A Domain Adaptation Technique for Fine-Grained Occupancy Estimation in Commercial Buildings

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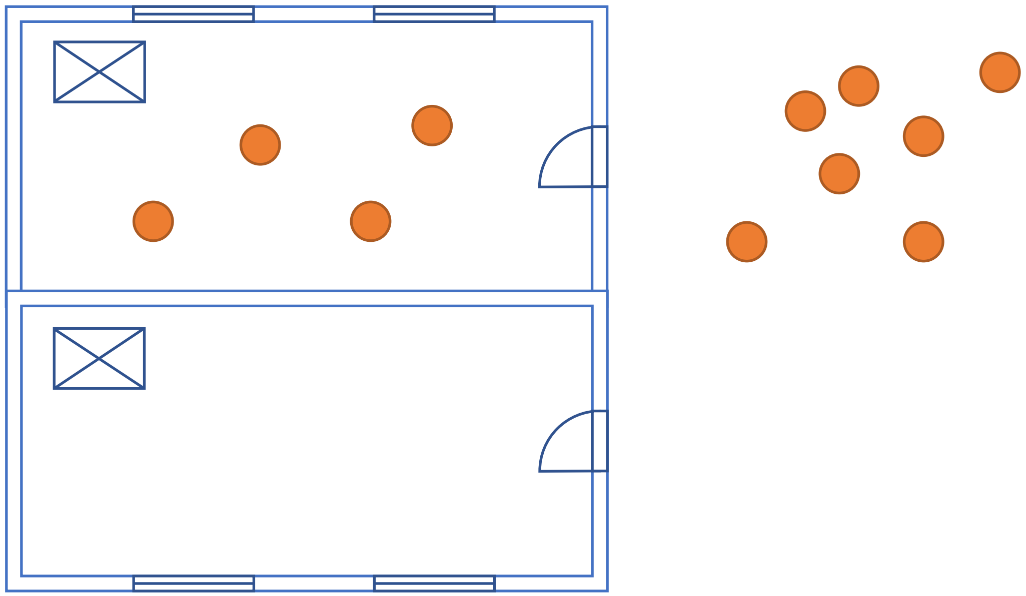
UNIVERSITY OF ALBERTA

Overview – Problem Definition

- How to reliably estimate the number of occupants in the many rooms of a commercial building?

Estimated Binary State: UnOccupied
Estimated Occupancy Count: [illegible]

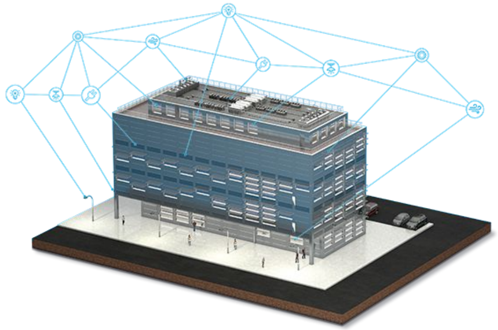


Overview – Applications of Occupant Count Determination

Demand-Driven HVAC Control

Security

Space Utilization



Many other applications in occupant-centred buildings

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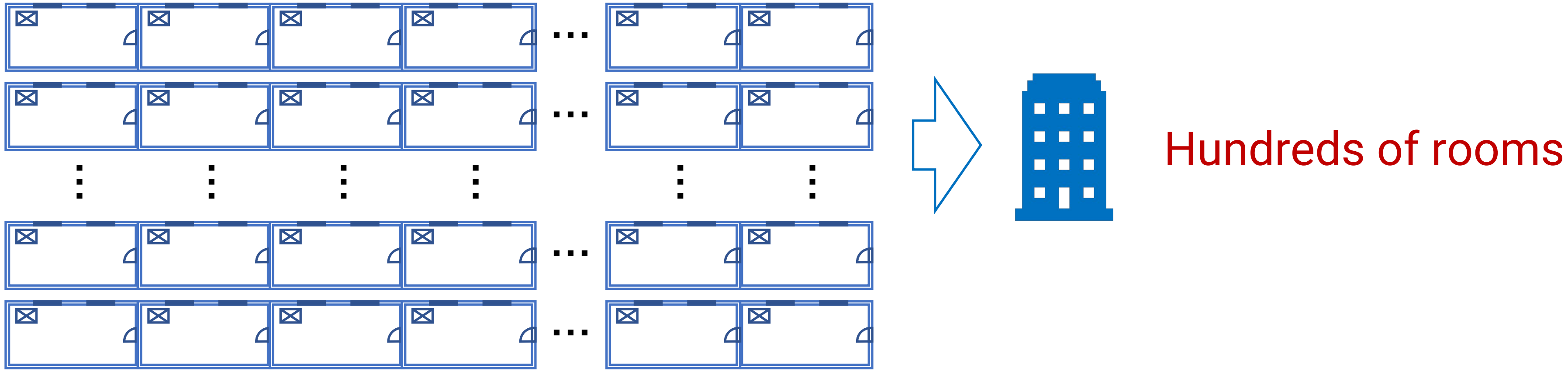
Overview – Problem Definition

- How to reliably estimate the number of occupants in the many rooms of a commercial building?
- Well-studied problem at the room level, but how about a large building?



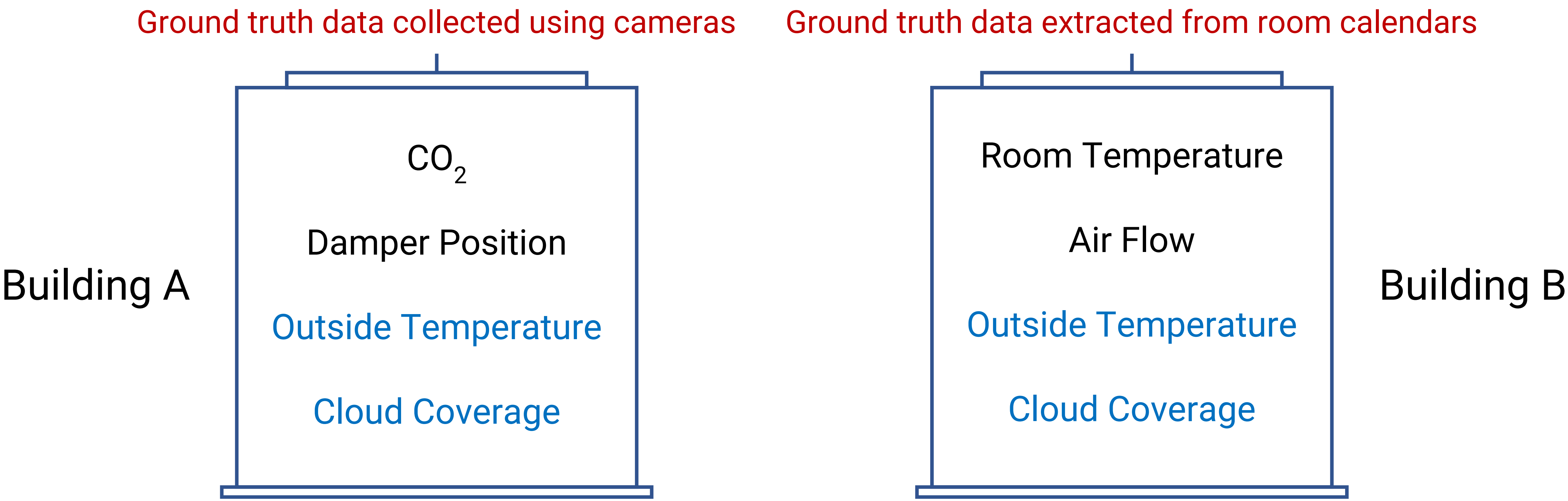
Overview – Domain Adaptation

- How to build a general model that can be reused in multiple rooms/buildings?
- How to build a black-box model for a room/building with no/limited available labeled data

- Solution: modify a well-tuned model for one room/building to adapt it to the target room/building leveraging some information

Overview – Experiments

- Data collected from two buildings located in Canada and Denmark
- Buildings have different room sizes, types, and sensing modalities



Outline

- Challenges and previous work
- Methodology
- Results
- Takeaways and future work

Challenges

- Multiple sensing modalities

Cameras [Erickson 13]

Wireless Network [Zou 17]

Thermal Arrays [Beltran 13]

Grid-EYE sensors

HVAC Sensors [Ardakanian 18]

Damper Position Sensors

CO_2, Temp & Humidity Sensors

Door Sensors [Agarwal 11]

Magnetic Reed Switches

https://www.cctvcamerapros.com/Dummy-Security-Camera-p/dum-d01.htm
https://web.sonxplus.com/en/5-practical-tips-to-optimize-your-home-wireless-network/
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https://www.tempcon.co.uk/shop/hobo-mx1102-bluetooth-co2-temp-rh-data-logger
https://www.wiltronics.com.au/product-category/magnetic-reed-switch-bar-magnets/

Different sensing modalities

	Cost	Privacy	Occ. Estimation Accuracy
Cameras [Erickson 13]	↑	↓↓	↑↑
Wireless Network [Zou 17]	↓	↓	↑
Thermal Arrays [Beltran 13]	↑	↑	↑
HVAC Sensors [Ardakanian 18]	↓	↑	↑
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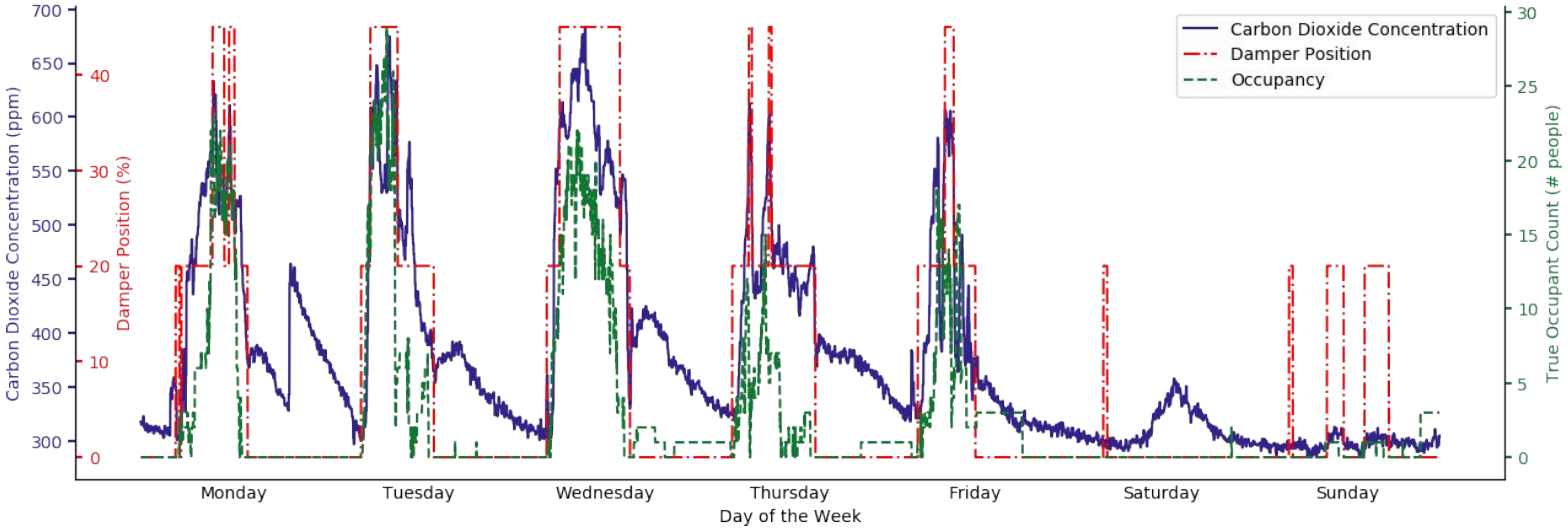
zero-cost sensors

Wait... Can HVAC sensors be used for occupancy estimation?



