Co-zyBench: Using Co-Simulation and Digital Twins to Benchmark Thermal Comfort Provision in Smart Buildings

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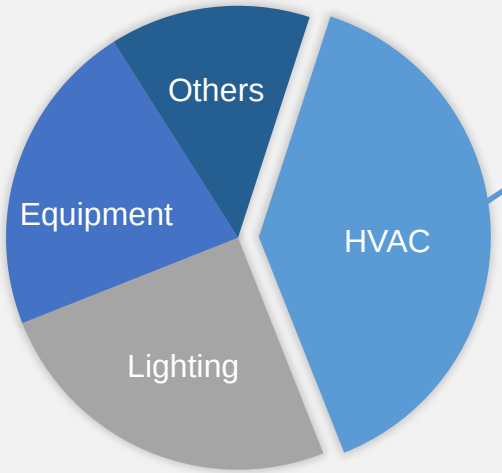
Building operations consume **30%** of global energy consumption [1]



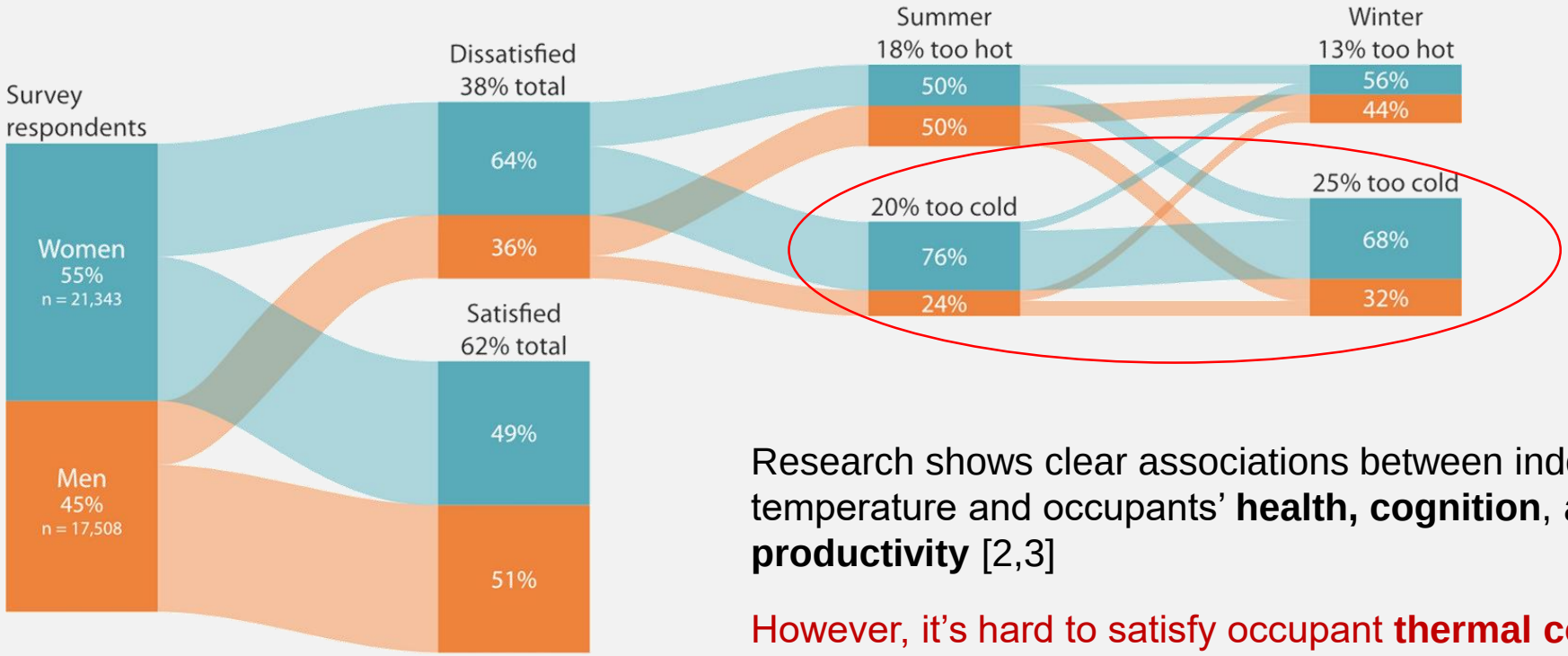
30-50%

Heating, Ventilation and Air Conditioning

[1] International Energy Agency(IEA), Buildings, 2022

Maintaining Thermal Comfort is Essential

Survey responses about office temperature [1]



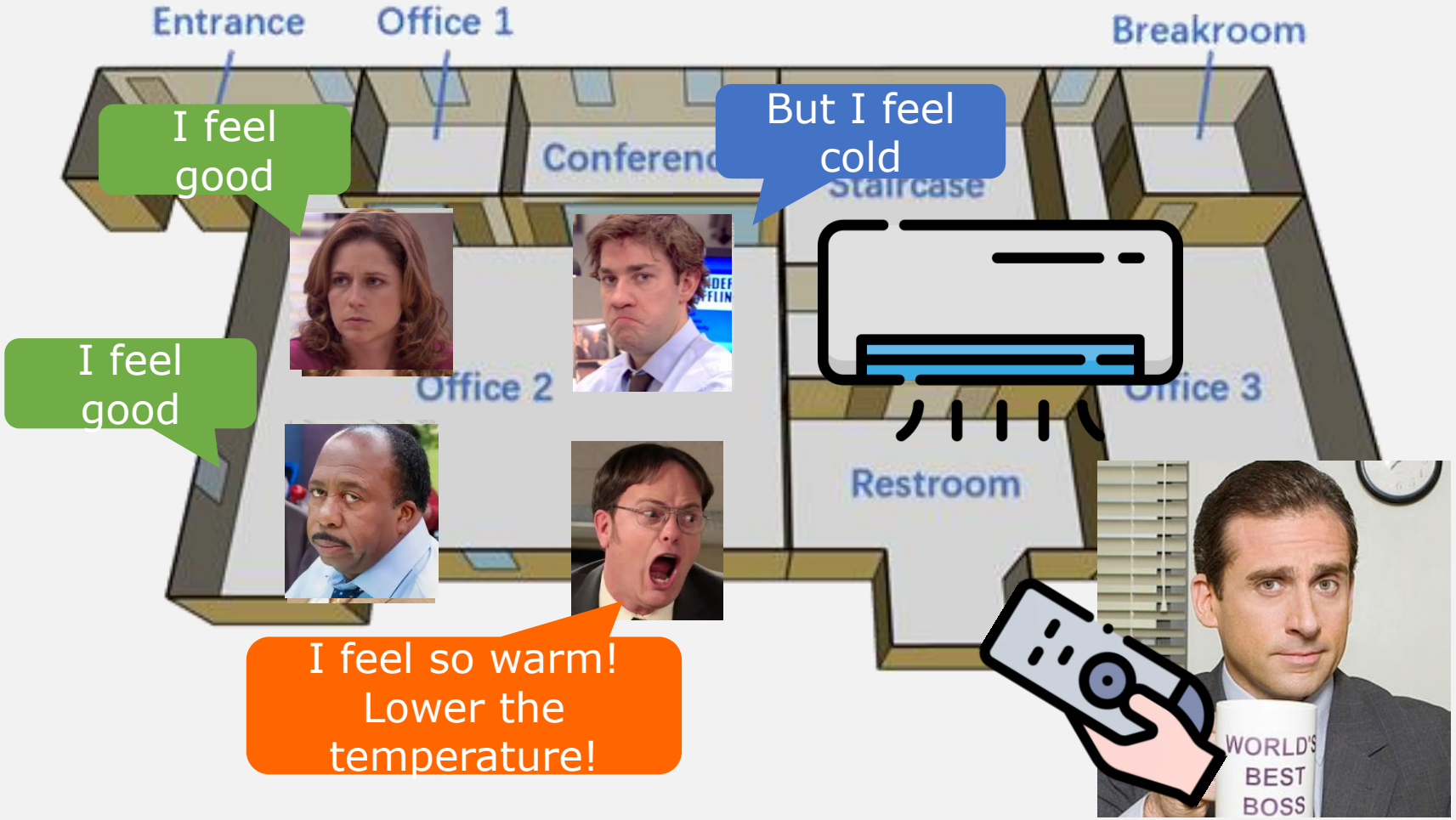
Gender vs. Thermal Comfort [4]

Research shows clear associations between indoor temperature and occupants' **health, cognition**, and **productivity** [2,3]

However, it's hard to satisfy occupant **thermal comfort** requirement

[1] Parkinson, et al., "Overcooling of offices reveals gender inequity in thermal comfort." Scientific reports, 2021.
[2] Seppanen, et al., "Effect of temperature on task performance in office environment." Lawrence Berkeley National Laboratory, 2006.
[3] Mazon, Jordi., "The influence of thermal discomfort on the attention index of teenagers: an experimental evaluation." International journal of biometeorology, 2014.
[4] Indraganti, et al., "A comparative study of gender differences in thermal comfort and environmental satisfaction in air-conditioned offices in Qatar, India, and Japan." Building and Environment, 2021.

