A Causal Inference Approach for Reliable Occupant-Centric Building Systems

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Background

- Occupant behaviors significantly influence energy consumption and carbon emissions from buildings.
- Understanding how and why occupants interact with building systems, **i.e., the causal structure**, is important to develop building energy solutions.

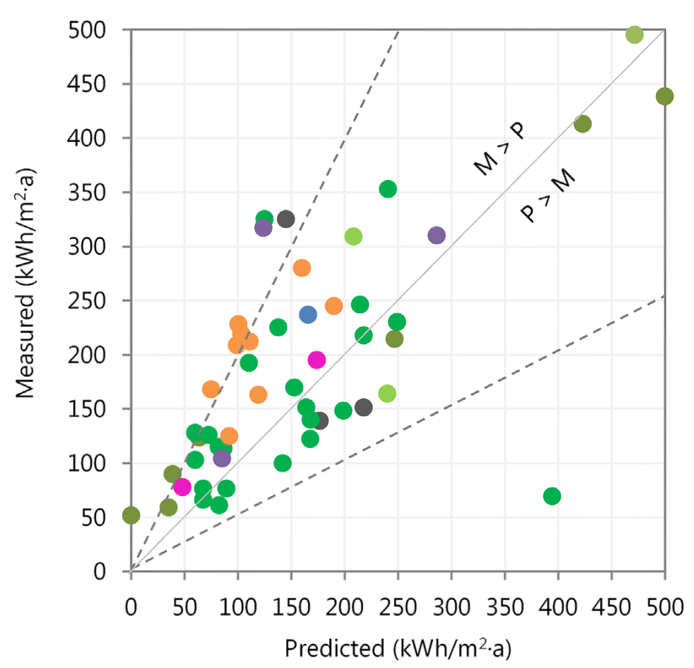

Figure 1. Energy consumption discrepancies (Van Dronkelaar et al.)

Research Goals

- Develop a causal inference methodology
- Demonstrate reliability of a causal model

Bayesian Causal Inference Method Development

Unconditional Independence Test

The first and second models represent two different hypotheses, (i) a and b are independent and (ii) a and b are dependent:

$$p(a|\beta_0, \sigma) = \mathcal{N}(a|\beta_0, \sigma^2),$$
$$p(a|b, \beta, \beta_0, \sigma) = \mathcal{N}(a|b\beta + \beta_0, \sigma^2)$$

Conditional Independence Test

The first and second models refer to the two different hypotheses, (i) a and b are independent given c, and (ii) a and b are dependent given c:

$$p(a|c, \beta_c, \beta_0, \sigma) = \mathcal{N}(a|c\beta_c + \beta_0, \sigma^2),$$
$$p(a|b, c, \beta_b, \beta_c, \beta_0, \sigma) = \mathcal{N}(a|b\beta_b + c\beta_c + \beta_0, \sigma^2).$$

Model Evidence Comparison

The weight of the second model based on the widely applicable information criterion (WAIC) refers to how much we can believe a and b are dependent.

Toy Data Development for Verification

- Indoor temperature (T) and relative humidity (R) will affect one's thermal sensation (S).
- The warmer an occupant feels, the more power (P) the occupant consumes to cool the space in summer.
- The power consumption (P) is also affected by the unseen coefficient of performance (C) of the building system.
- The relationships between variables are designed to be linear with noises following normal distributions.
- Toy datasets were developed according to the true DAG (Figure 2).