Challenges

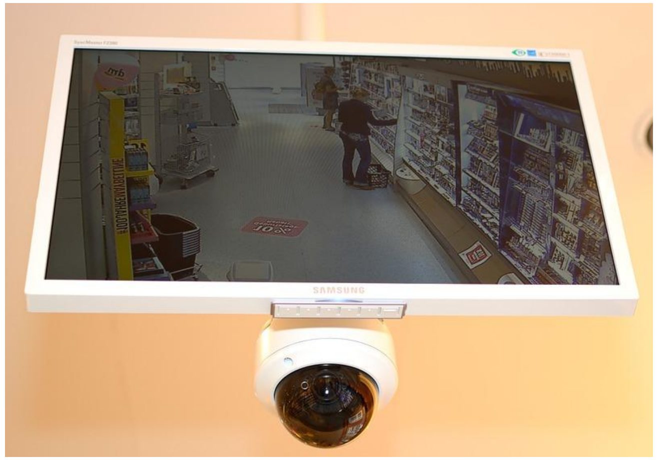
- Multiple sensing modalities, some are less correlated with occupancy (HVAC sensors)
- Several sensor data fusion algorithms
    - Physics-based model to quantify heat gain due to occupancy
        - Have to customize for each room/building. Too complex to build high-order models.
    - Black-box model
        - Easier to build, but requires large amounts of labelled data for training

Challenges

- Multiple sensing modalities, some are less correlated with occupancy (HVAC sensors)
- Different sensor data fusion algorithms (black-box model)
  - Time-series models (using a sequence of data to predict)
    - RNN / NARX
  - Single snapshot prediction models (using one data point to predict)
    - SVR / SVM / Random Forest

Challenges

- Multiple sensing modalities, some are less correlated with occupancy (HVAC sensors)
- Different sensor data fusion algorithms (black-box model)
- Ground truth data is often sparse or nonexistent (expensive to collect)



https://pixabay.com/photos/camera-monitoring-813747/
https://www.aliexpress.com/item/Metal-Mechanical-Manual-Counters-Counters-Counters-Hand-Held-Counter-Flow-Meters-Free-Shipping/32785311038.html

Our hypothesis is...

models that are built in a controlled environment (source domain) can be reused in a new environment (target domain) after some adaptation

and that the adapted model has higher accuracy than a model built from scratch for the target domain

Domain Adaptation

Basic Idea: transform a well-trained model from a source domain to a related target domain after performing some modifications on the model.

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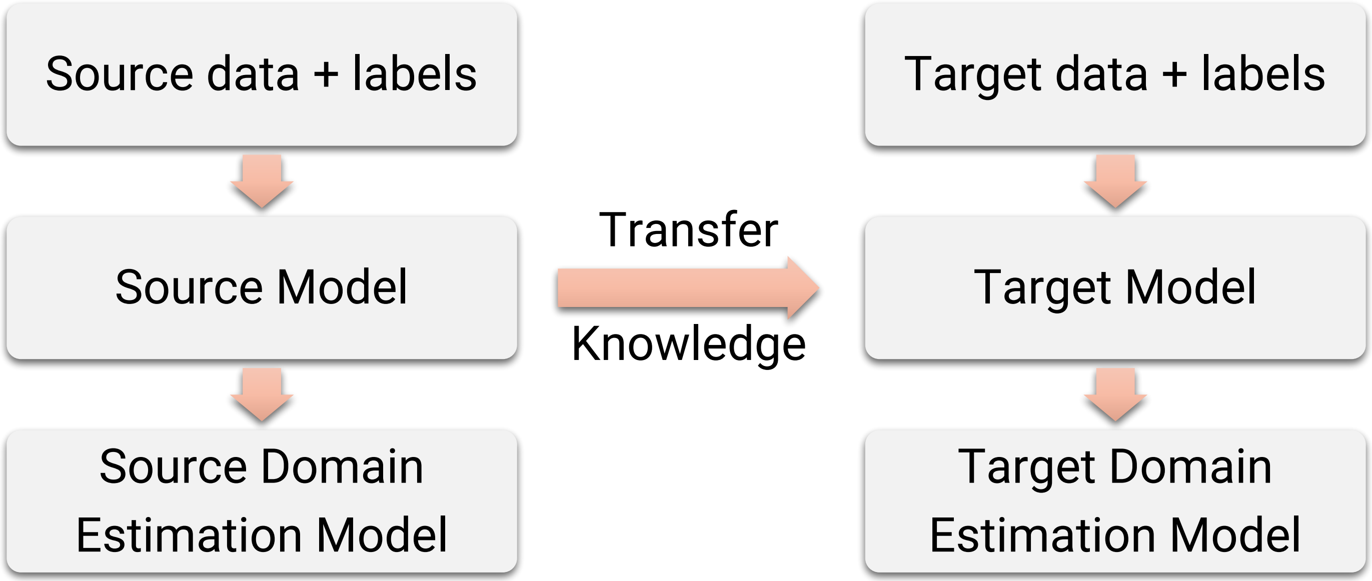
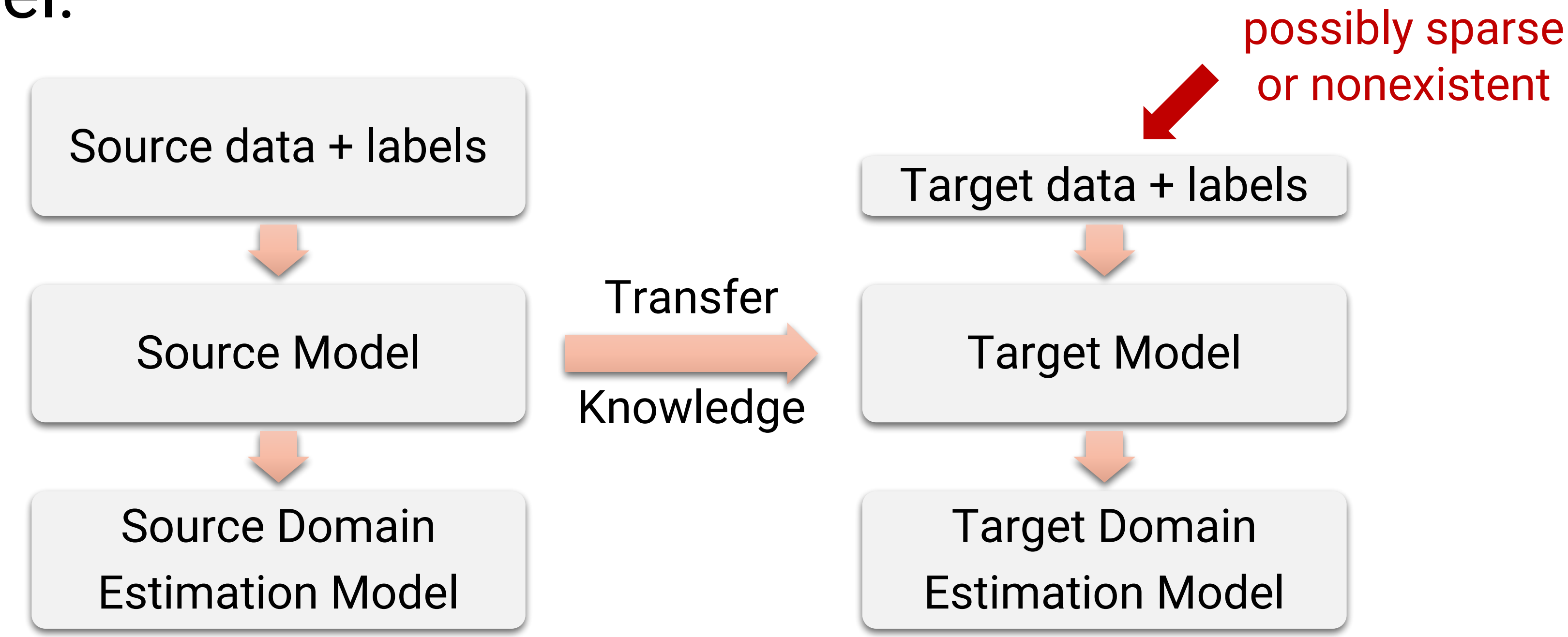


Domain Adaptation

Basic Idea: transform a well-trained model from a source domain to a related target domain after performing some modifications on the model.



Domain Adaptation

How is it applied to our problem?

- Train a well-suited model in a room equipped with a high-accuracy occupancy monitoring system (source domain)
- Adapt it to another room within the same building (target domain) using some information about the apparent differences between the rooms

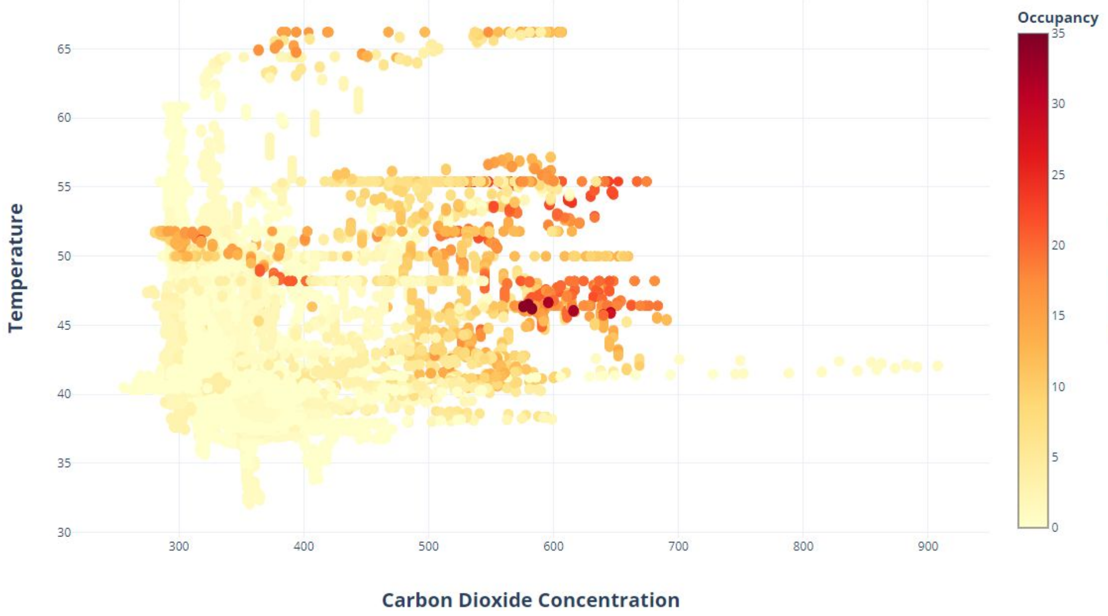
- Main benefit: we do not need a lot of labeled data in the target domain; hence, it can be widely applied to the many rooms in a given building

Assumptions

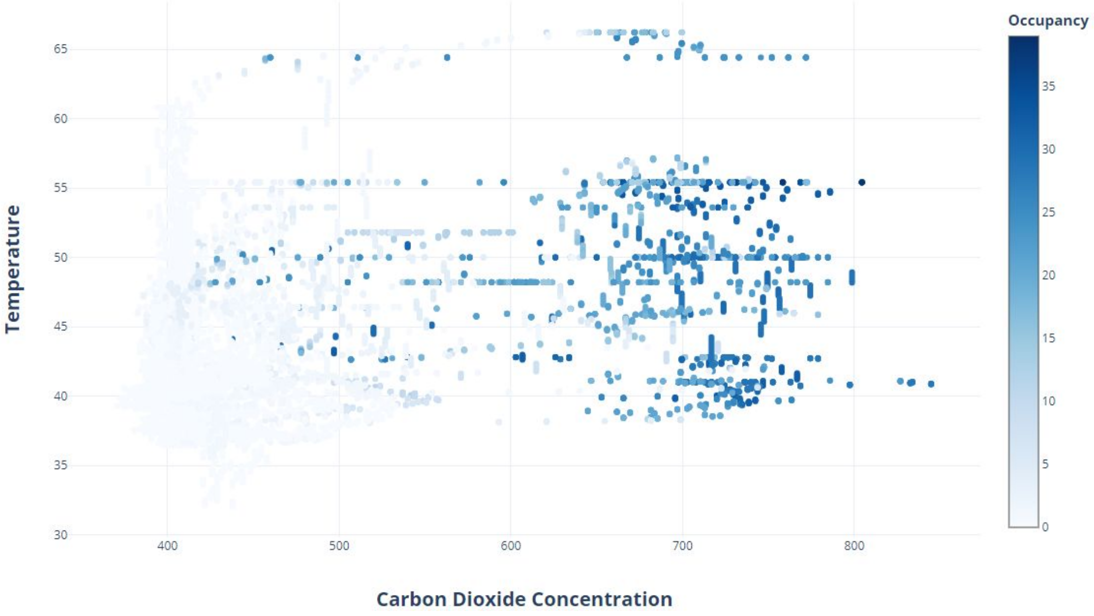
- Occupancy influences measured quantities in both source and target domains in a similar way.
- The same types of sensors are deployed in both domains (same feature space)

Why domain adaptation is necessary?