Conventional Thermal Comfort Provisioning



Smart Thermal Comfort Provisioning

Building & Occupants real-time Information

TCPS: Thermal Comfort Provision System

1. How individuals feel?
2. How to control HVAC?

HVAC control

State-of-the-Art

Number of papers since 2020 [1]

Category	Number
HVAC and Energy	3874
Individual Thermal Comfort	1465

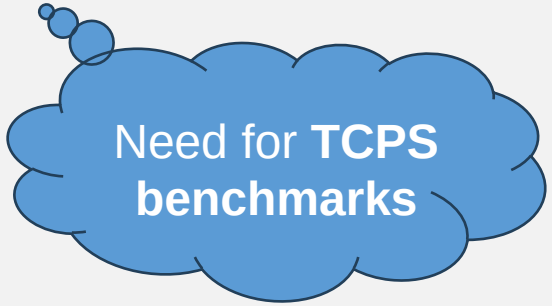
Evaluating performance in the real world [2, 3, 4]:

- Fixed scenarios and limited experiment time.
- Small number of people and countries.

Evaluating performance with simulations [5, 6]:

- Unrealistic scenarios - static occupant location.
- Lack of direct connection between building and occupants.

→ Time consuming
→ Difficult to compare between TCPSs



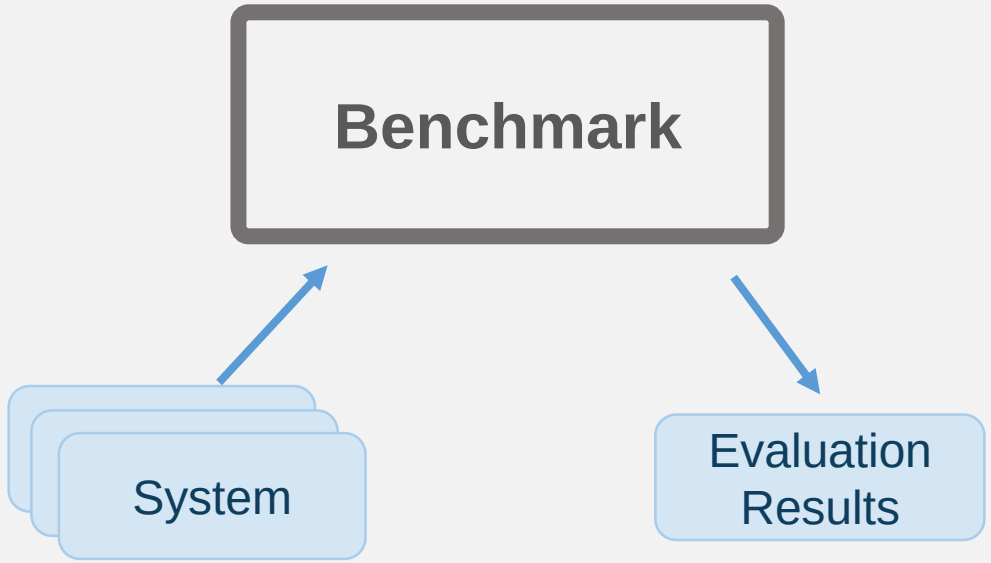
[1] Data obtained on Scopus, 07/03/2024
[2] Myeong-in Choi et al., PerCom Workshops, 2017.
[3] Almeida, et al., Energy and Buildings, 2023.
[4] Meimand, Mostafa, et al., ACM BuildSys. 2023.
[5] Deng, Zhipeng, et al., Energy and Buildings, 2020.
[6] Meimand, Mostafa, et al., Construction Research Congress, 2022.

What is a Benchmark?

→ **Standard or point of reference**

→ **Enables performance comparisons of systems**

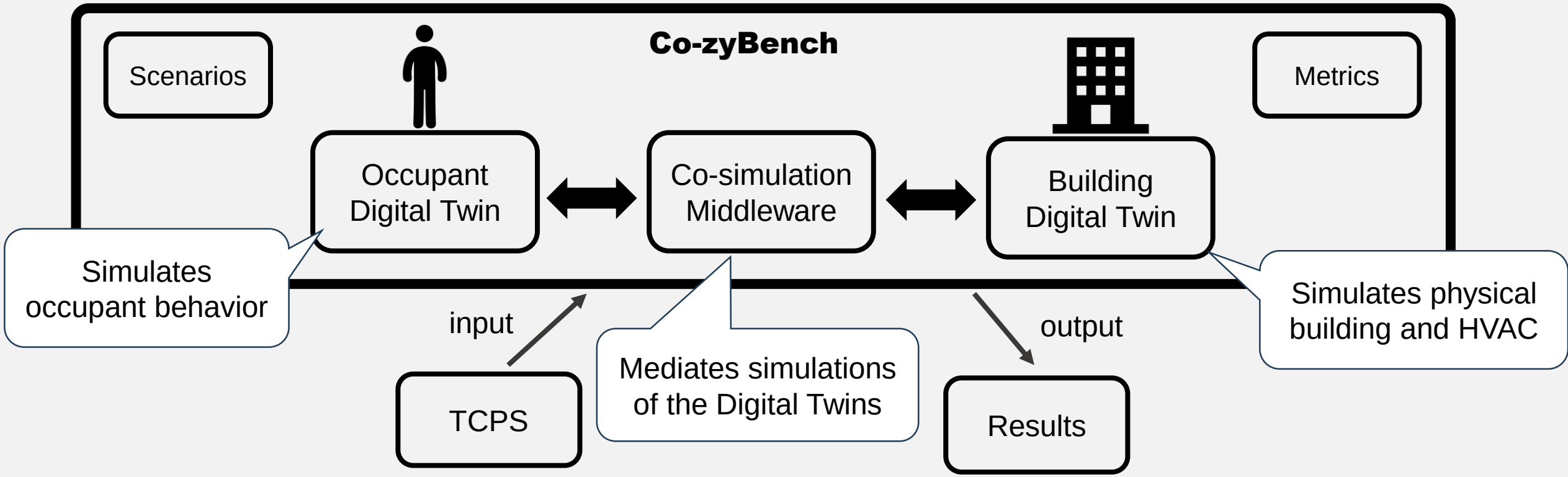
- Provides **standard evaluation environments and metrics** for fair comparison with others.
- Makes it **easy to evaluate** the strengths and weaknesses of a system.
- Encourages a continual **enhancement** and helps developers **discover innovative strategies**.
- ……



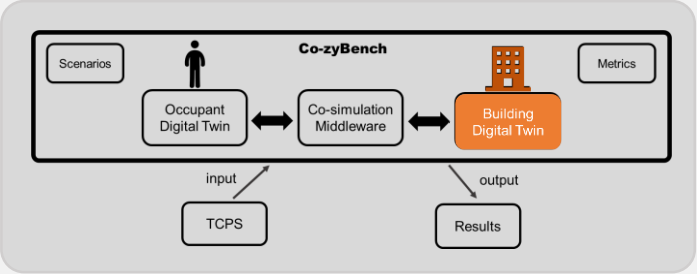
No existing benchmarks consider **both energy** and **individual thermal sensations** [1, 2]

