DigiGuide: A DT-based Occupant Guiding System for Optimizing Comfort and Energy Consumption

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Jun Ma[1]

jun_ma@telecom-sudparis.eu

Roberto Yus[2]

ryus@umbc.edu

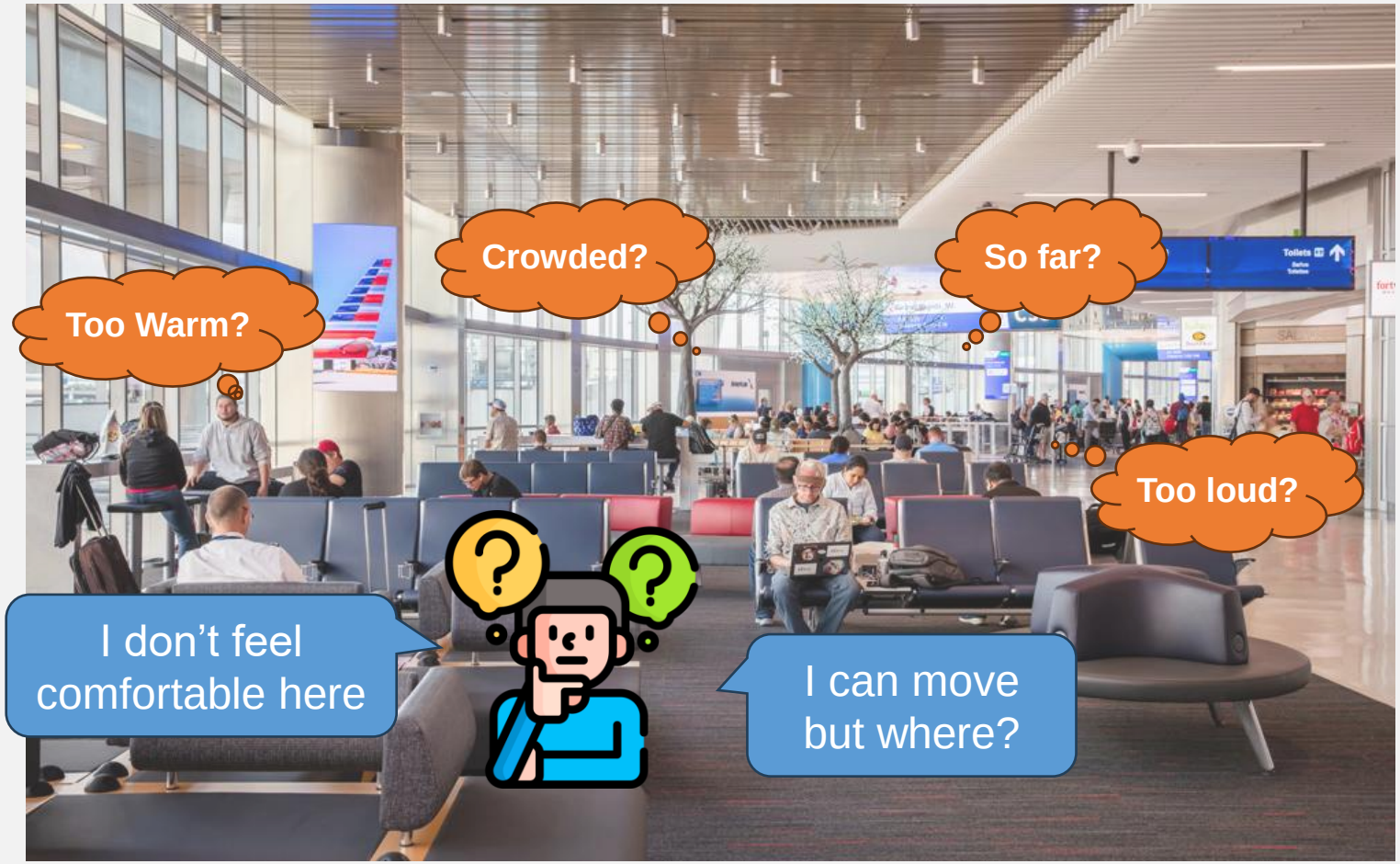
Georgios Bouloukakis[1,3]