Source and target domains may have different distributions



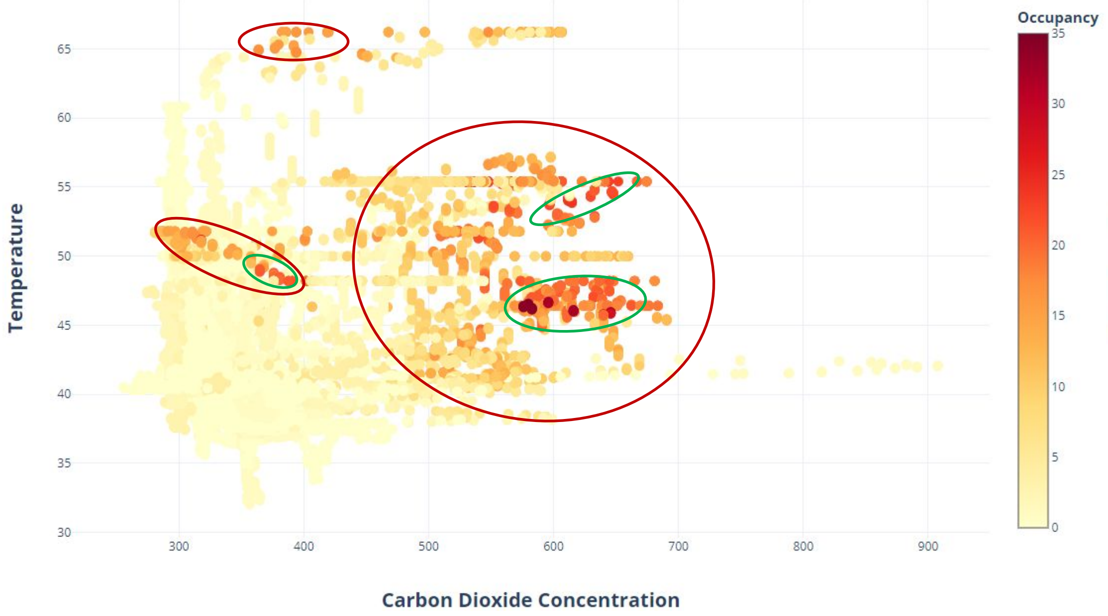
Room 1 in Building A



Room 2 in Building A

Why domain adaptation is necessary?

Source and target domains may have different distributions



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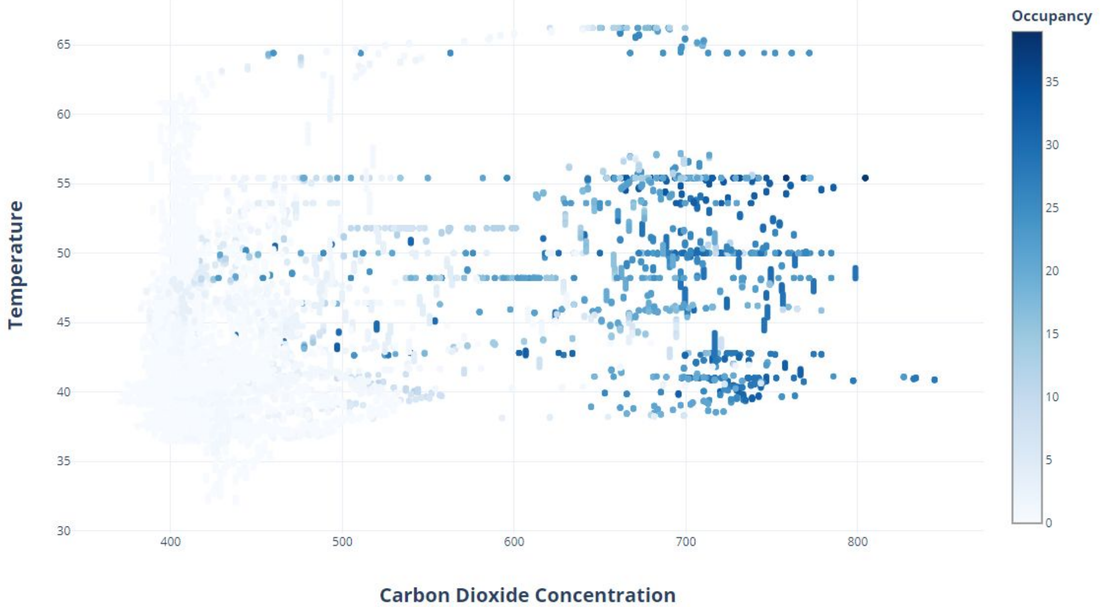

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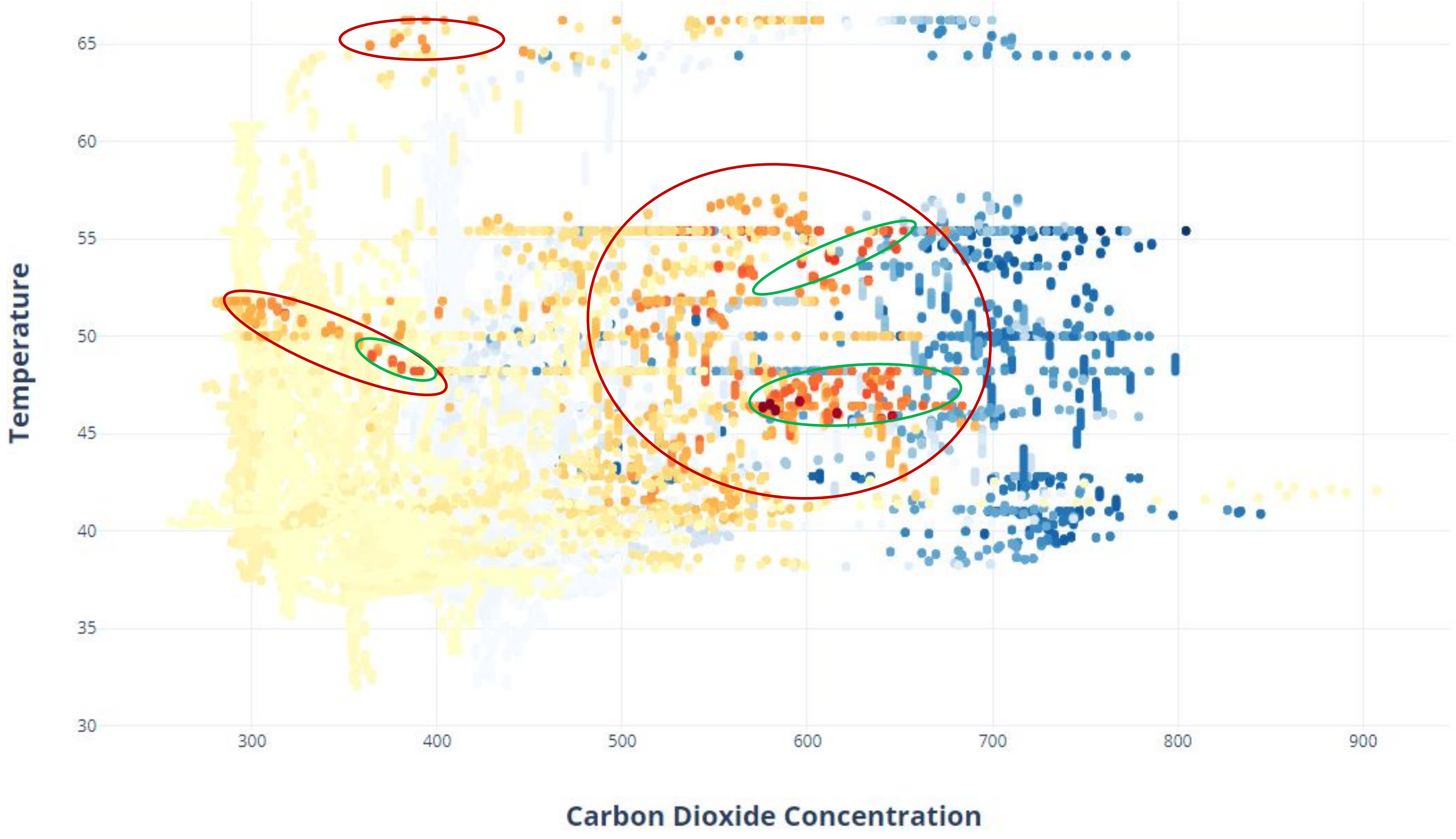