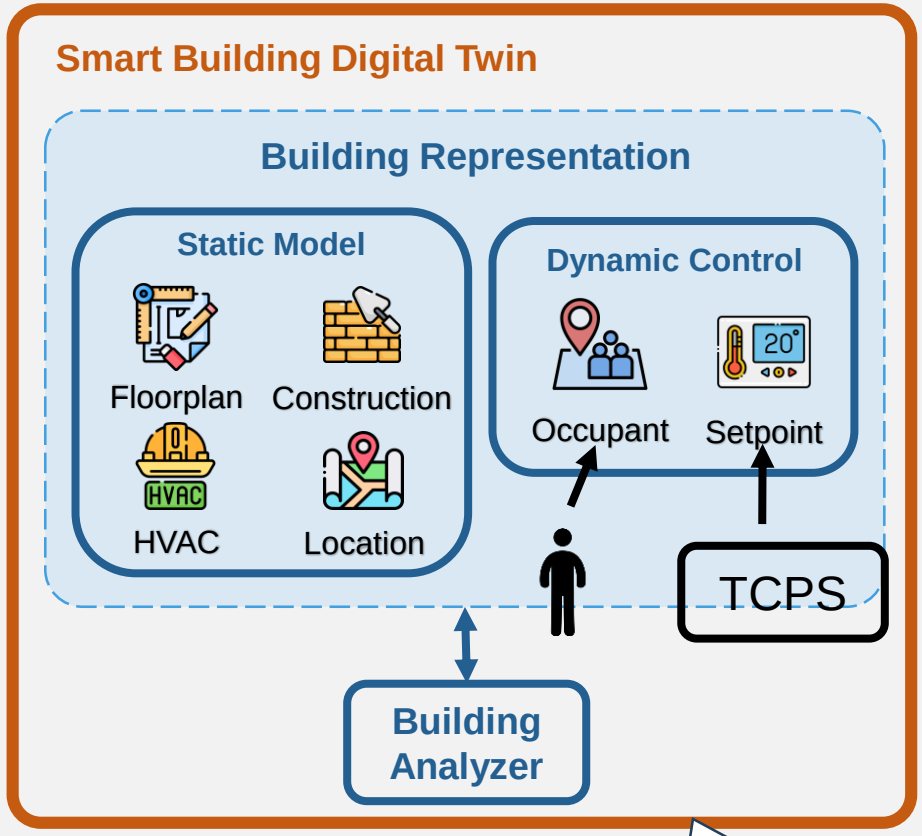
[1] Wooyoung Jung et al., Comparative assessment of HVAC control strategies using personal thermal comfort and sensitivity models, Building and Environment, 2019
[2] Xing Lu et al., Benchmarking high performance HVAC Rule-Based controls with advanced intelligent Controllers: A case study in a Multi-Zone system in Modelica, 2023

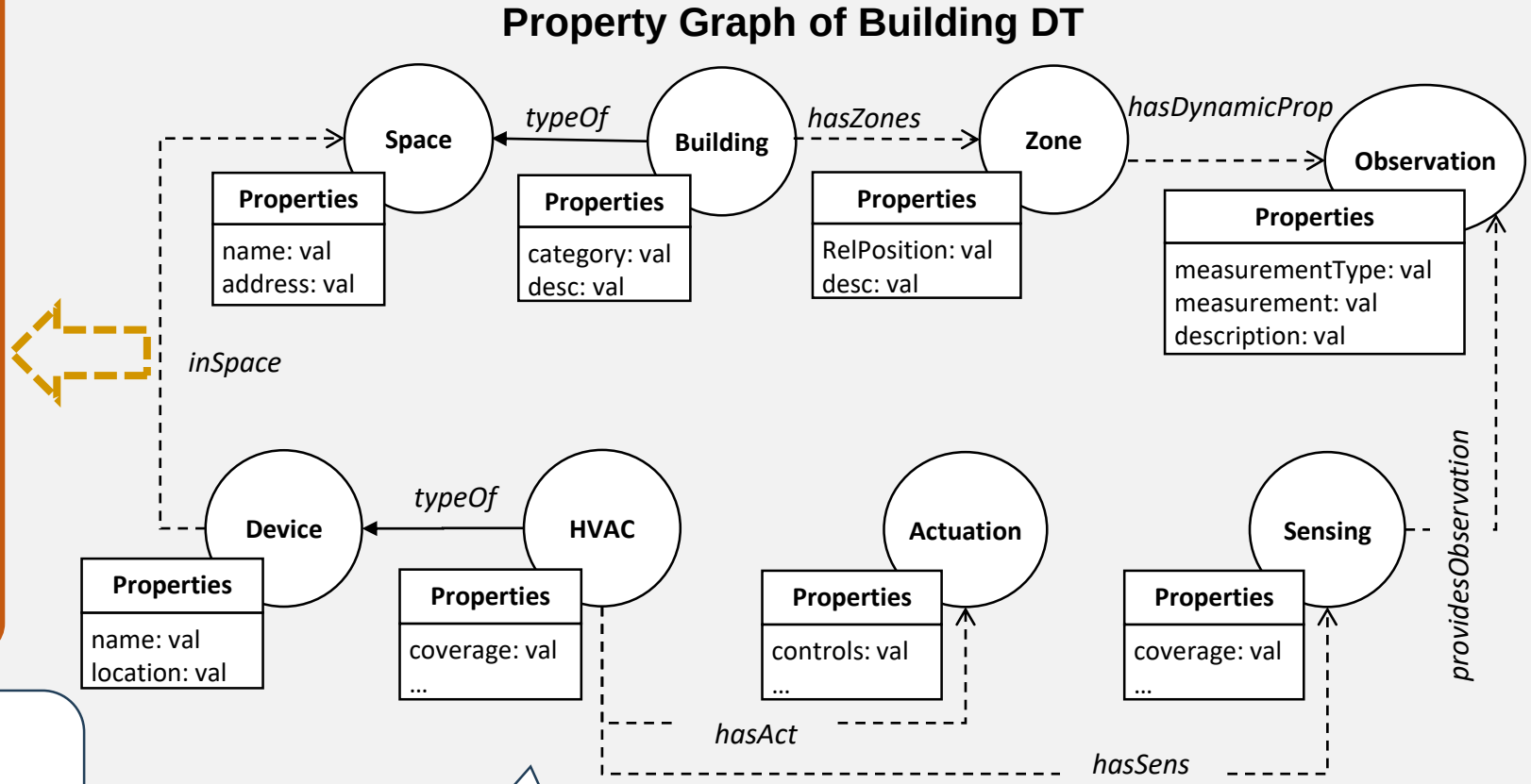
Co-zyBench: A Benchmark Using Co-Simulation and Digital Twins for Thermal Comfort Provision Systems



Smart Building Digital Twin





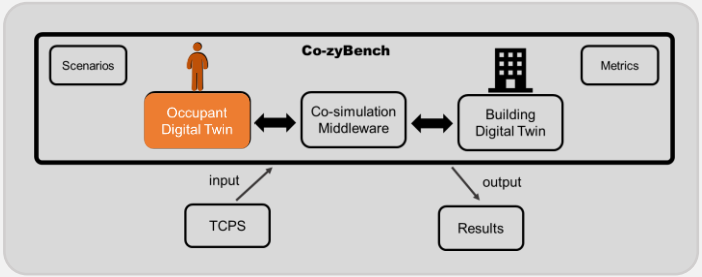


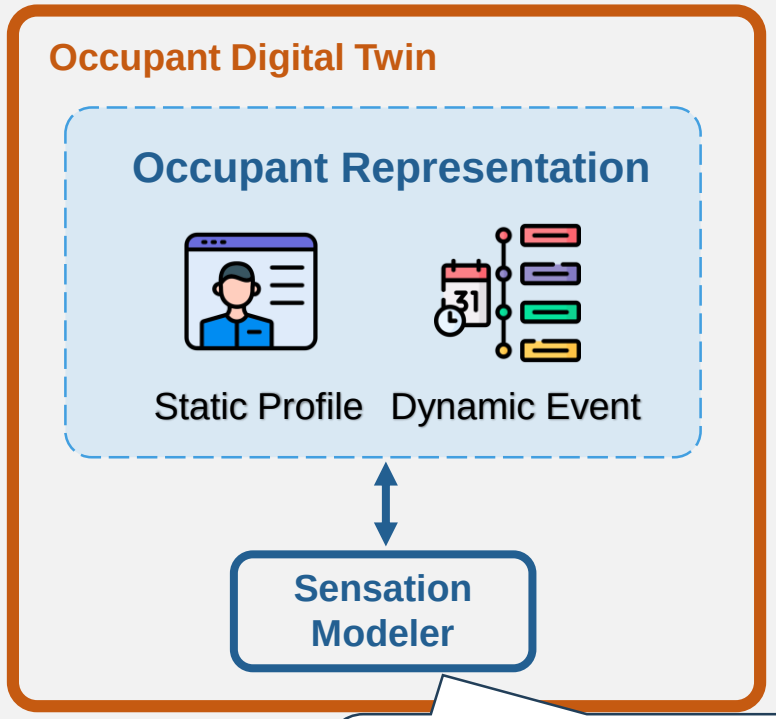
EnergyPlus [1]