○ : unobserved variable

● : observed variable

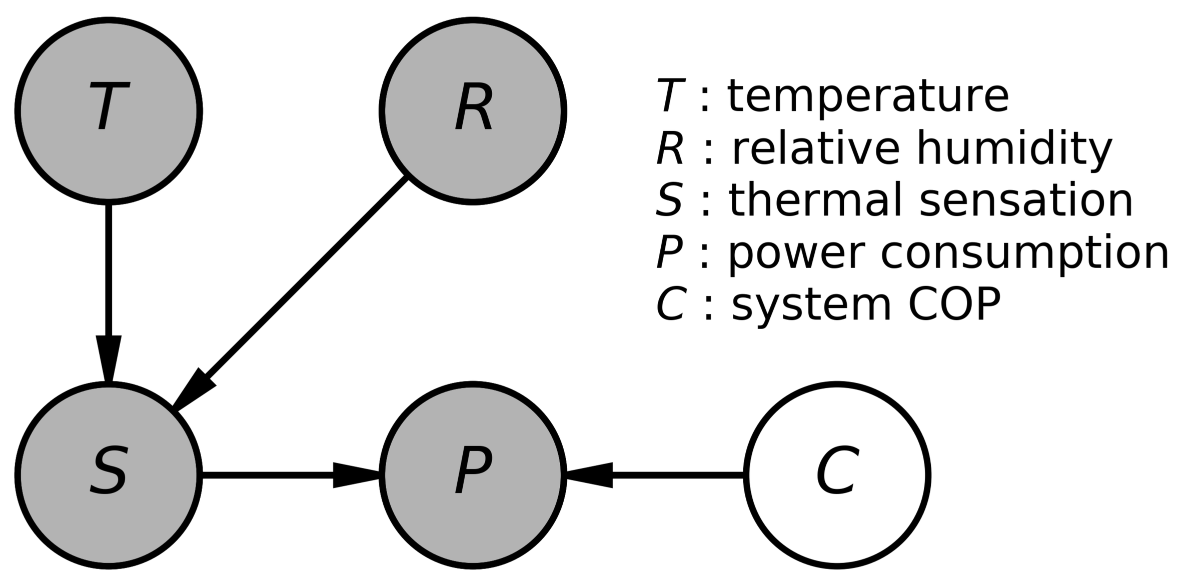

Figure 2. Ground truth causal graph.