gbouloukakis@upatras.gr

[1] Télécom SudParis, IP Paris, France

[2] University of Maryland, Baltimore Country, USA

[3] University of Patras, Greece

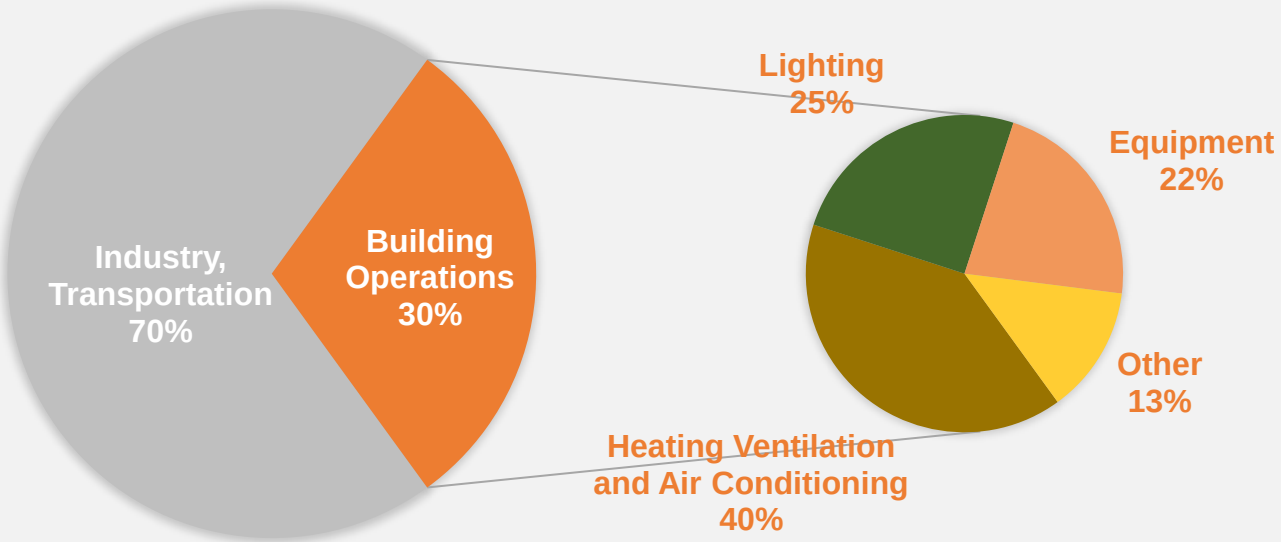


I can help you find the best location

Assistance

While I should also consider **energy** and **overall comfort** of all people

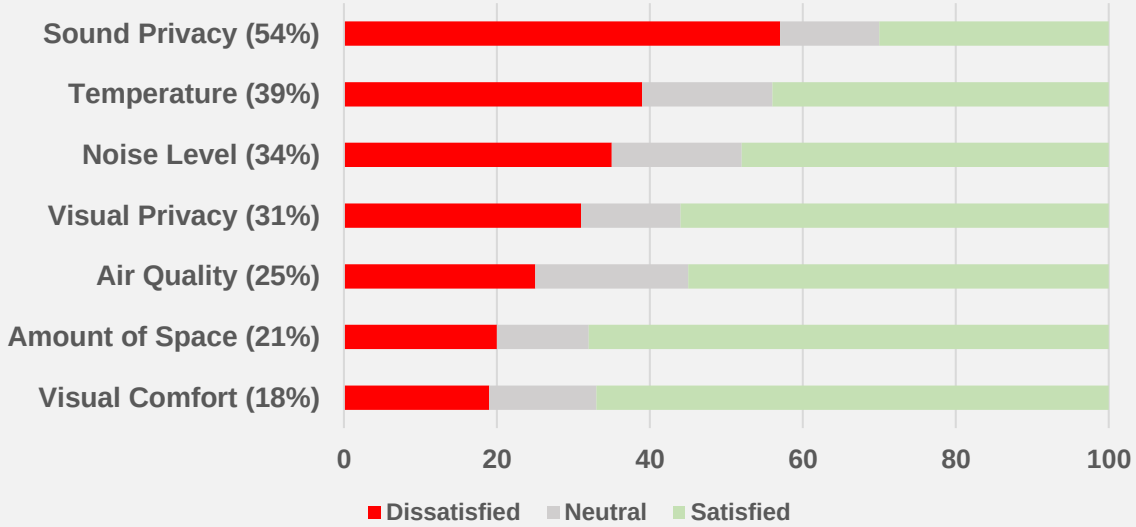
Energy Consumed But Still Not Comfortable



Building operations is the main contributor to global energy consumption **(28-30%)** and CO2 emission **(27-30%)** [1]

Most energy consumed in building operations is used to maintain **occupant comfort**.