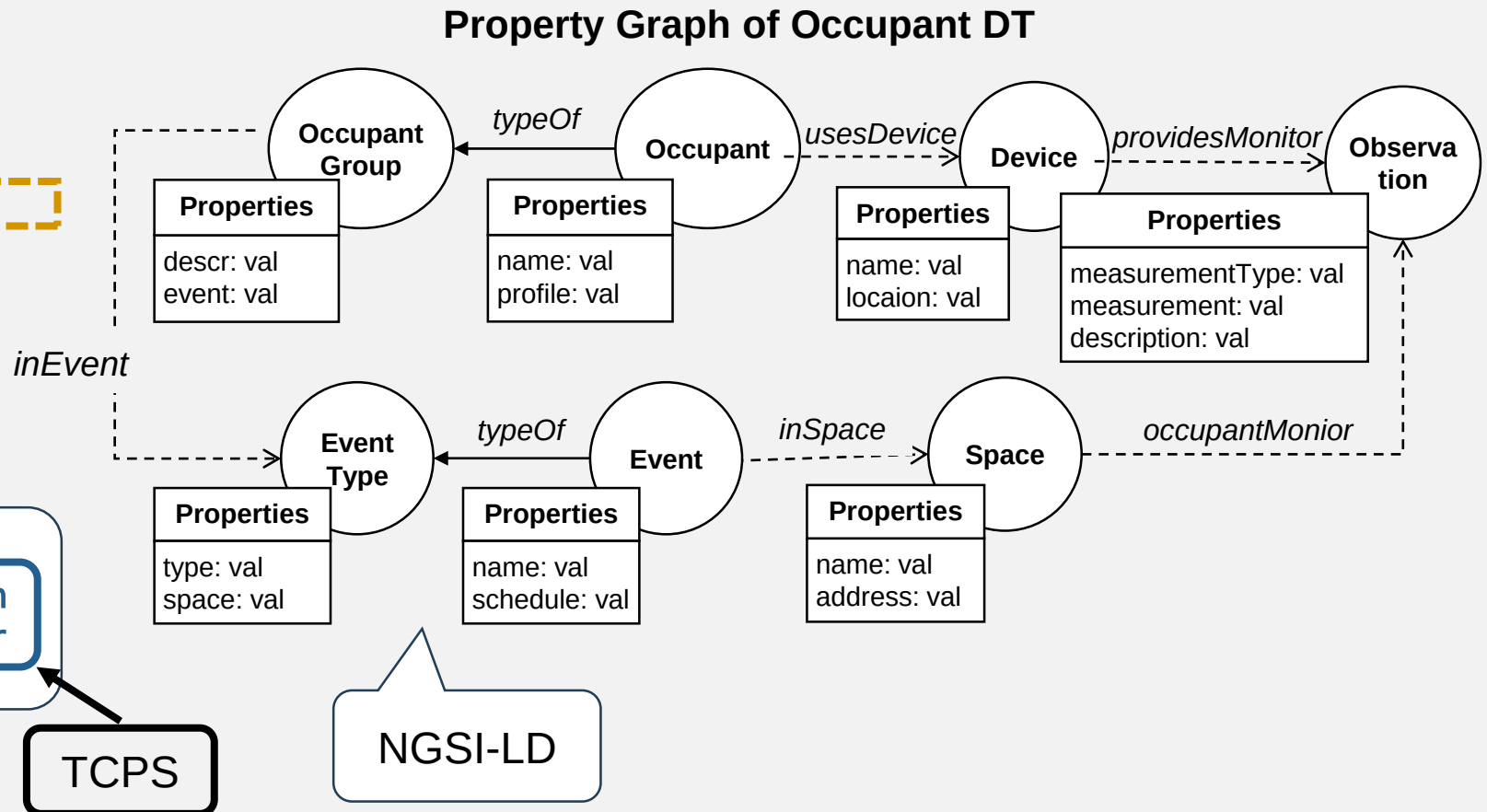
NGSI-LD [2]

[1] https://energyplus.net/
[2] https://ngsi-ld-tutorials.readthedocs.io/

Occupant Digital Twin

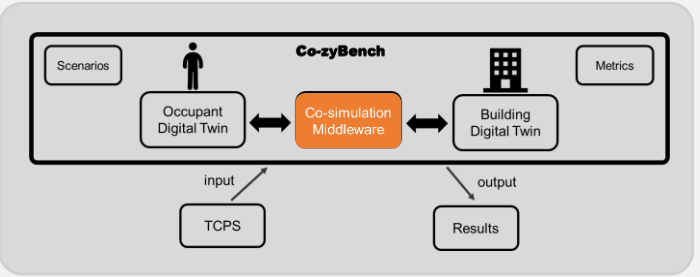




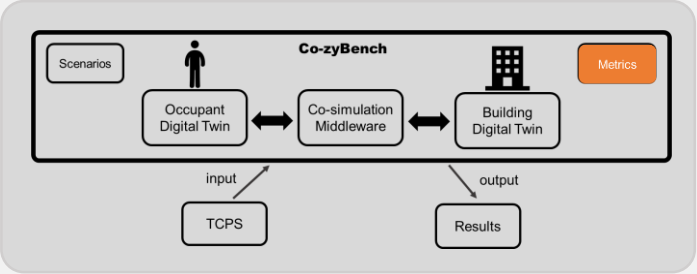


[1] Chio, Andrew, et al. SmartSPEC: Customizable Smart Space Datasets via Event-driven Simulations, IEEE PerCom, 2022.

Co-Simulation Middleware



Evaluation Metrics



- **Energy Consumption (EC)**

  KW/h consumed by the HVAC.

- **Individual Thermal Comfort (ITC)**

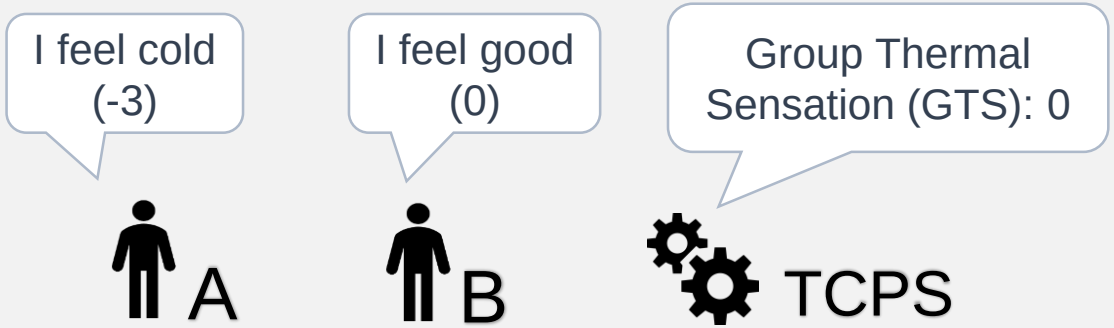
  How uncomfortable people feel?

  Individual discomfort:

  $\mathbf{D}[i] = \boldsymbol{TS}[i] - \boldsymbol{GTS}[i]$

  Discomfort for the population:

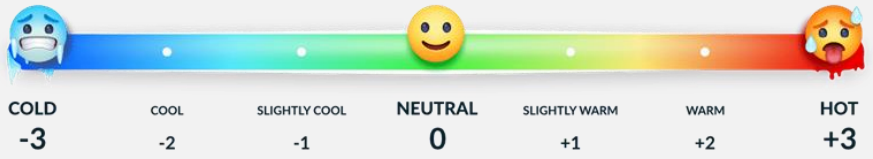
$$\boldsymbol{ITC} = \frac{\sum_{i=0}^{n} |\, \boldsymbol{Loss}[i] \,|}{\boldsymbol{n}}$$



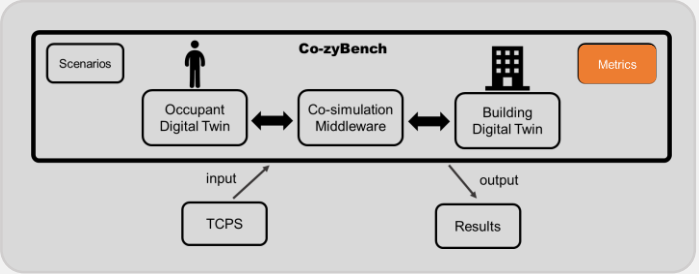
D[A] = -3 D[B] = 0

ITC = (3 + 0) / 2 = 1.5

Comfort level averagely deviates 1.5 from comfortable



Evaluation Metrics



- **Energy Consumption (EC)**

  KW/h consumed by the HVAC.

