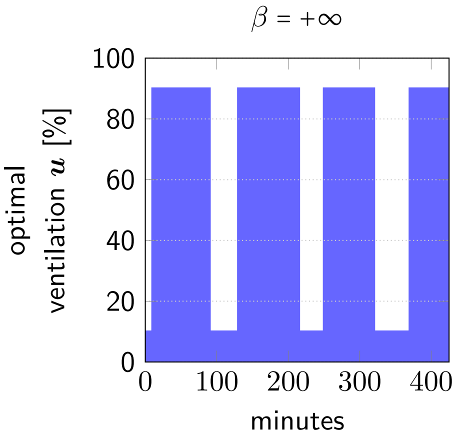
$\Longrightarrow$ Monte Carlo on simulated "true" occupancy levels $\boldsymbol{o}$



EQUA
IDA Indoor Climate and Energy

Numerical results – design of the ventilation input $\boldsymbol{u}$

sampling time = 5 minutes, one single MC run on $\boldsymbol{o}$



Numerical results – design of the ventilation input $\boldsymbol{u}$

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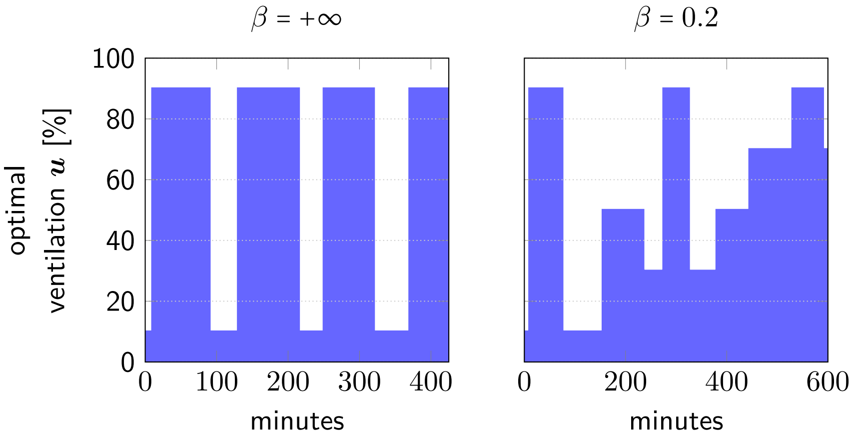
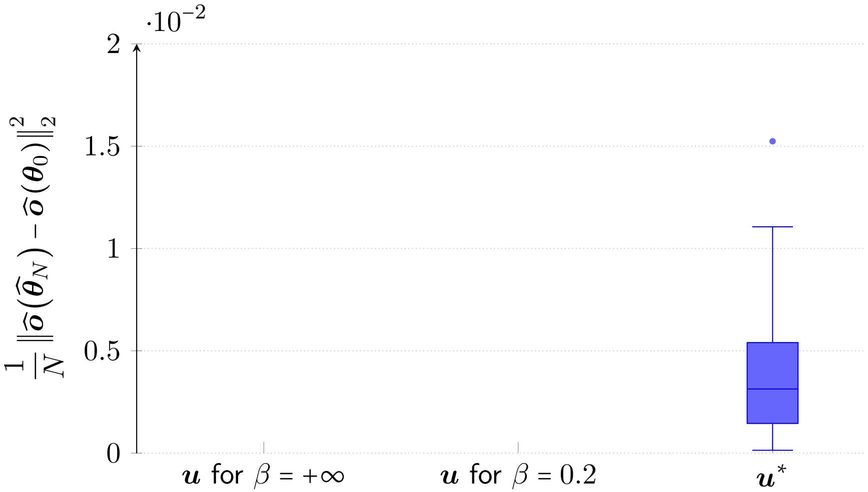


Numerical results – estimation performance on the whole MC on $\boldsymbol{o}$



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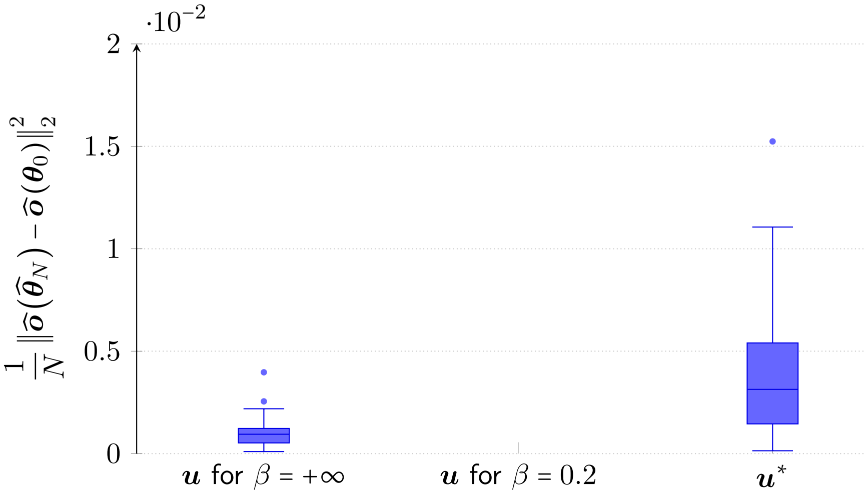

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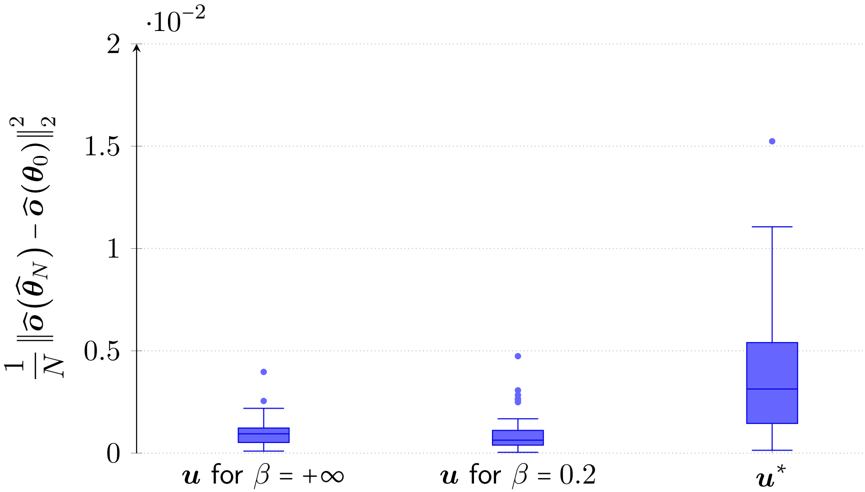

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Problem:

- how well will it work on a real system?

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damiano.varagnolo@ltu.se

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