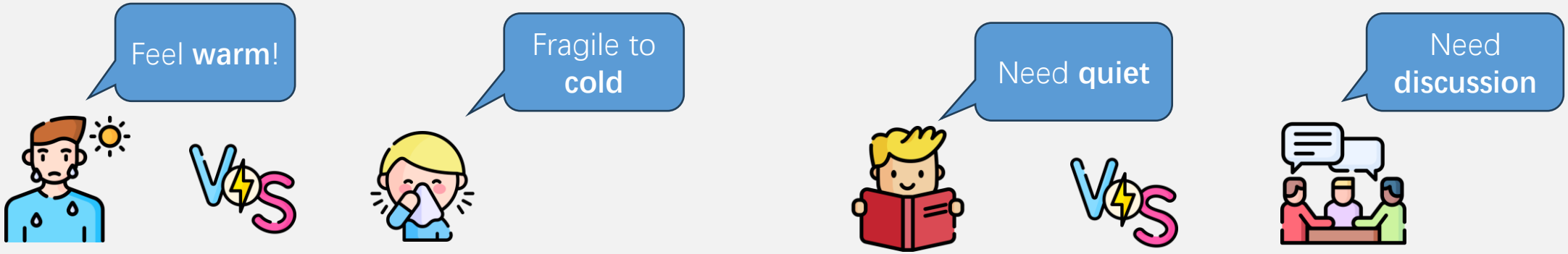
But people don't feel comfortable in many factors [2]



[1] International Energy Agency(IEA), Buildings, 2023
[2] Parkinson, Thomas, et al. Buildings & Cities, 2023.

Difficult to Let Everyone Feel Comfortable

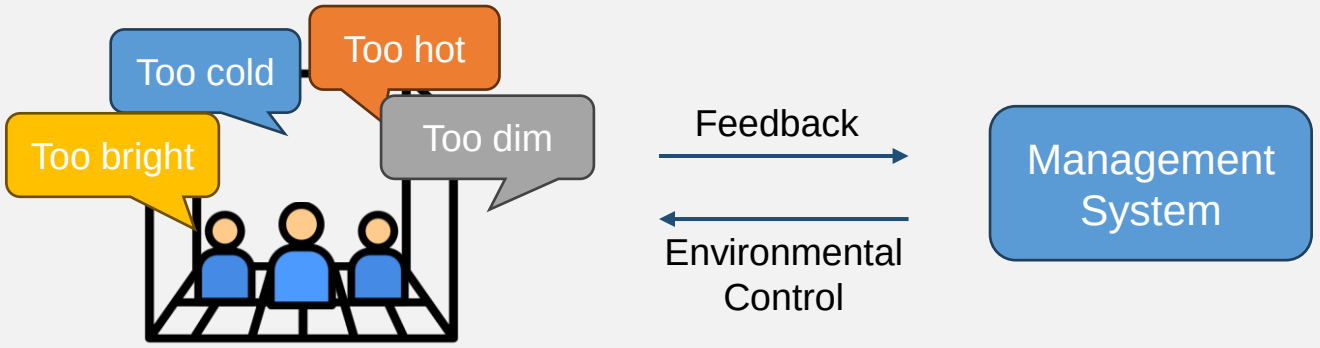
People have various comfort needs



Comfort needs are dynamic by mood, activities…

Related Work on Balancing Energy and Individual Comfort

- Rely on environmental control based on occupant feedback [1]