- **Individual Thermal Comfort (ITC)**

  How uncomfortable people feel?

- **Thermal Comfort Equality (TCE)**

  How unfairly people are treated?

  Based on discomfort:

$$D[i] = TS[i] - GTS[i]$$

  "***Extra" Discomfort [1]:***

$$ED[i] = D[i] - avg(D)$$

D[A] = -3 D[B] = 0

avg(D) = -1.5

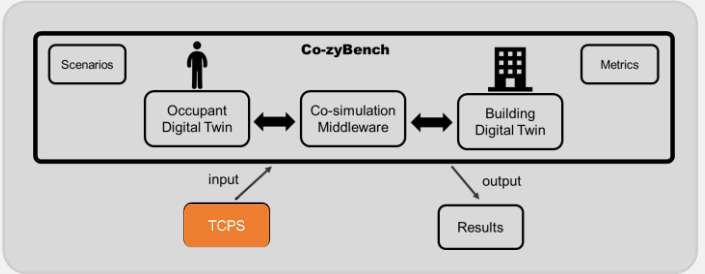
ED[A] = -3 – (-1.5) = -1.5

ED[B] = 0 – (-1.5) = 1.5

The bigger the gap between EDs, the more unfair the system is

[1] Fagin, Ronald, and John H. Williams. "A fair carpool scheduling algorithm." IBM Journal of Research and development, 1983

Thermal Comfort Provision System (TCPS)



Occupant Profile
Individual location, Temperature
……

TCPS

Sensation Collector → **Sensation Aggregator** → **HVAC Controller**

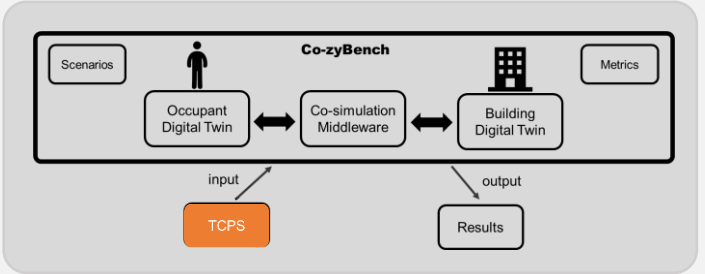
HVAC Control Action

Estimate how individuals feel

Aggregate the groups' sensations
(e.g., majority voting)

Generate HVAC control actions

A Template for the TCPS



Occupant Profile
Individual location,
Temperature
……

TCPS

Sensation Collector → **Sensation Aggregator** → **HVAC Controller**

HVAC Control Action

Occupant Info

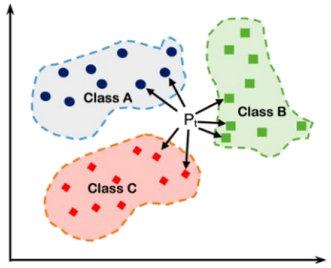
Name	Gender	Age	Height	Weight
Michael	male	51	175	2
Erin	female	33	165	2
Jim	male	33	191	1
Dwight	male	47	189	2
Pam	female	39	168	1

Indoor Temperature

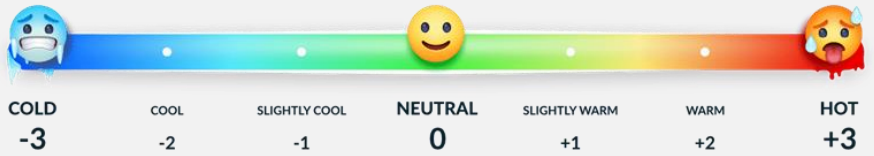
age	gender	ht	wt	temp	tc
21	male	1.77	77	25.1	0
19	male	1.75	70	27.3	0
19	male	1.71	63	25.8	- 1
39	female	1.56	62	23.4	- 2
55	female	1.68	53	23.6	0

Historical Sensation Data

Classifier

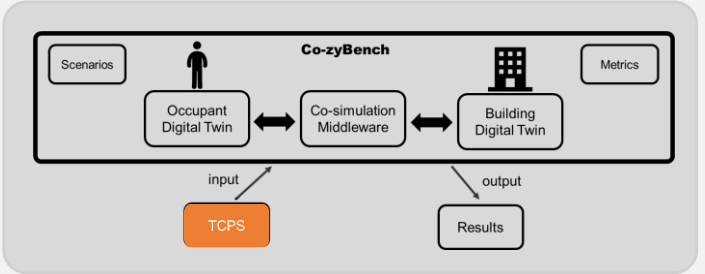


Individual Thermal Sensation on 7-scale



[1] https://github.com/CenterForTheBuiltEnvironment/ashrae-db-II

A Template for the TCPS



Occupant Profile
Individual location,
Temperature
Energy consumed
……

TCPS

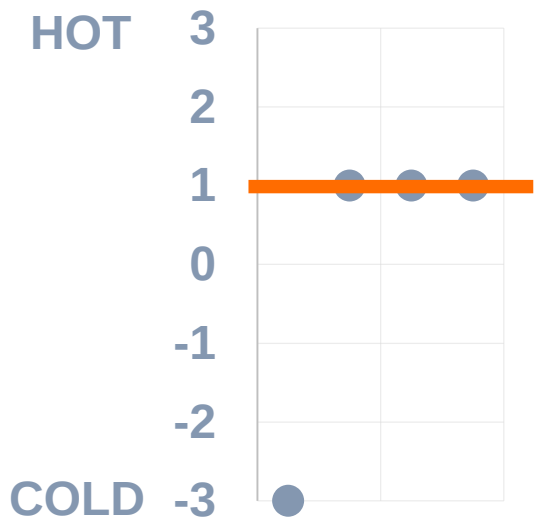
Sensation Collector → **Sensation Aggregator** → **HVAC Controller**

HVAC Control Action

Majority Rule [1]

→ Optimizes ITC

Individual Thermal Sensation on 7-scale



[1] Jung、Wooyoung, et al., Building and Environment, 2019
[2] Purdon, Sean, et al., IEEE LCN Workshops, 2013.
[3] Shin, Eun-Jeong, et al., ACM BuildSys, 2017.

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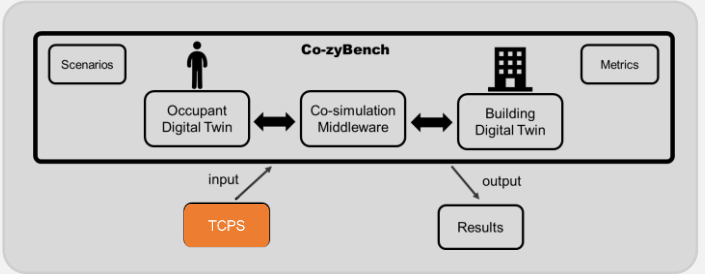

Occupant Profile
Individual location,
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……

TCPS

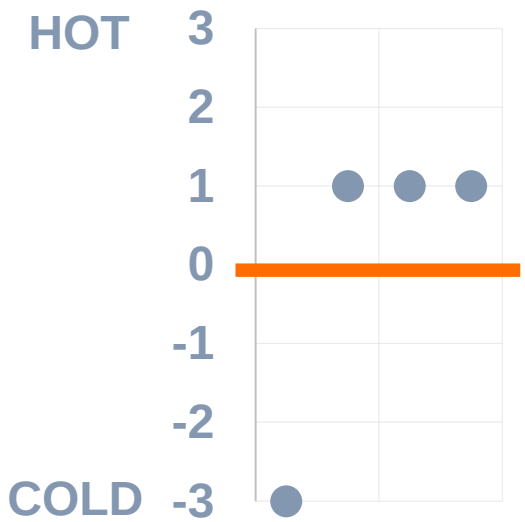
Sensation Collector → **Sensation Aggregator** → **HVAC Controller**

HVAC Control Action

Individual Thermal Sensation on 7-scale

Majority Rule [1]
→ Optimizes ITC

Drift Approach [2]
→ Optimizes EC



Temperature will be increased in summer

[1] Jung、Wooyoung, et al., Building and Environment, 2019
[2] Purdon, Sean, et al., IEEE LCN Workshops, 2013.
[3] Shin, Eun-Jeong, et al., ACM BuildSys, 2017.