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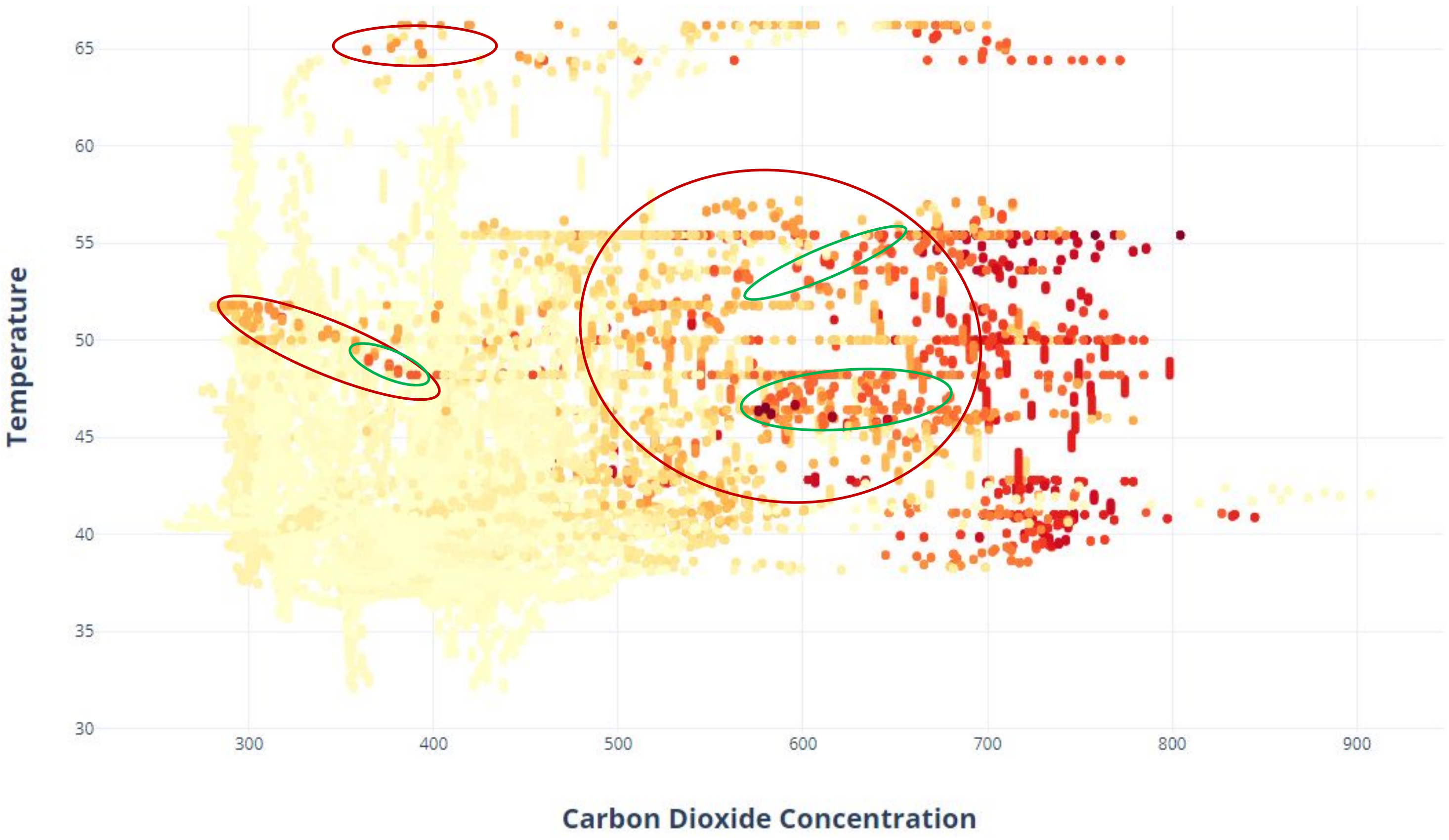
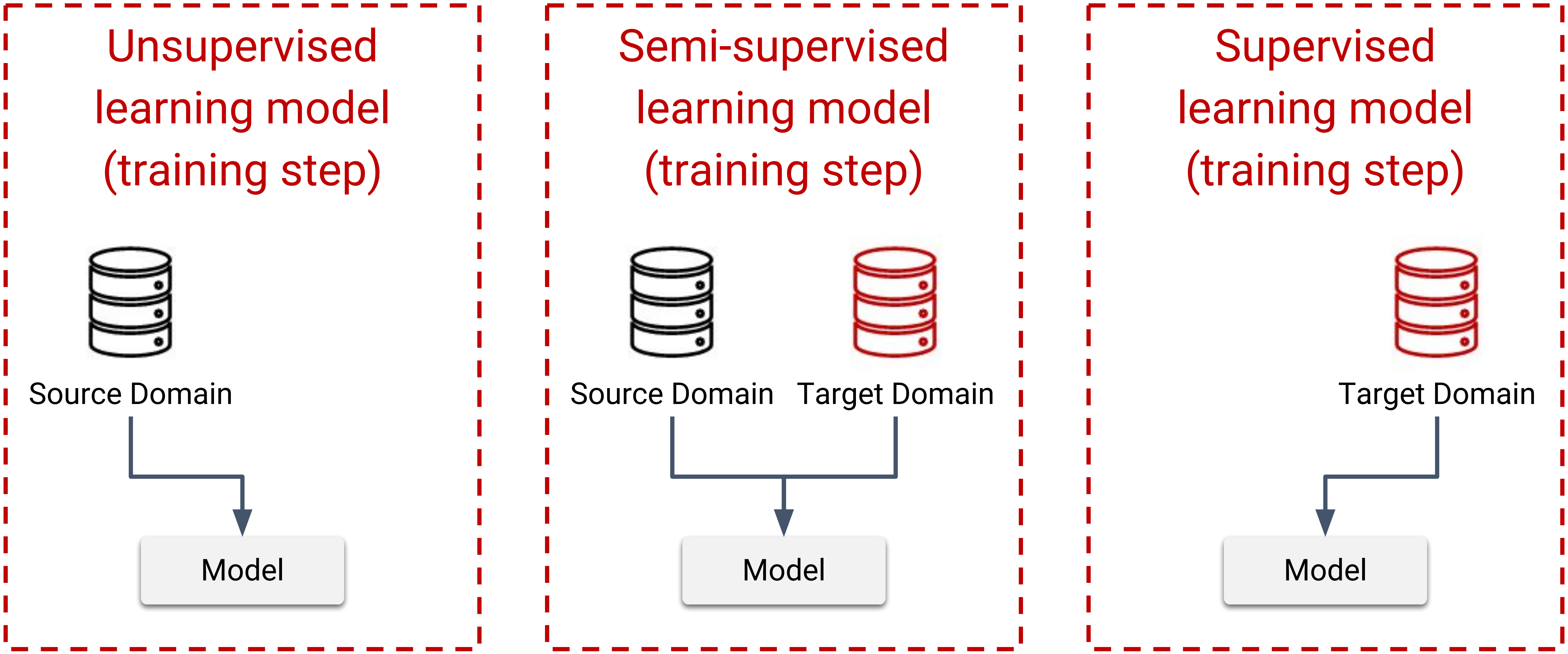


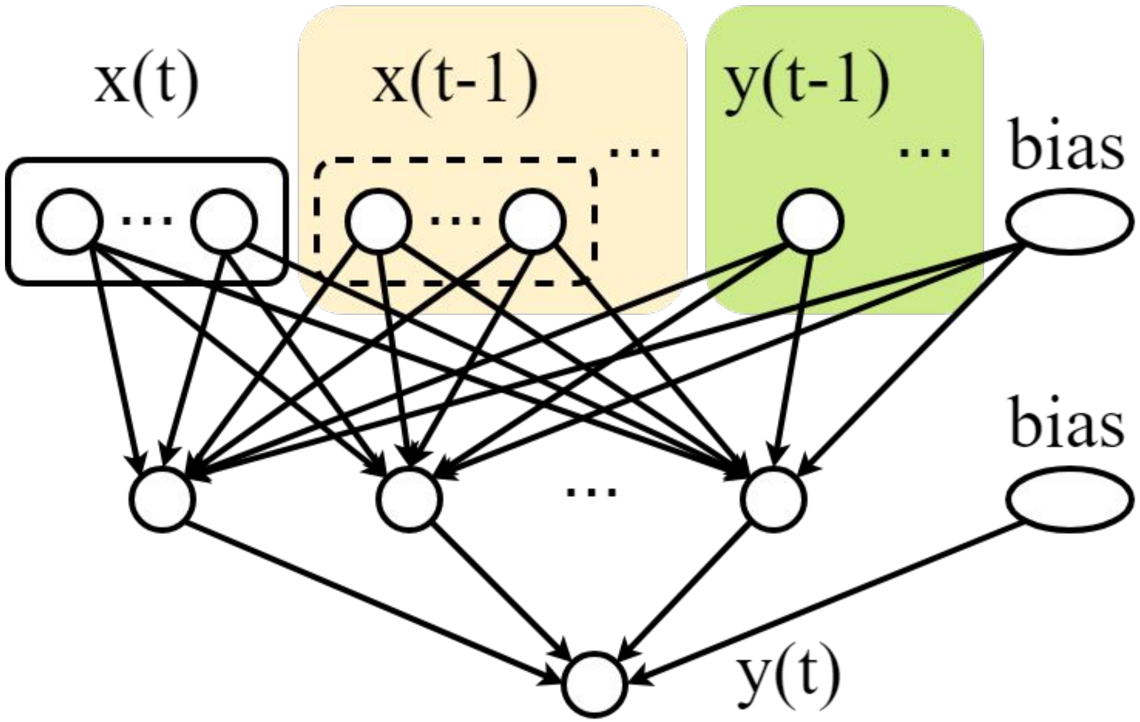
Domain Adaptation Techniques



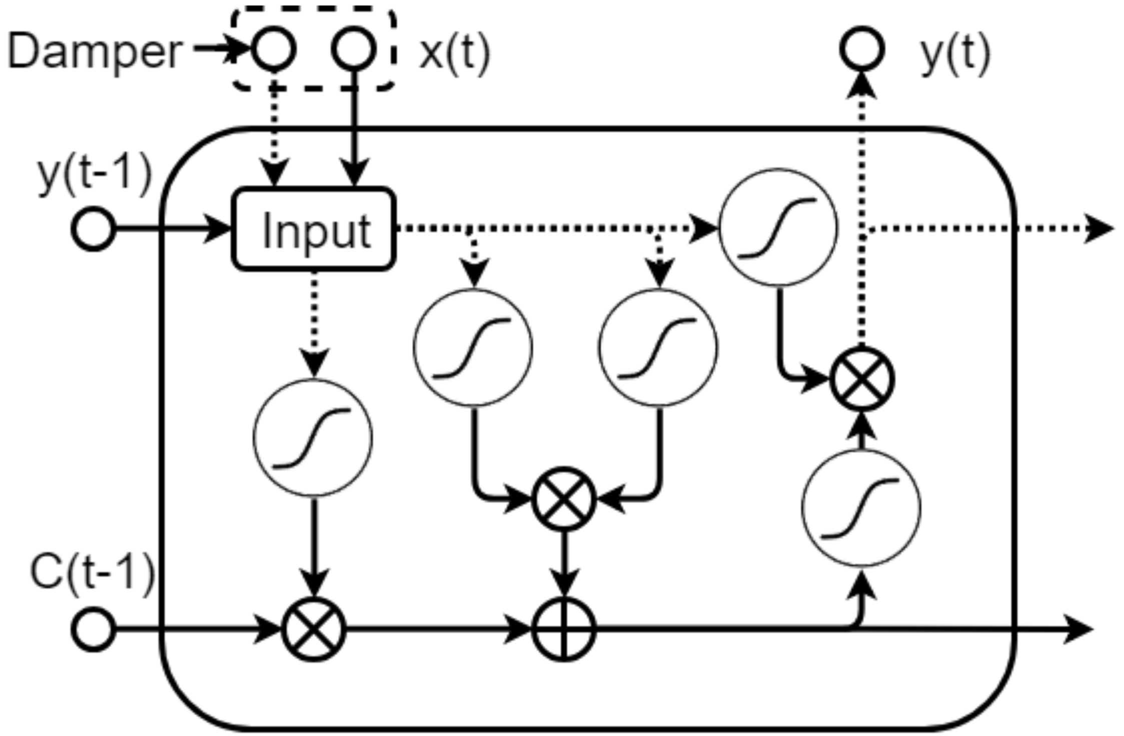
Domain Adaptive Recurrent Neural Networks

- Re-weighting (may be carried out for semi-supervised and unsupervised domain adaptation):
  - Adjust the weights of output layer based on the maximum occupancy
  - Adjust the weights of input layer corresponding to the CO_2 values based on the size of the room and the ventilation power of the room
- Re-training (only for semi-supervised domain adaptation):
  - Use the limited labeled data from the target domain to calibrate the weights