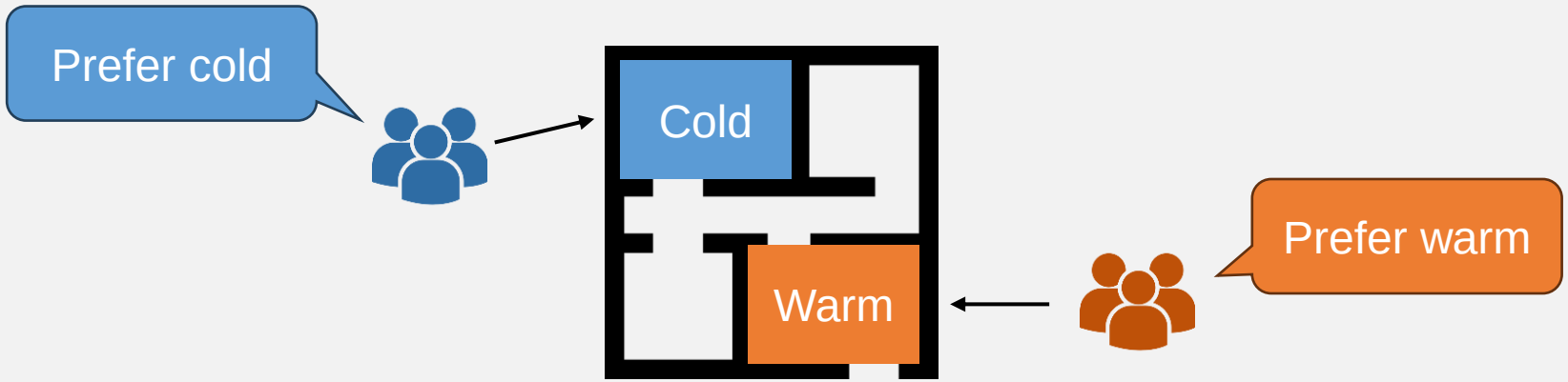


❗ Satisfying some people can result in discomfort for others.

[1] Ma et al., PerCom, 2024

Related Work on Balancing Energy and Individual Comfort

- Rely on environmental control based on occupant feedback [1]
- Grouping occupants by preferences and assigning them to appropriate spaces [2, 3]



! Cannot handle diverse needs

[1] Ma et al., PerCom, 2024
[2] Nagarathinam et al., ACM TCPS, 2021
[3] Ding et al., Energy and Buildings 2023

Related Work on Balancing Energy and Individual Comfort

- Rely on environmental control based on occupant feedback [1]
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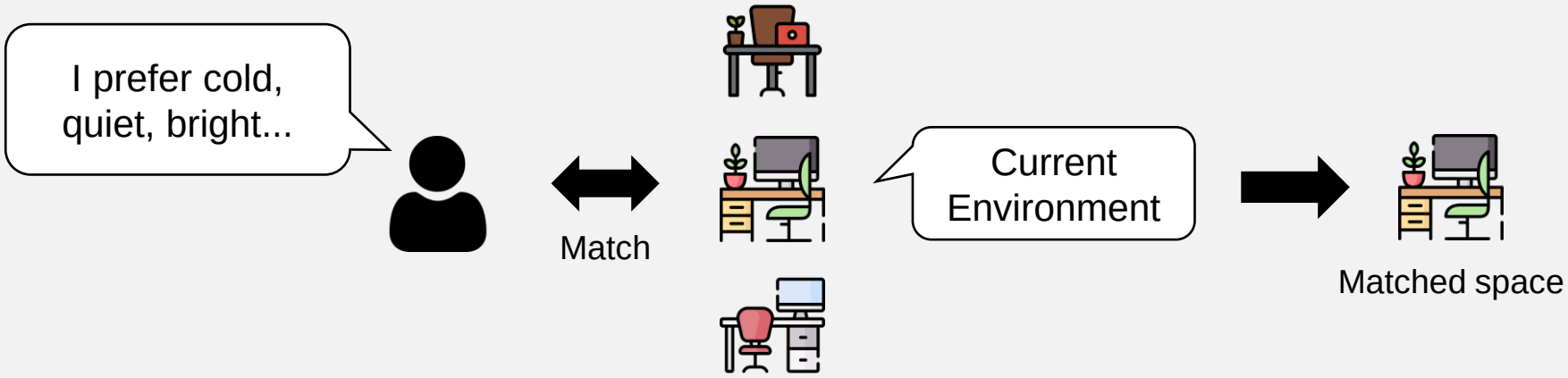
- Recommend locations by matching individuals' preferences and environment of each location [4, 5]



❗ Do not model real-time dynamics, comfort may degrade before arrival.