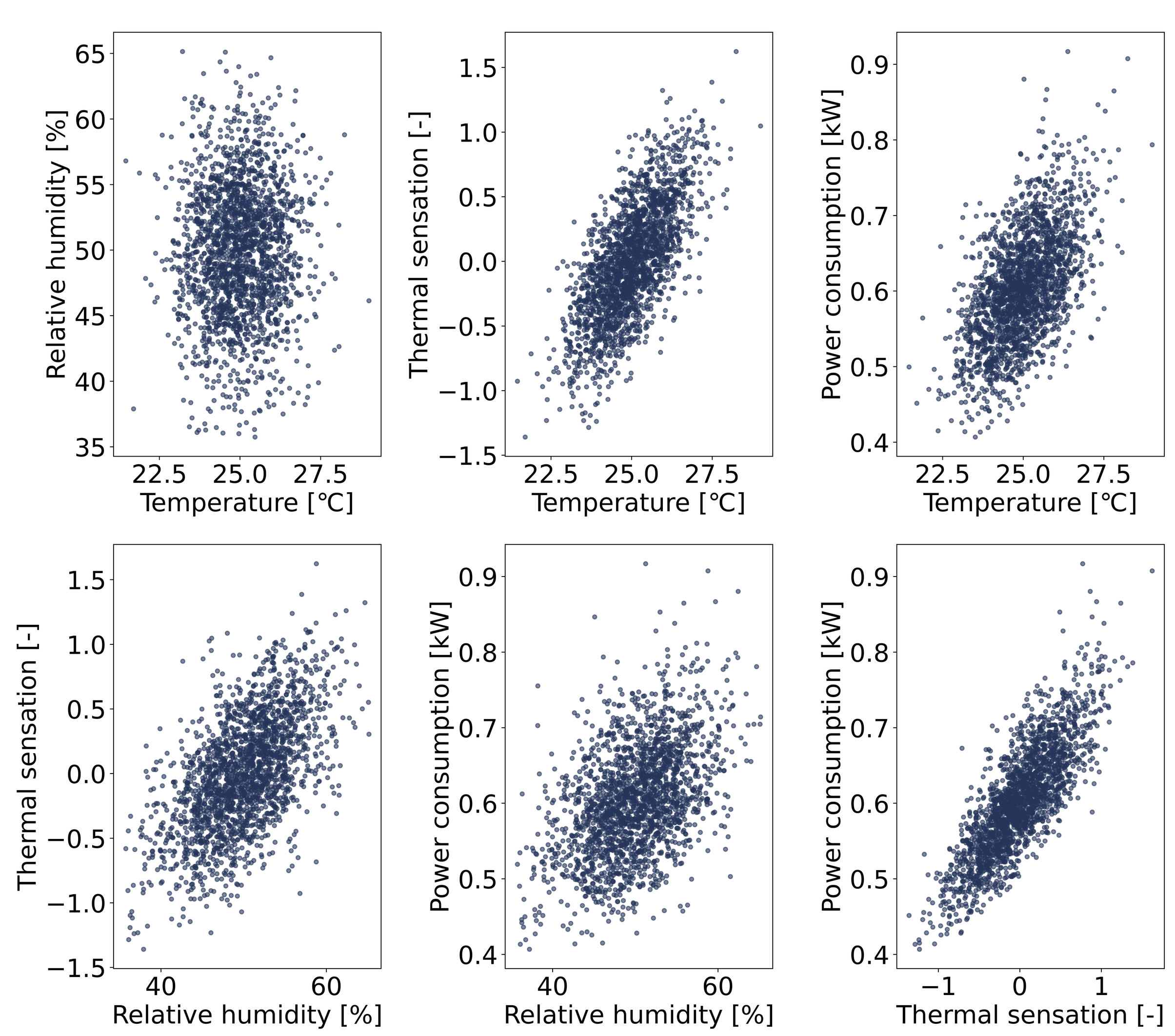

Figure 3. Relationship between variables.

Causal Discovery Results

By following the PC algorithm, the true causal graph could be inferred from the data from Figure 4 (a).

1. T and R are independent ($\omega_{T \not\perp R} < 0.5$) : remove the direct edge between T and R (Figure 4 (b))
2. (i) T and P and (ii) R and P are independent given S ($\omega_{T \not\perp P|C}, \omega_{R \not\perp P|C} < 0.5$) : remove the direct edges between (i) T and P and (ii) R and P (Figure 4 (c)).
3. T and R are dependent given S ($\omega_{T \not\perp R} < 0.5, \omega_{T \not\perp R|S} > 0.5$) : determine the edge directions from T and R to S and the edge direction from S to P (Figure 4 (d)).

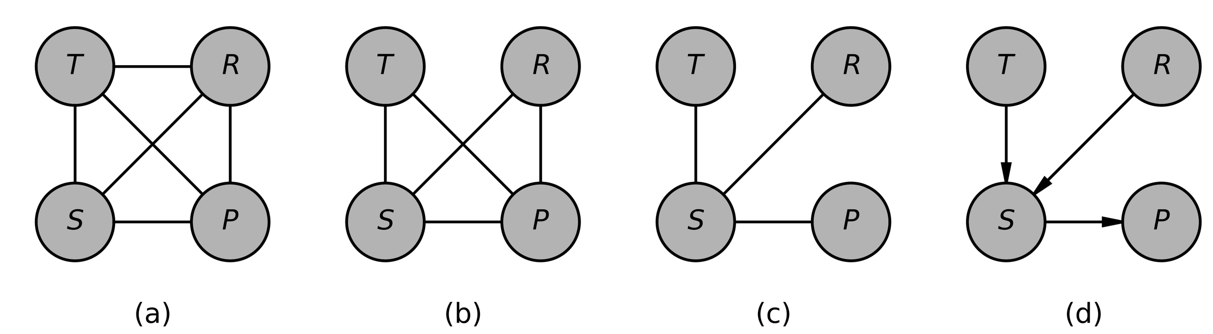

Figure 4. Causal discovery process

Model Development

Based on the inferred causal graph, two different models were developed to evaluate their reliability.

- A causal model includes causal variables, temperature and relative humidity, to predict sensation:

$$p(S|T, R, \beta_T, \beta_R, \beta_0, \sigma) = \mathcal{N}(S|T\beta_T + R\beta_R + \beta_0, \sigma^2).$$

- An association-based model includes all associated variables to predict sensation:

$$p(S|T, R, P, \beta_T, \beta_R, \beta_P, \beta_0, \sigma) = \mathcal{N}(S|T\beta_T + R\beta_R + P\beta_P, \beta_0, \sigma^2).$$