Methodology

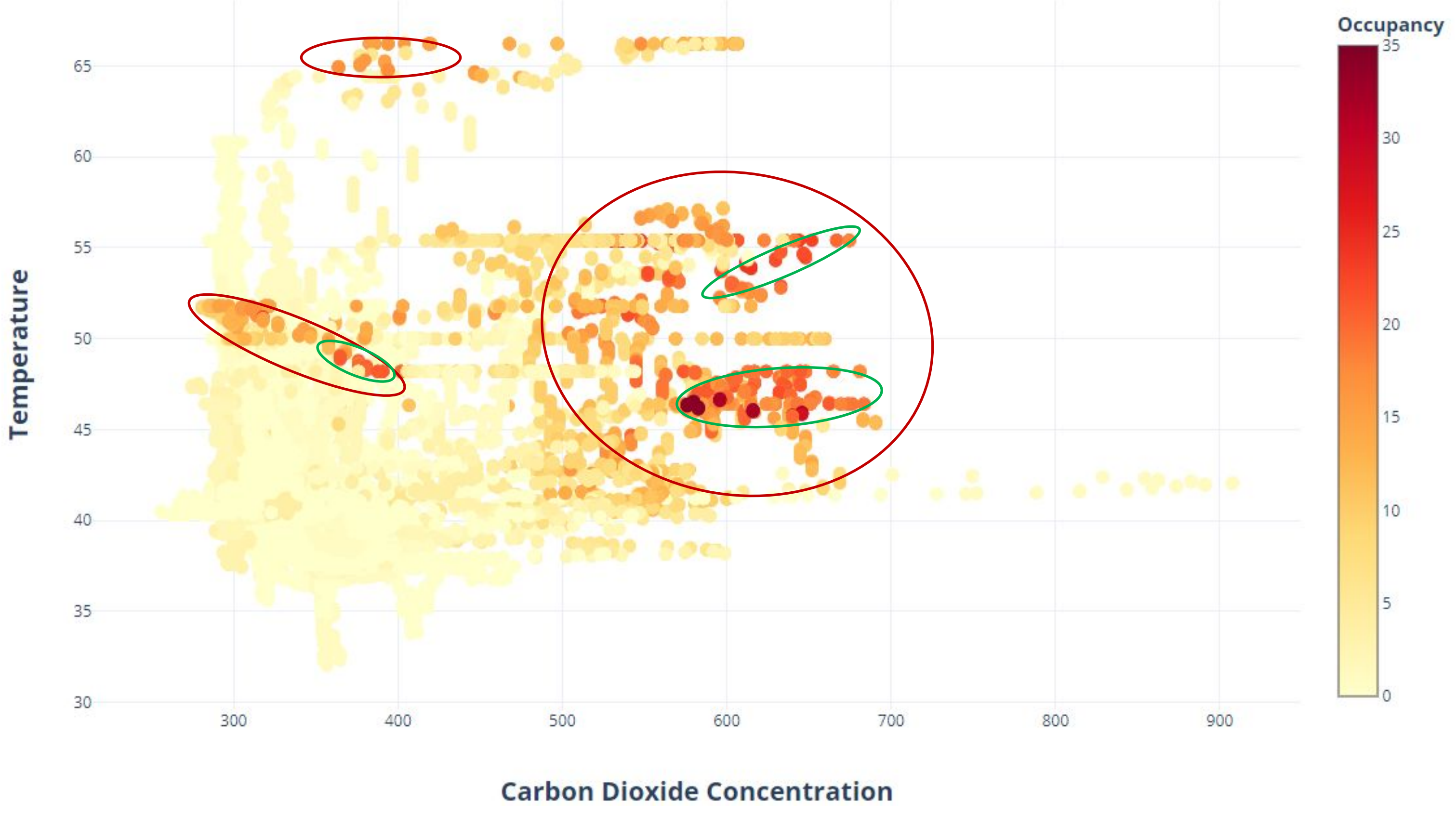


Domain Adaptive
NARX Network

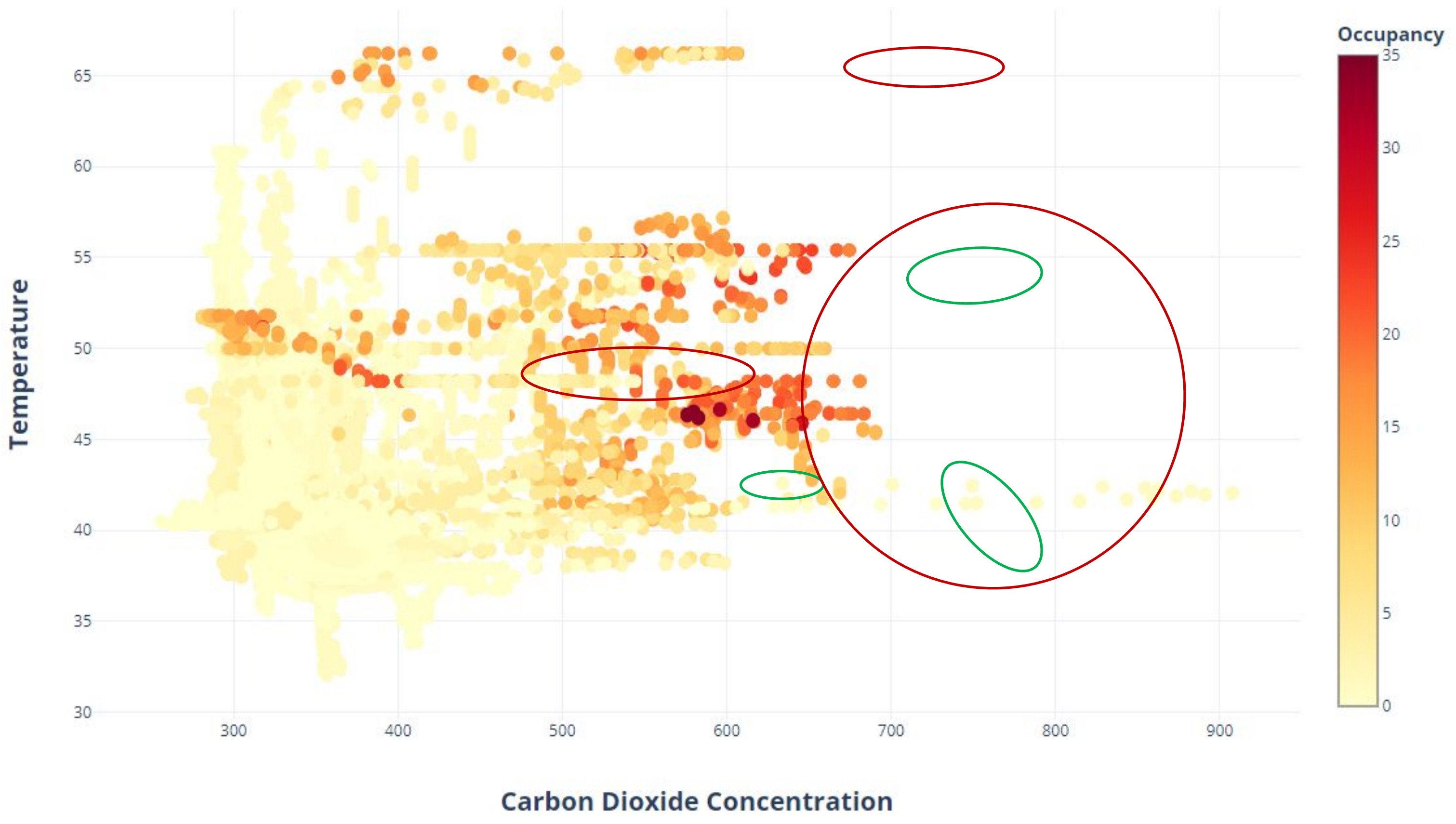


Domain Adaptive
LSTM Cell

Applying Domain Adaptation



Applying Domain Adaptation



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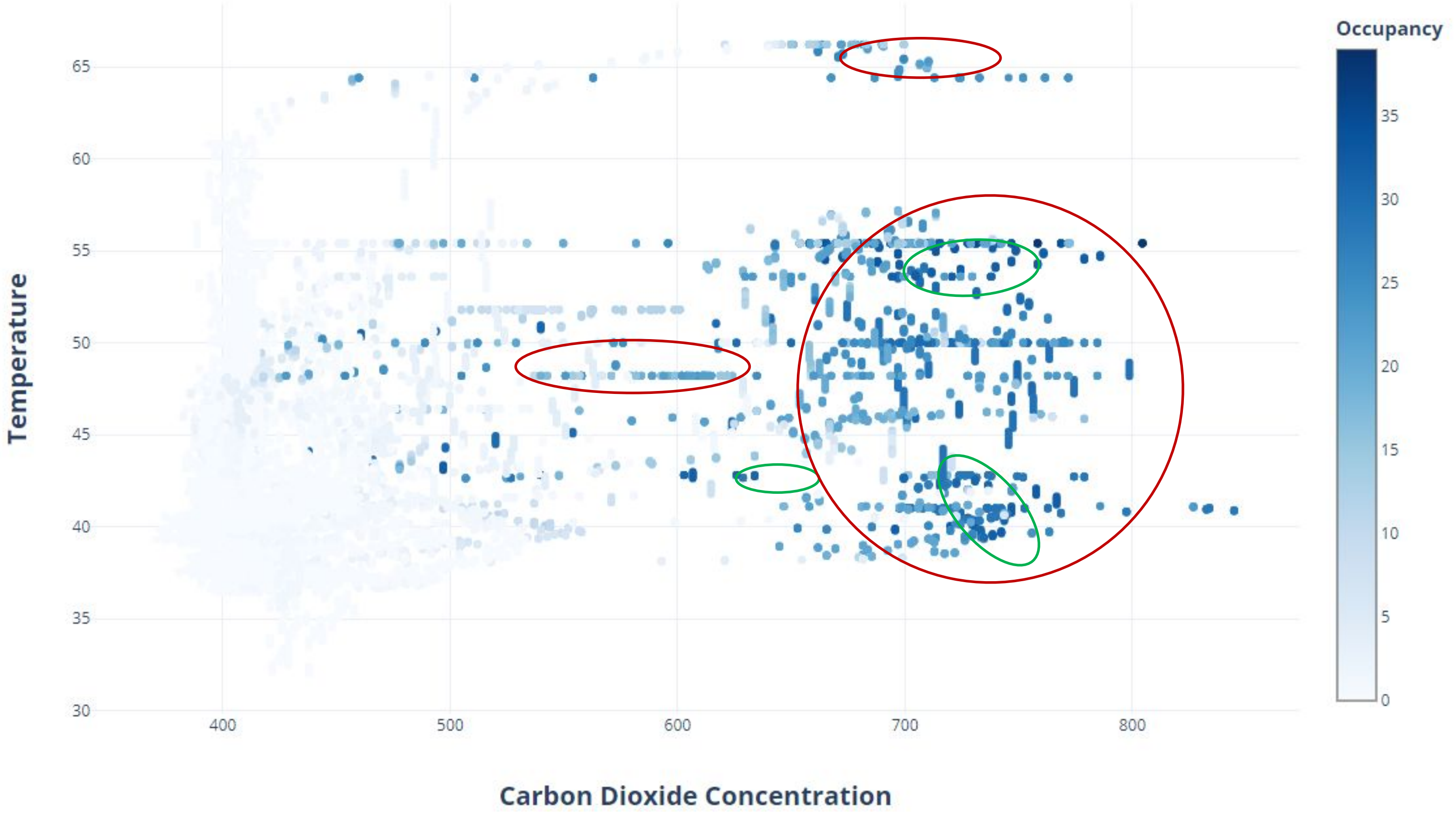
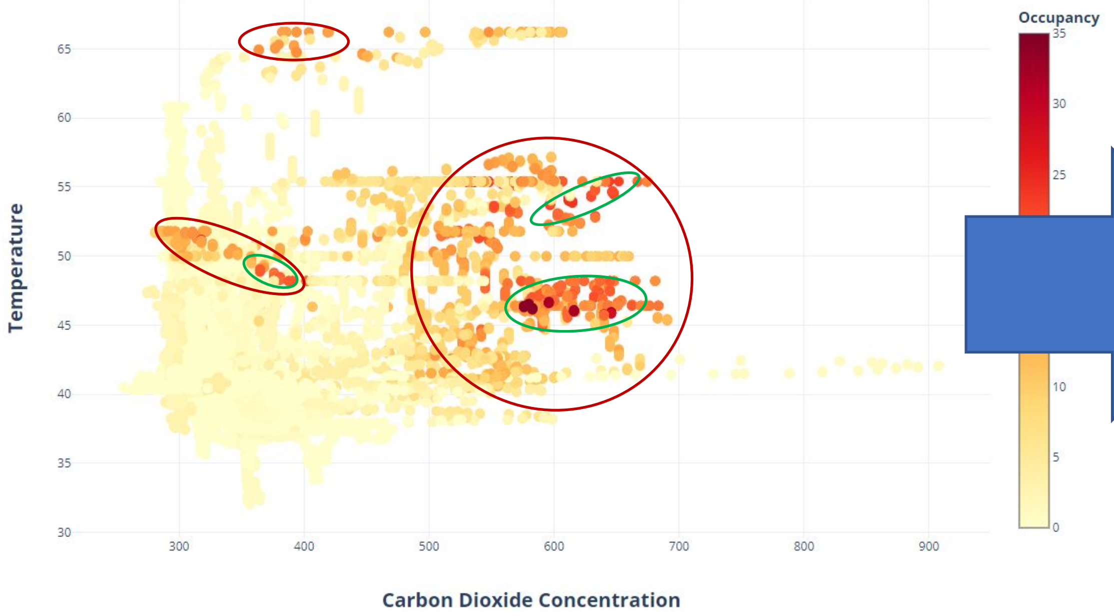
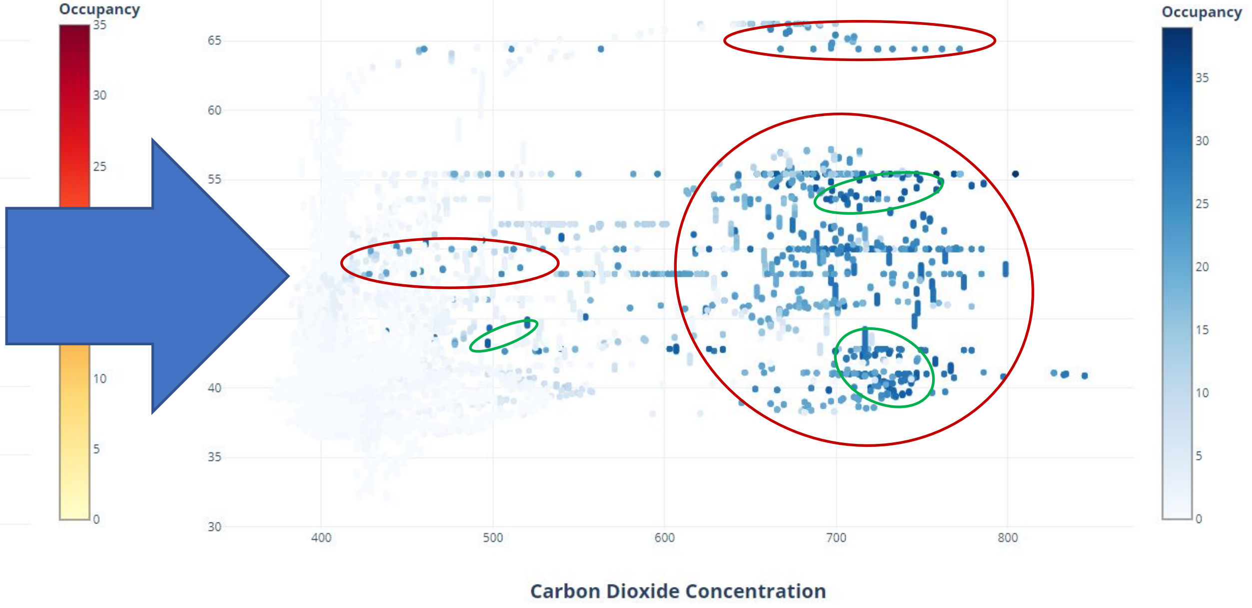