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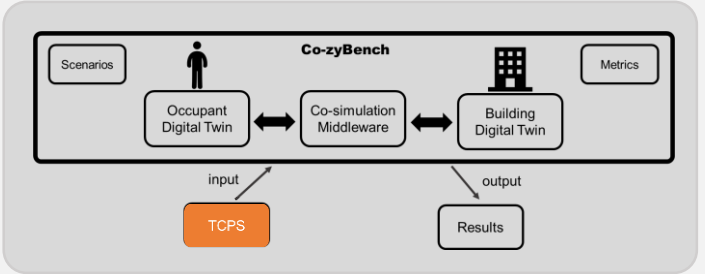

Occupant Profile
Individual location,
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TCPS

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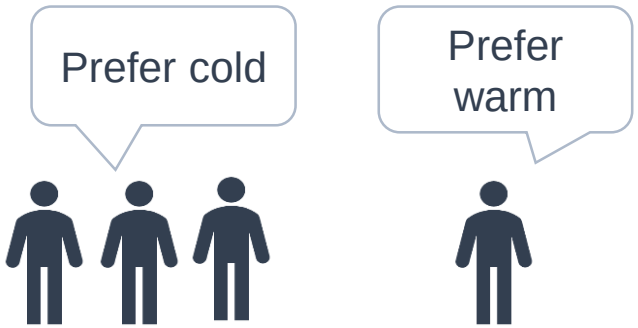
HVAC Control Action

Individual Thermal Sensation on 7-scale

Majority Rule [1]
→ Optimizes ITC

Drift Approach [2]
→ Optimizes EC

Fairness Approach [3]
→ Optimizes TCE



Tries to let everyone experience same level of comfort

[1] Jung、Wooyoung, et al., Building and Environment, 2019
[2] Purdon, Sean, et al., IEEE LCN Workshops, 2013.
[3] Shin, Eun-Jeong, et al., ACM BuildSys, 2017.

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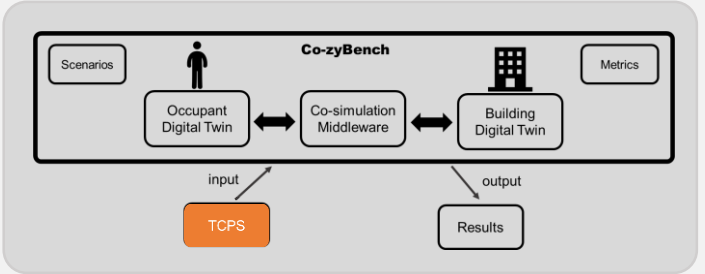

Occupant Profile
Individual location,
Temperature
Energy consumed
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TCPS

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HVAC Control Action

Individual Thermal Sensation on 7-scale

Majority Rule [1]
→ Optimizes ITC

Drift Approach [2]
→ Optimizes EC

Fairness Approach [3]
→ Optimizes TCE

Group Thermal Comfort

[1] Jung、Wooyoung, et al., Building and Environment, 2019
[2] Purdon, Sean, et al., IEEE LCN Workshops, 2013.
[3] Shin, Eun-Jeong, et al., ACM BuildSys, 2017.

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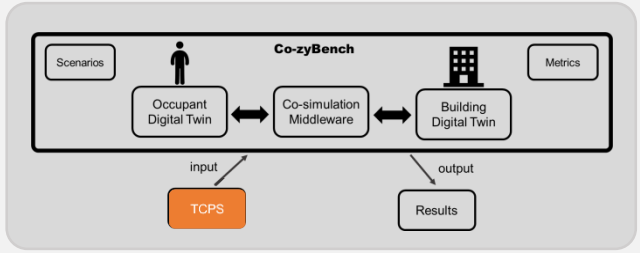


Occupant Profile
Individual location,
Temperature
Energy consumed
……

TCPS

Sensation Collector → **Sensation Aggregator** → **HVAC Controller**

HVAC Control Action

Group Thermal Comfort

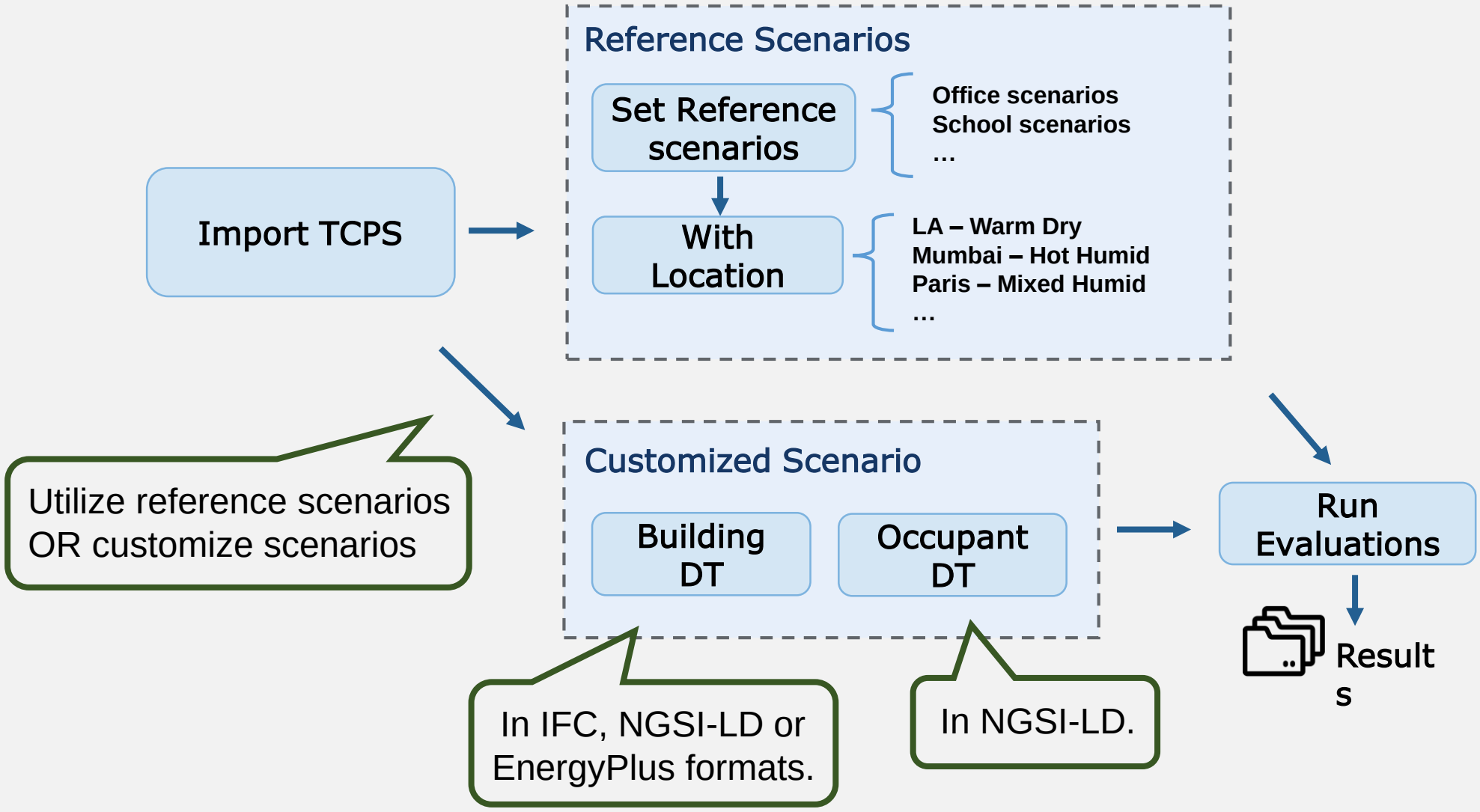
Change temperature by 1 degree per 30 mins[1]

+3	Hot	**- 1.5 °C**
+2	Warm	**- 1.0 °C**
+1	Slightly Warm	**- 0.5 °C**
0	Neutral (Comfort)	**/**
-1	Slightly Cool	**+ 0.5 °C**
-2	Cool	**+ 1.0 °C**
-3	Cold	**+ 1.5 °C**

New temperature setpoint

[1] Purdon, Sean, et al., IEEE LCN Workshops, 2013.