Causal Effect Estimation

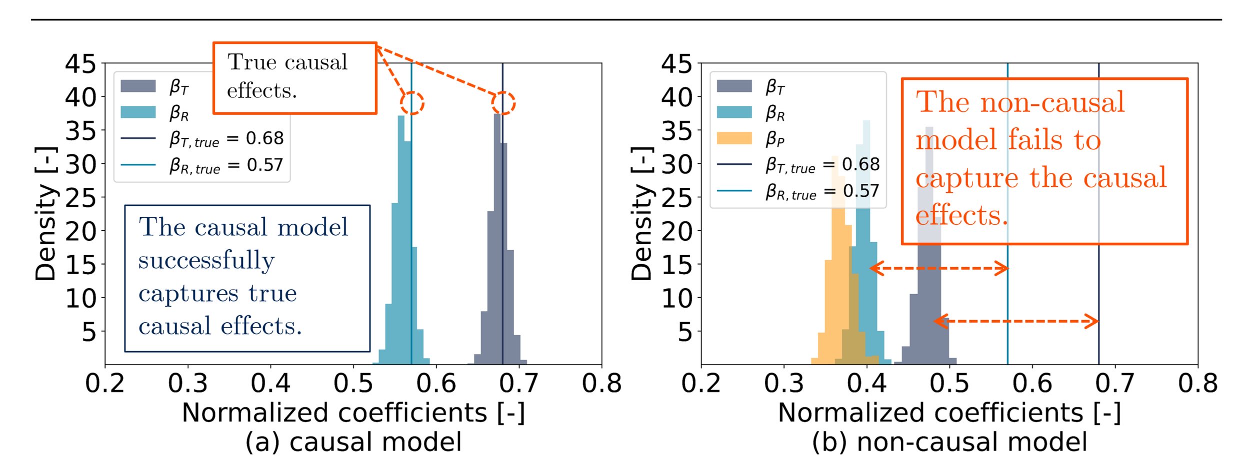

Figure 5. Parameter estimation of each predictor.

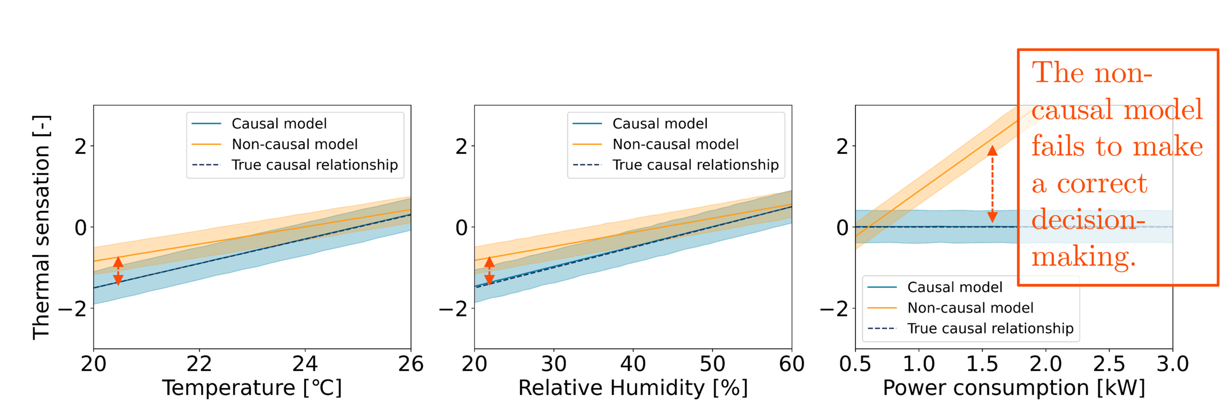

Figure 6. The expected changes in thermal sensation.

Robustness over Dataset Shift

While both models showed comparable predictions over the in-distribution data, the causal model showed more robust predictions over the Out-of-distribution data.