Re-weighting

Applying Domain Adaptation

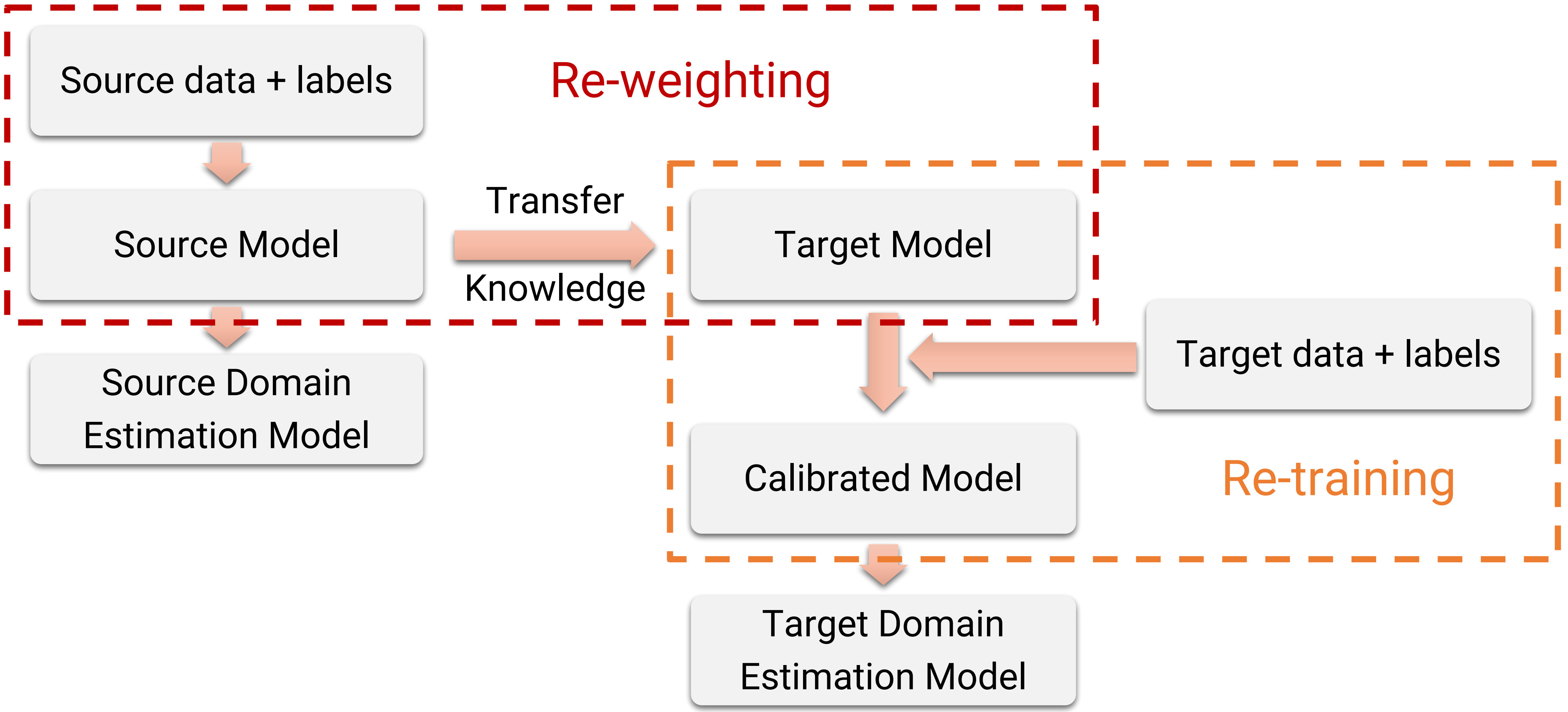


Room 1 in Building A

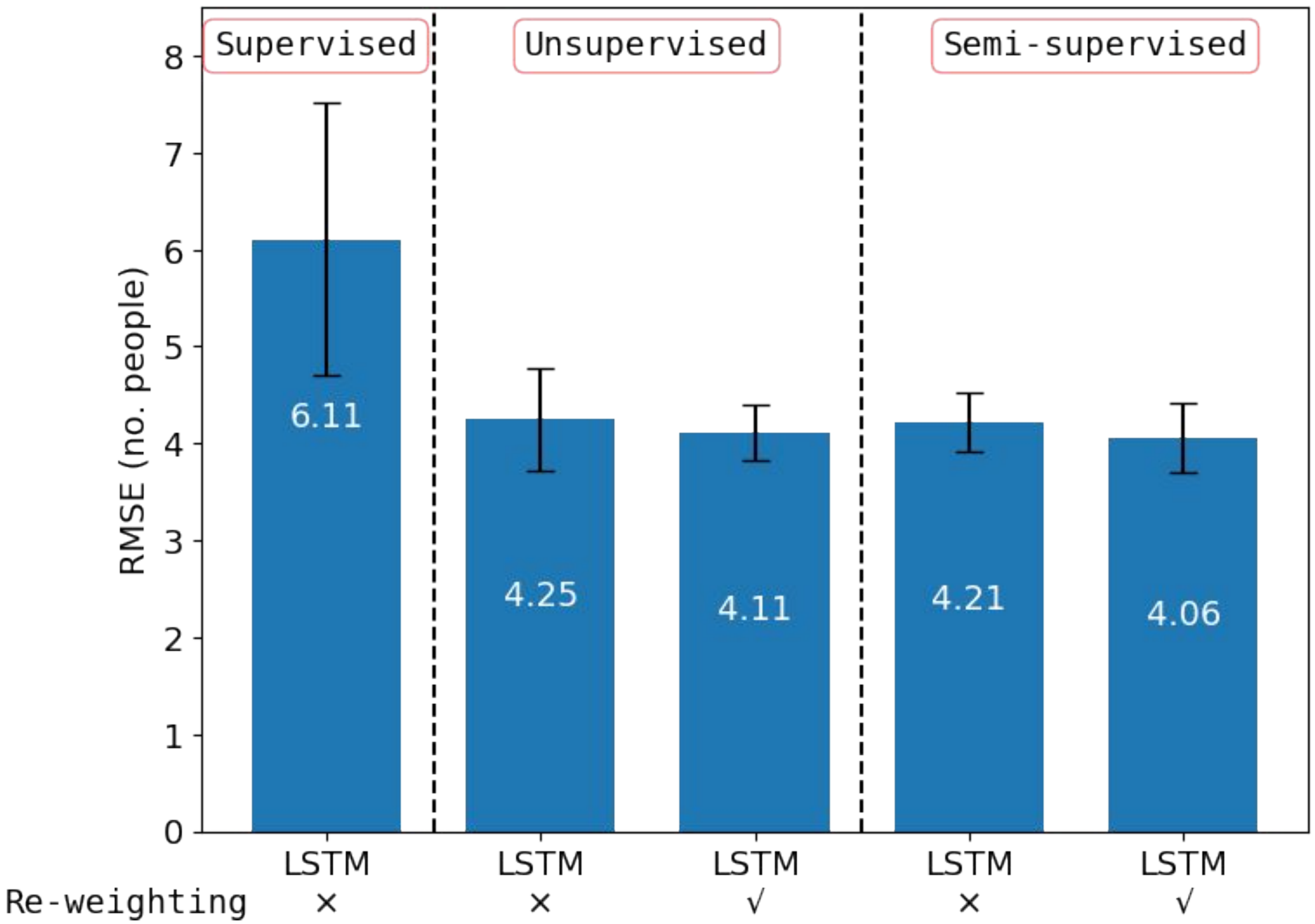


Room 2 in Building A

The whole process...

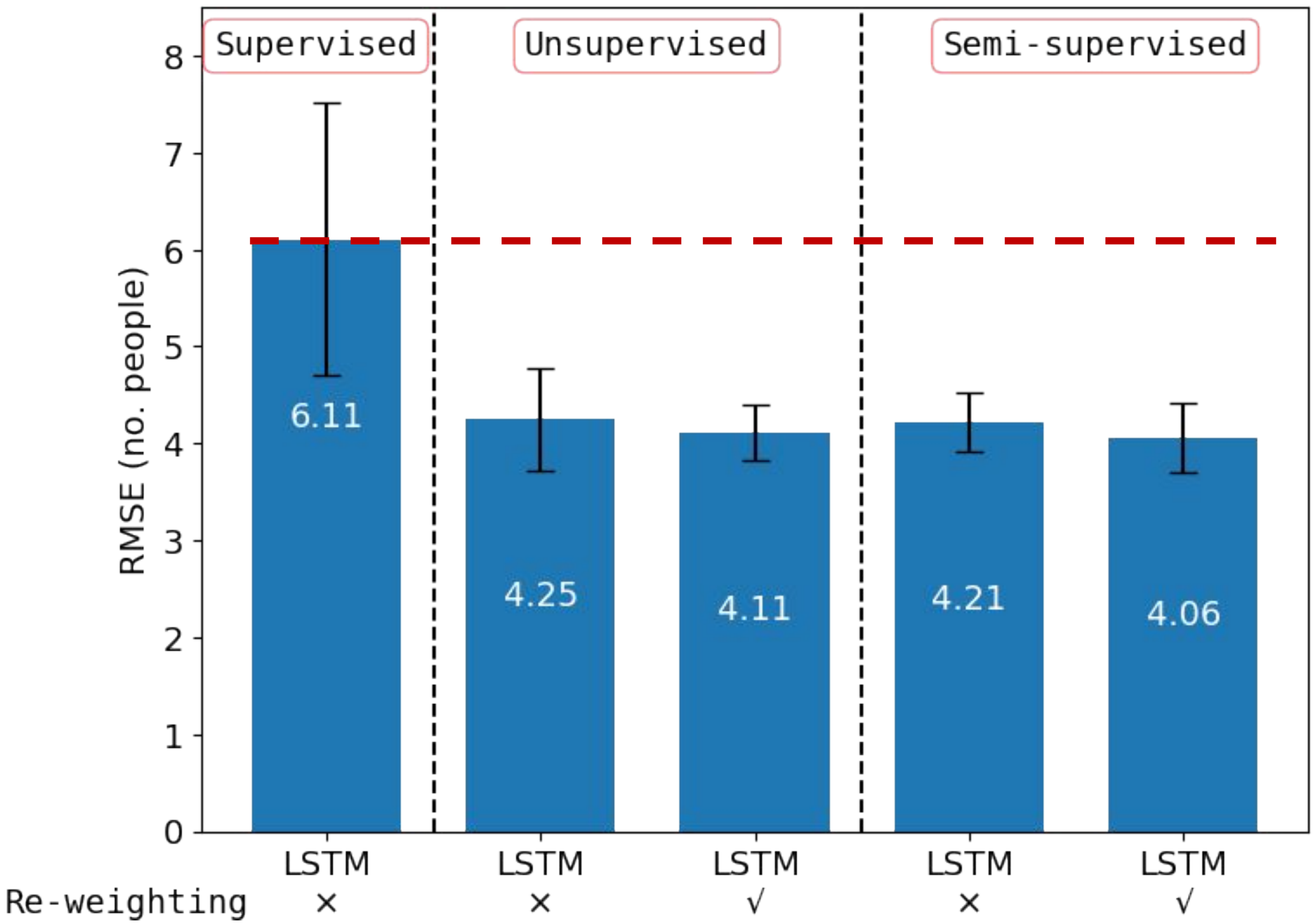


Results


Supervised
Unsupervised
Semi-supervised
RMSE (no. people)
0
1
2
3
4
5
6
7
8
6.11
4.25
4.11
4.21
4.06
LSTM
LSTM
LSTM
LSTM
LSTM
Re-weighting
×
×
√
×
√