How to Use Co-zyBench?



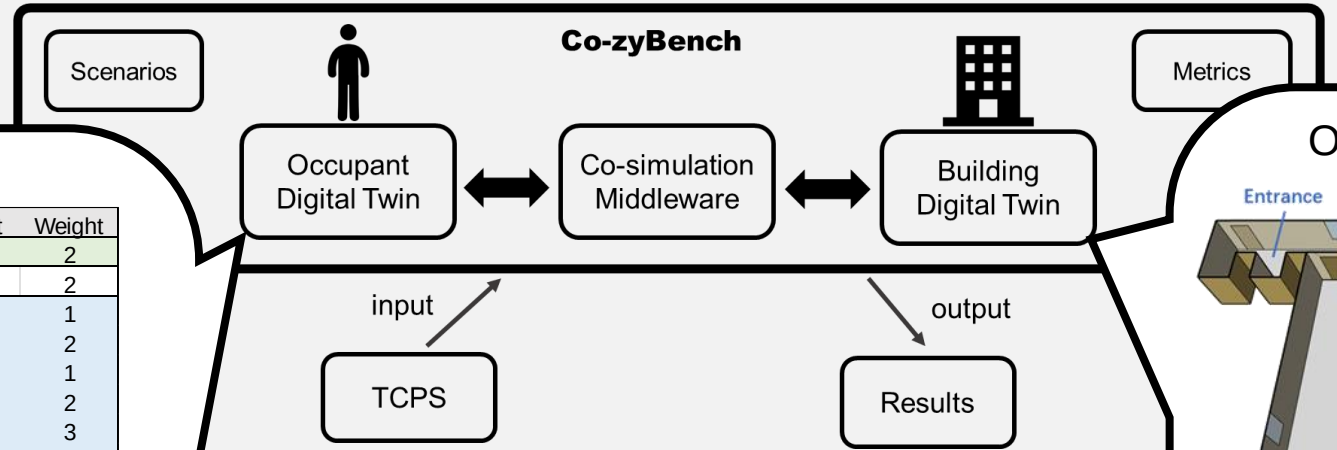
Using Co-zyBench

→ Analysis 1: What's the Influence of **Inaccurate Thermal Sensation Estimation?**

→ Analysis 2: What's the impact of Aggregation Strategies on **Equality?**

→ Analysis 3: How does the Climate Zone affect **Energy Consumption?**

Building and Occupant Scenario



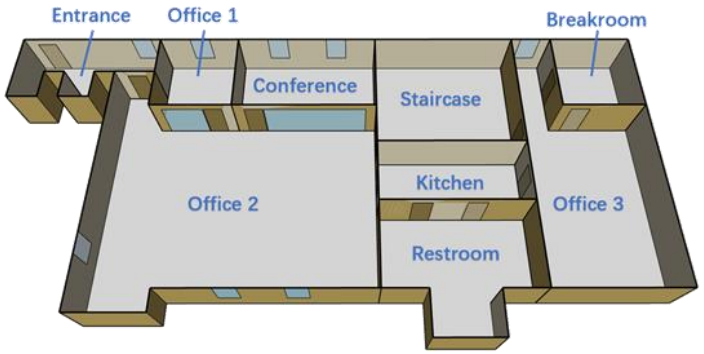
Occupant Profile

Name	Gender	Job	Age	Height	Weight
Michael	male	Boss	51	175	2
Erin	female	Receptionist	33	165	2
Jim	male	Seller	33	191	1
Dwight	male	Seller	47	189	2
Pam	female	Seller	39	168	1
Andy	male	Seller	39	182	2
Stanley	male	Seller	55	180	3
Phyllis	female	Seller	64	166	2
Oscar	male	Accountant	54	175	1
Kevin	male	Accountant	40	185	3
Angela	female	Accountant	42	155	2

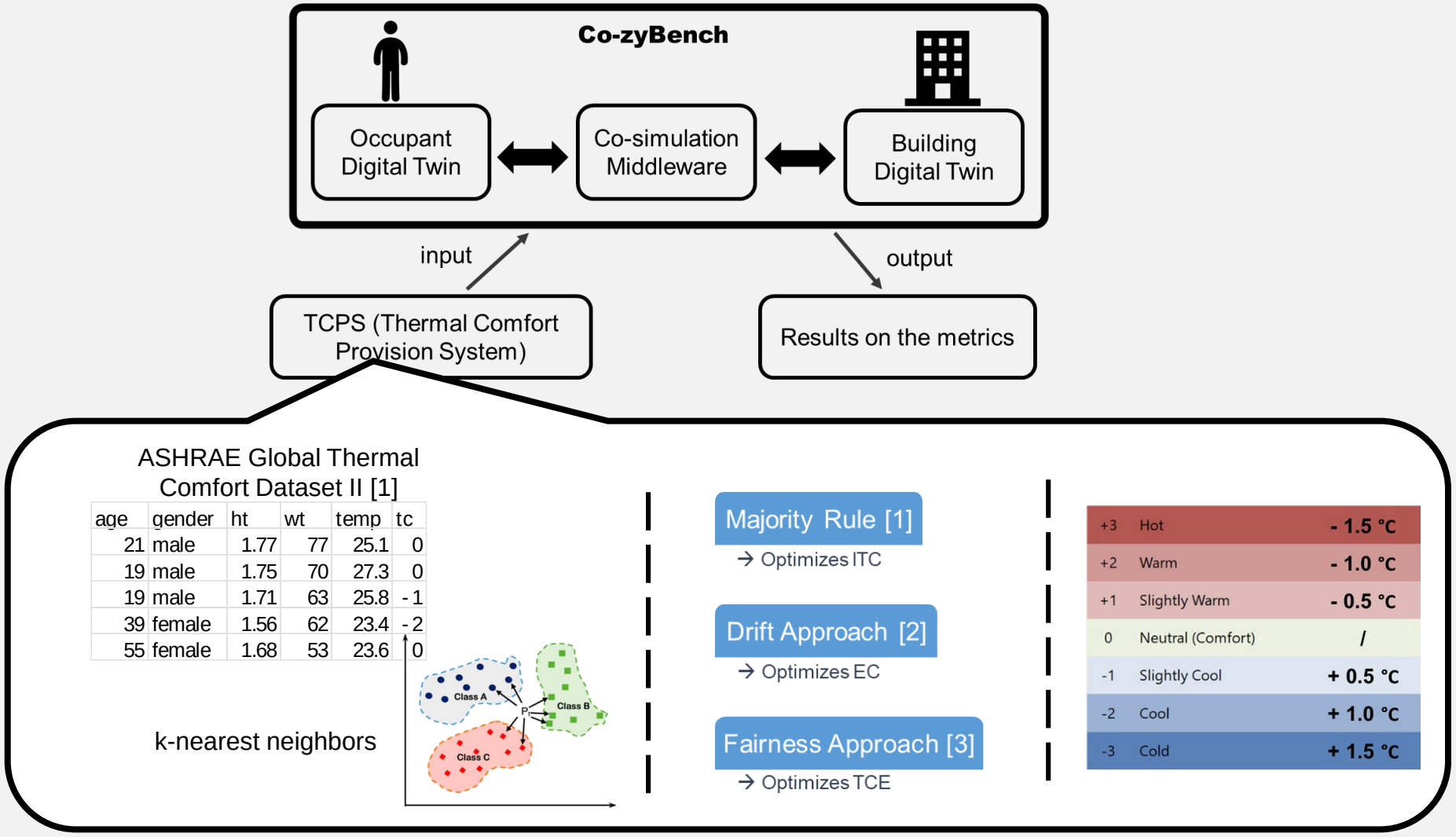
TIME	Monday	Tuesday	Wednesday	Thursday	Friday
9:00	Boss, Sellers				
9:30			Boss, Accountants, Supplier Manager		
10:00		Sellers		Sellers	
10:30	Sellers, Marketing, Sales Representative				Sellers, Marketing, Sales Representative,
11:00					
11:30					
12:00 – 14:00	Lunch Time				
14:00					All
14:30	Accounts		Sellers, Marketing, Sales Representative,		
15:00					
15:30					