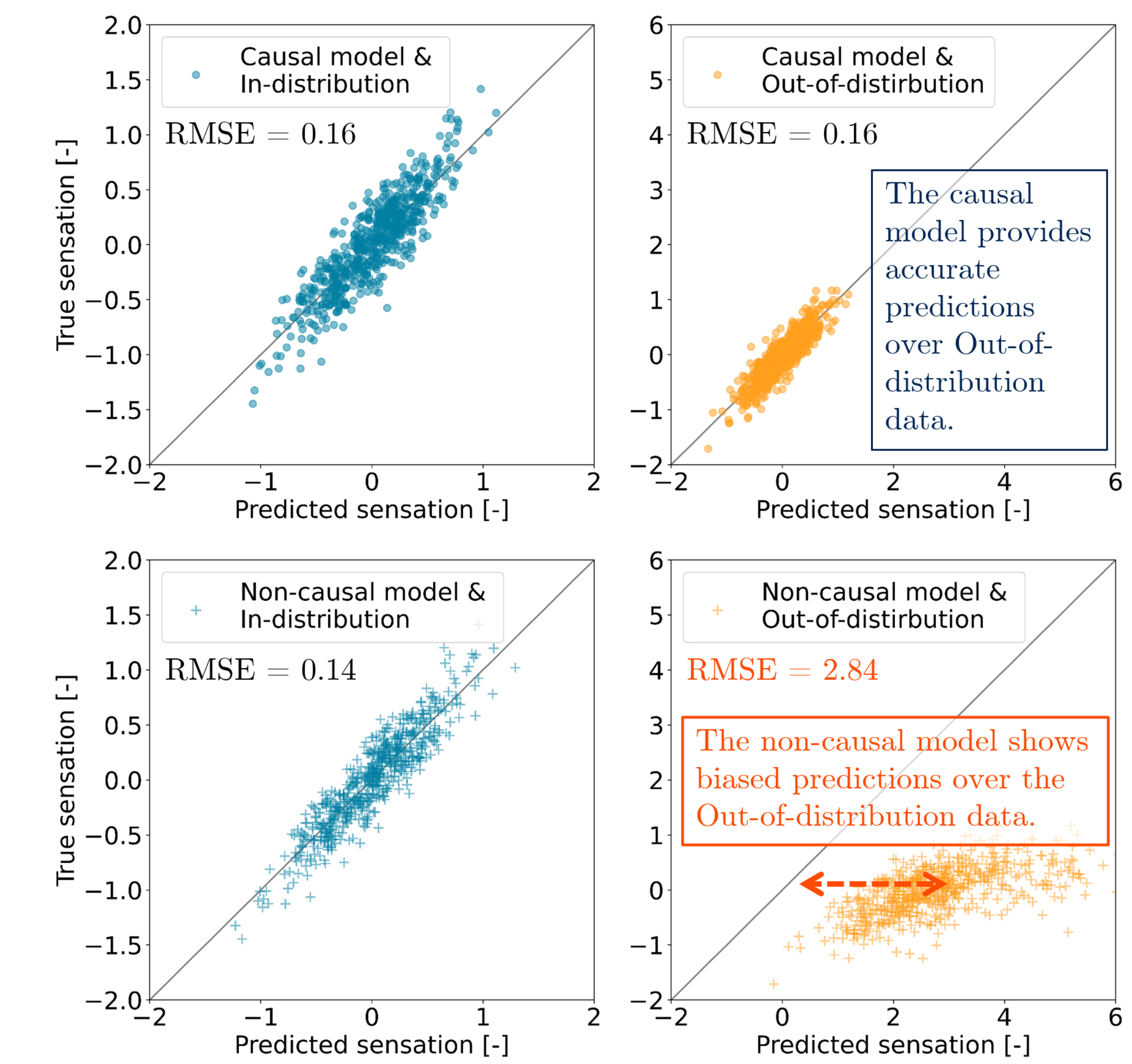

Figure 7. Prediction over test datasets.

Conclusion

This groundbreaking study introduces our innovative Bayesian causal inference method aimed at discovering potential causal structures within observational data. With a synthetic dataset inspired by a hypothetical scenario, we verified the proposed causal inference method.

The developed method and modelling approach based on the causal knowledge enable us to

- identify potential causal relationships,
- estimate causal effects properly,
- provide reliable predictions over dataset shifts.

Our work emphasizes the need for causal models in building energy solutions. We consequently expect that the proposed method will enable occupant-centric building systems to

- improve occupants' quality of life,
- help occupants' energy-aware decision-making,
- achieve carbon neutrality in buildings.

In this regard, we believe the proposed method is indispensable to realize a carbon-free society.