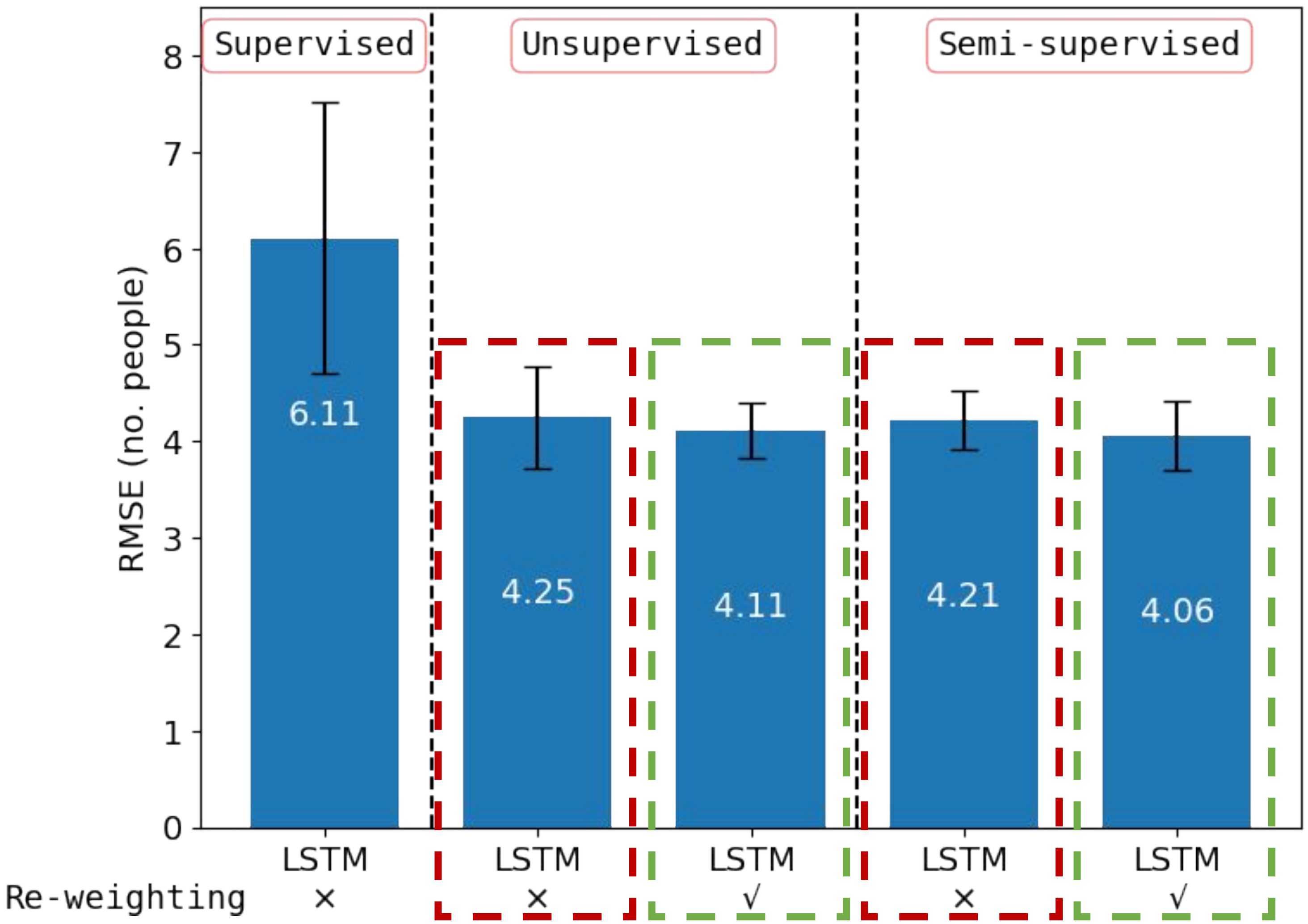
Results

- Domain-adaptation improves the accuracy



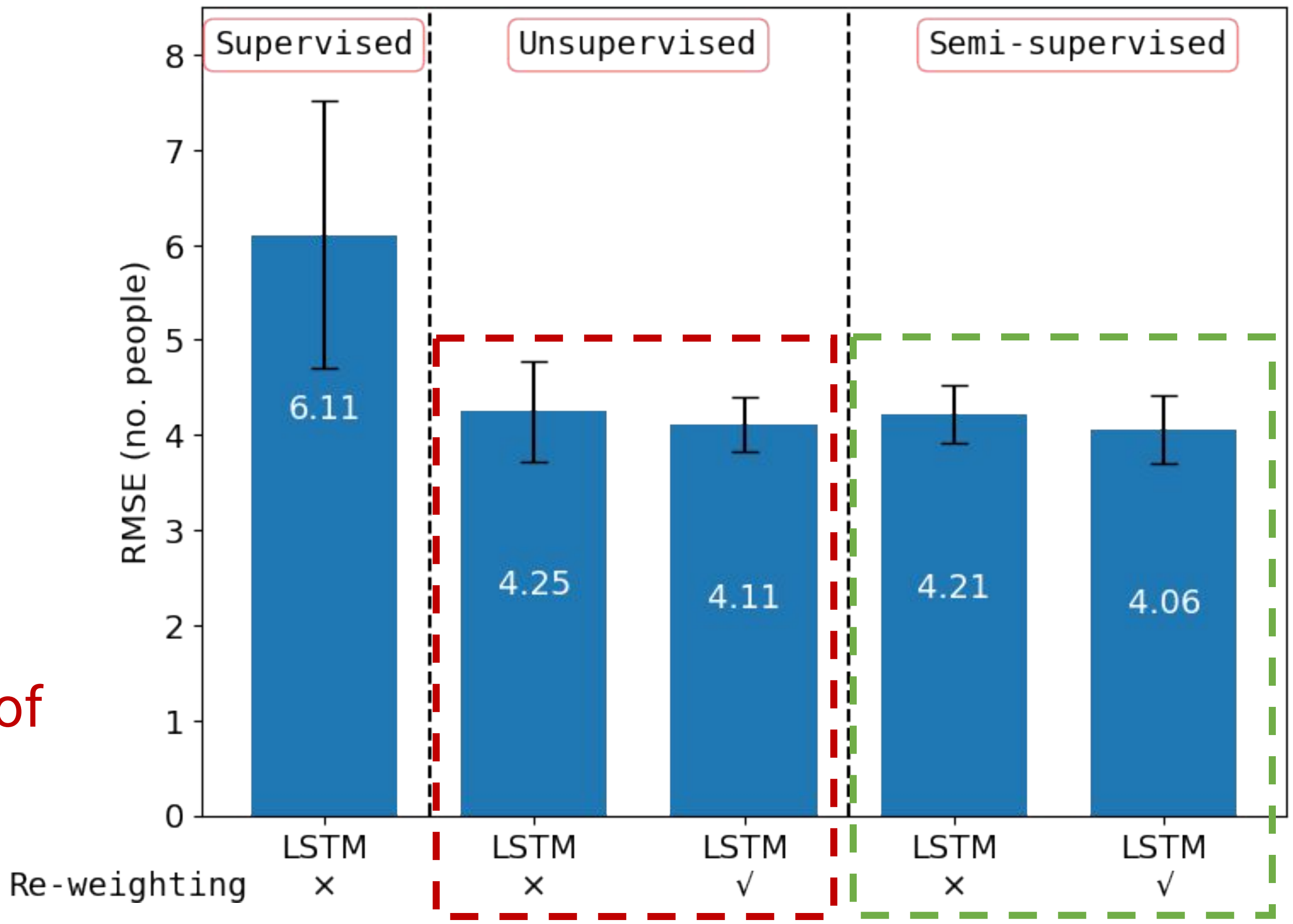
Results

- Domain-adaptation improves the accuracy
- Semi-supervised performs better (re-training is useful)

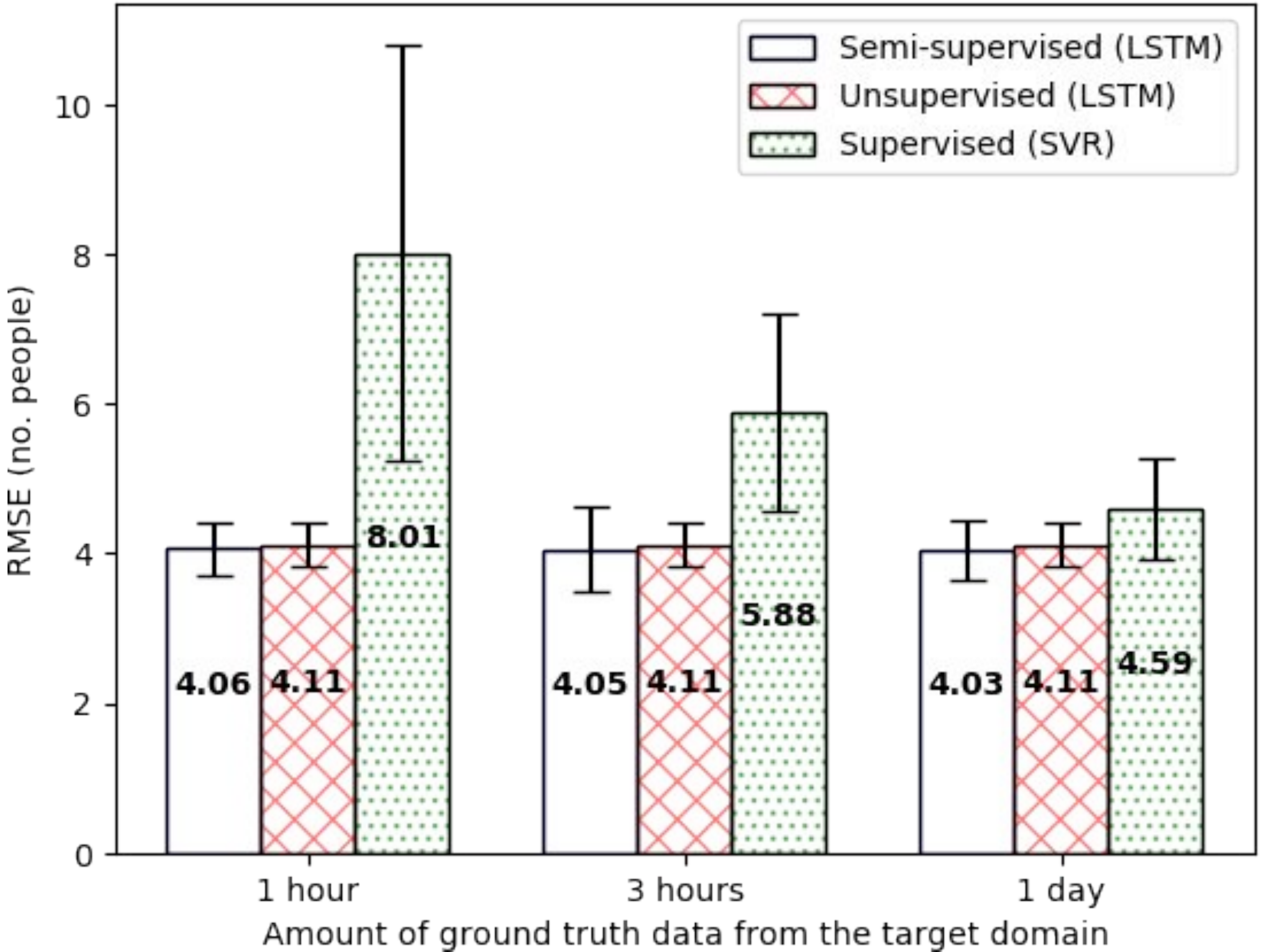


Results

- Domain-adaptation improves the accuracy
- Semi-supervised performs better (re-training is useful)
- Re-weighting can help reduce the RMSE, BUT requires the knowledge of the differences between the two domains