Activity Schedule

Office Building Floorplan



Thermal Comfort Provision Systems

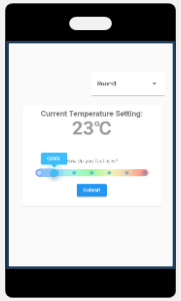


[1] https://github.com/CenterForTheBuiltEnvironment/ashrae-db-II

Analysis 1: Inaccuracy vs. ITC

Scenario 1 (S1)

Problem: Some people do not participate



Occupants actively provide their sensation

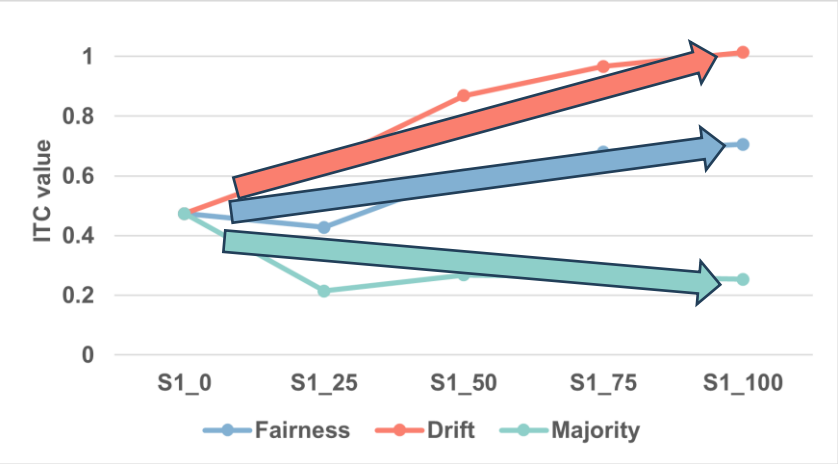
Scenario 2 (S2)

Problem: Sensors sometimes fail

Sensors monitor sensation

Analysis 1: Results

S1: ITC vs. X% of people participating



S2: ITC vs. X% of correct sensor data

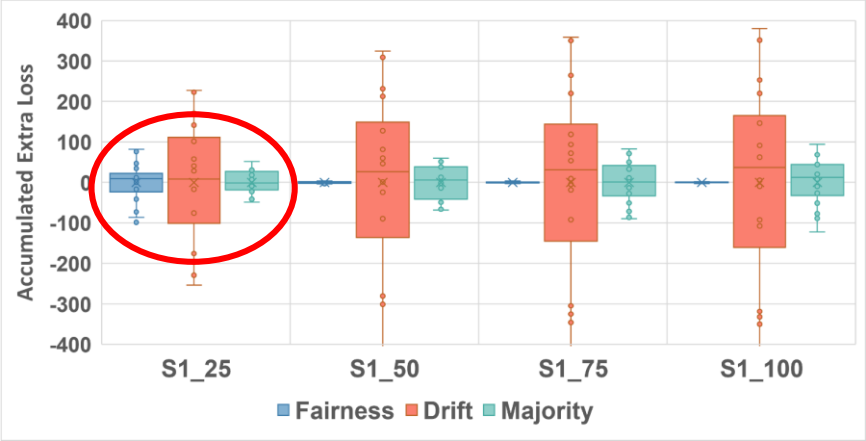
Observations:

- Majority > Fairness > Drift
- S1 generally outperforms S2 at the same percentage level.
- Majority performs better with more accurate info
- Fairness and Drift perform worse with more accurate info

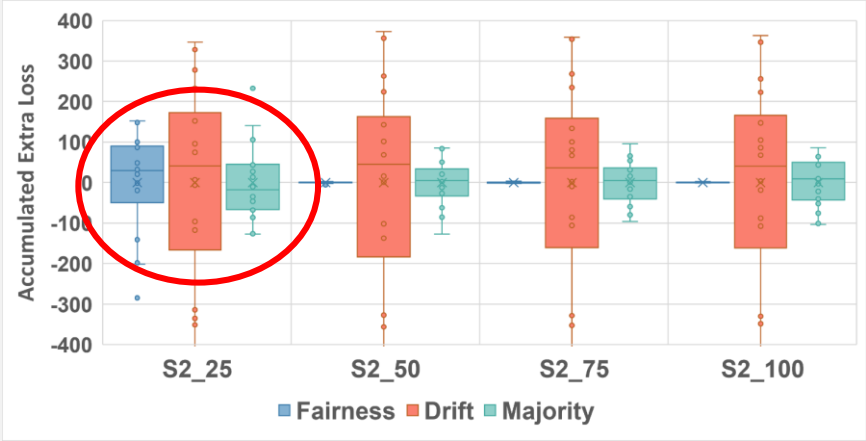
Take Aways:

- For systems that take ITC into account, accuracy is necessary
- When accuracy cannot be ensured, letting people actively provide sensation (S1) results in better performance

Analysis 2: TCE vs. Aggregation Strategies



S1: TCE vs. X% of people participating



S2: TCE vs. X% of correct sensor data

Observations:

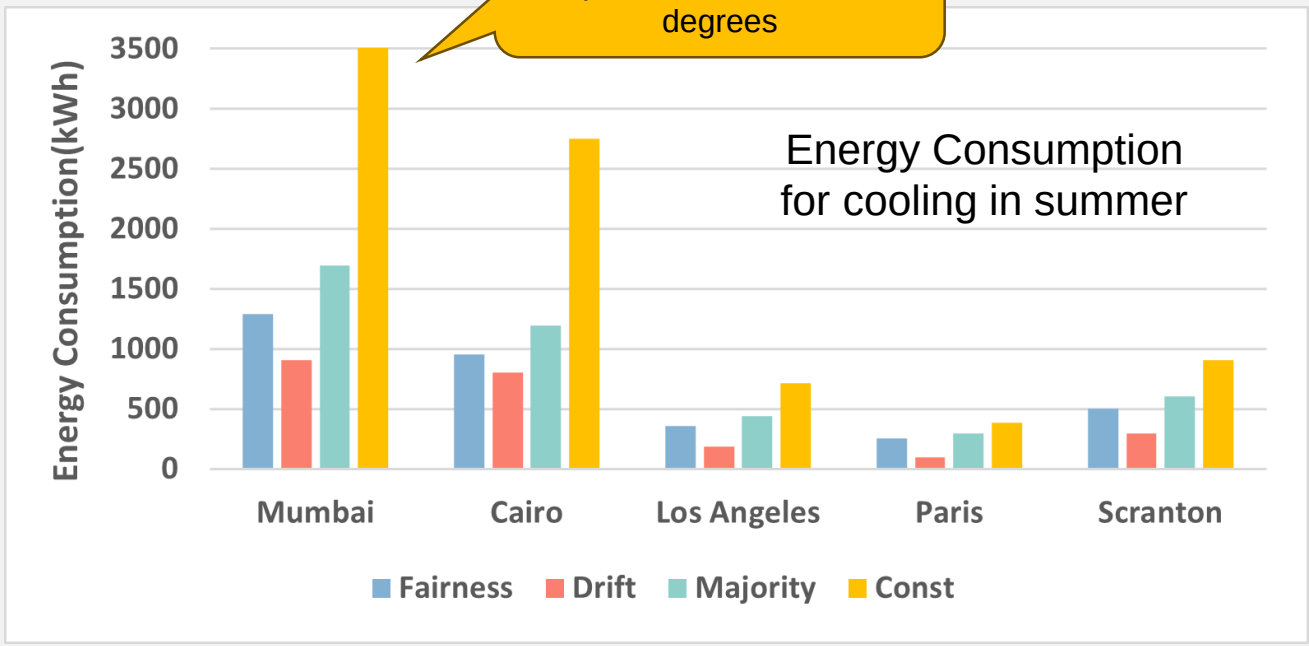
- Fairness > Majority > Drift
- Accuracy of comfort estimation has impact on Fairness at 25%

Take Aways:

- Fairness can achieve significant performance even if sensation estimation is not that accurate

Analysis 3: Climate Zone Vs. Energy Consumption

What if the office is in other regions with different climate?



Observations:

- Drift performs the best while Const the worst
- Strategies in Paris condition perform similarly

Take Aways:

- Strategies have advantages for different aspect

Conclusions

- **Co-zyBench helps** evaluating thermal comfort provision systems
- The benchmark includes **standard scenarios and metrics** to measures energy consumption, thermal comfort, and equality
- Scenarios can be customized using Co-zyBench's **Digital Twin modeler**

→ Co-zyBench is open-source and available on GitHub

→ https://github.com/satrai-lab/cozybench

Thank You!