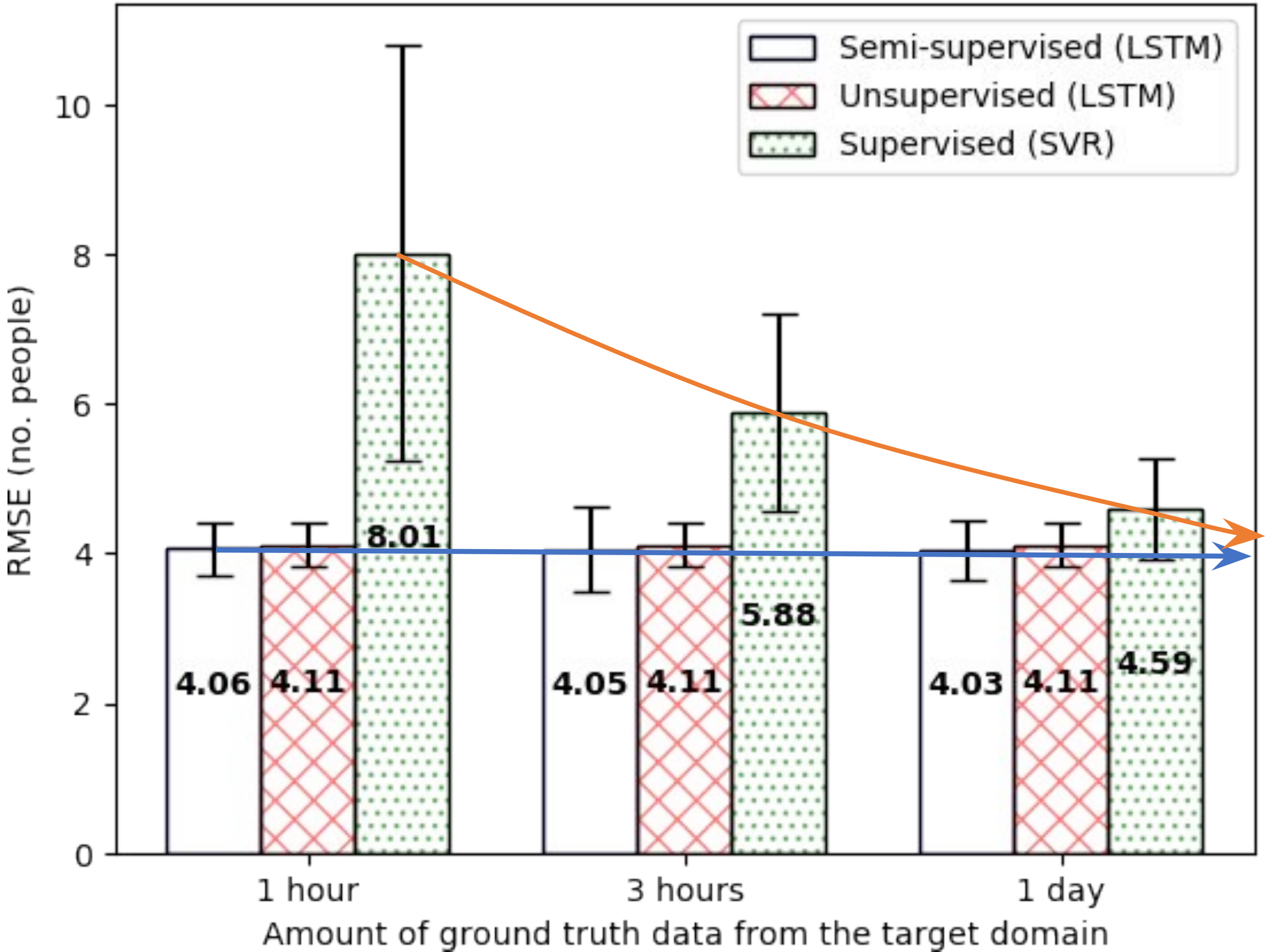


Results



Semi-supervised (LSTM)
Unsupervised (LSTM)
Supervised (SVR)
RMSE (no. people)
0
2
4
6
8
10
4.06
4.11
8.01
4.05
4.11
5.88
4.03
4.11
4.59
1 hour
3 hours
1 day
Amount of ground truth data from the target domain

Results



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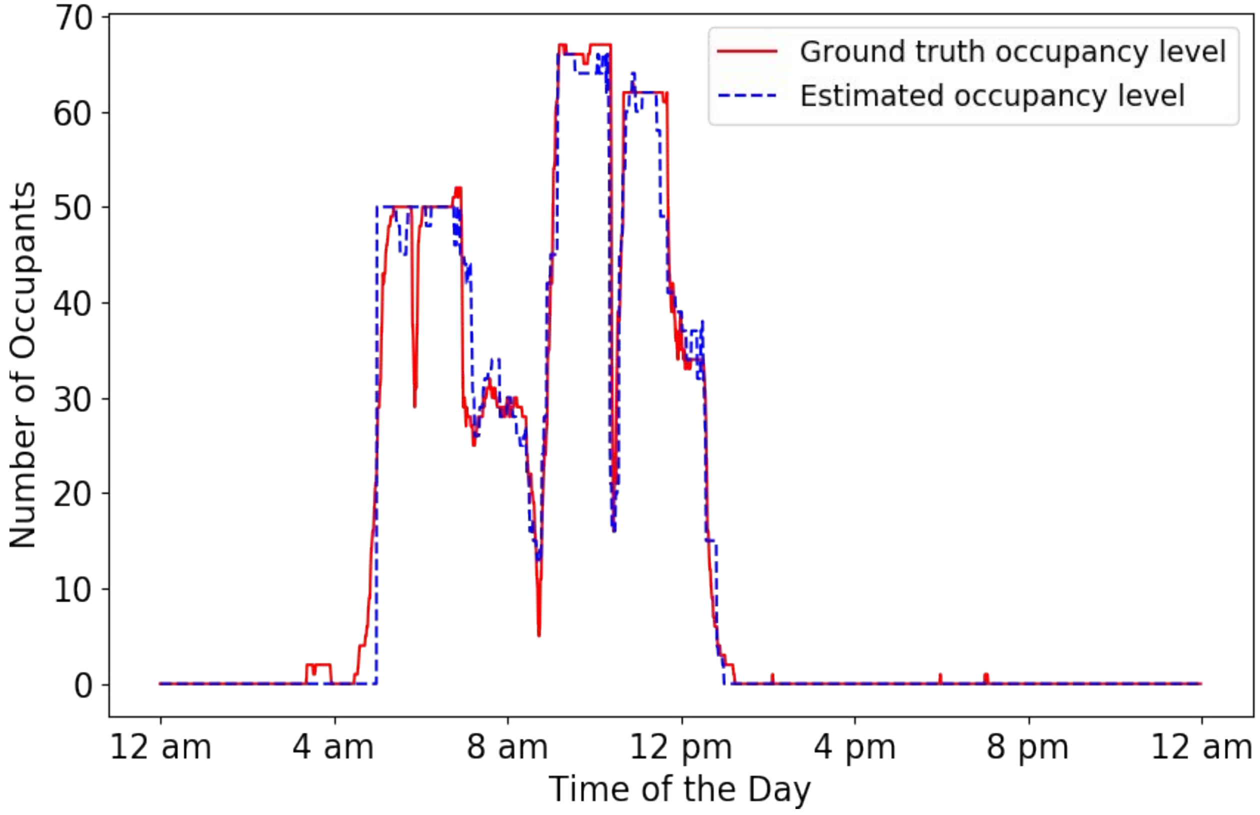

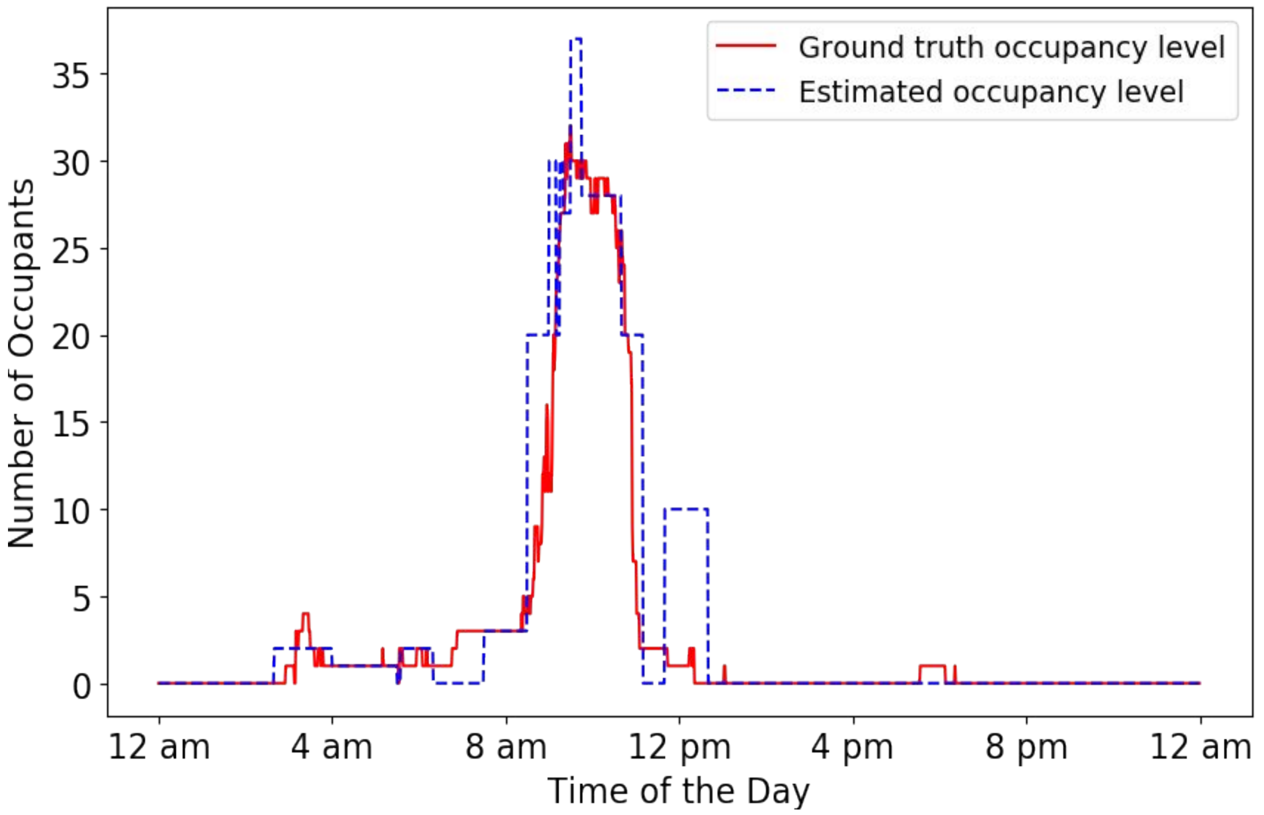

two rooms in Building A

Takeaways

- Time-series black-box model can estimate the number of occupants accurately
- Domain-adaptation techniques can be applied to occupancy estimation task to improve the performance
- Domain-adaptation can significantly reduce the amount of ground truth data required in the target domain

Directions for future work

- What if the source and target domains are in two different geographies?
- What if the feature spaces are different?
- Can we apply domain adaptation to other types of models (e.g., heat transfer models, occupant comfort models, etc.)?

Questions?