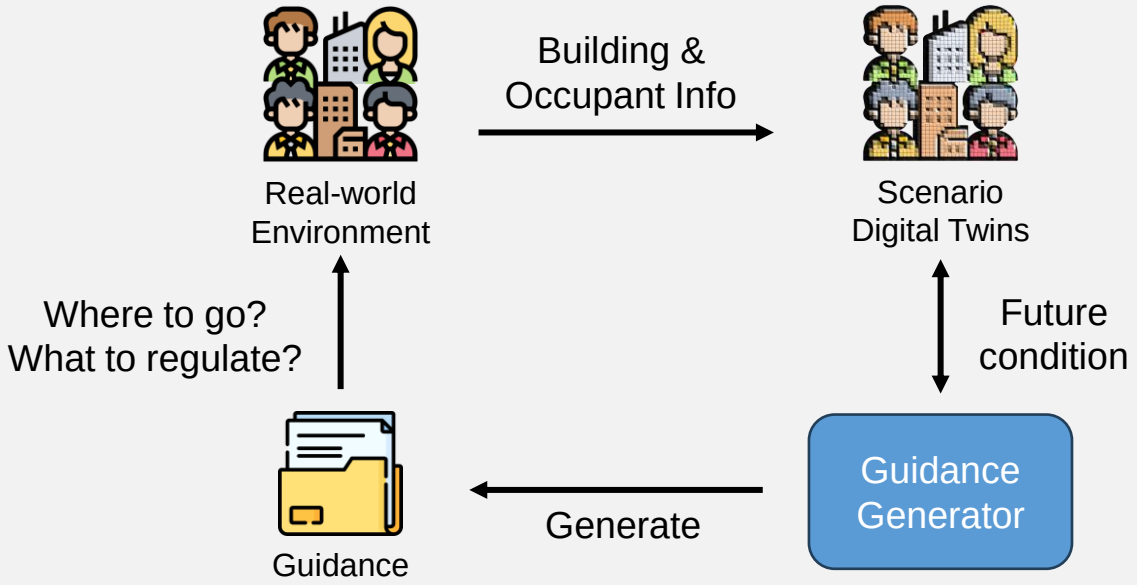
❗ Guiding one person may affects others' comfort (e.g., noise or crowdedness).

[1] Ma et al., PerCom, 2024
[2] Nagarathinam et al., ACM TCPS, 2021
[3] Ding et al., Energy and Buildings 2023
[4] Sood et al., Frontiers in Built Environment 2020
[5] Berelson et al., Digital Tools & Uses Congress 2018

Overview of DigiGuide

💡 **DigiGuide: A DT-based Occupant Guiding System for Optimizing Comfort and Energy**

- Uses **Digital Twins to forecast environmental and occupant dynamics**
- Thoroughly accounts for **various comfort needs of all people, and energy consumption**
- Guides both **occupant movement** and administrators to **regulate the environment**



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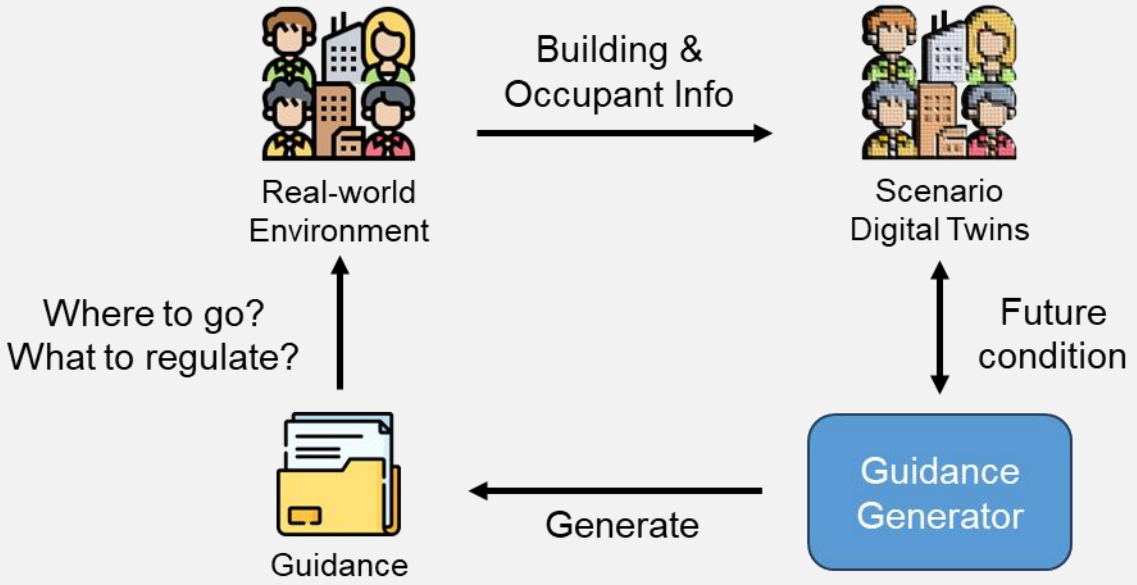
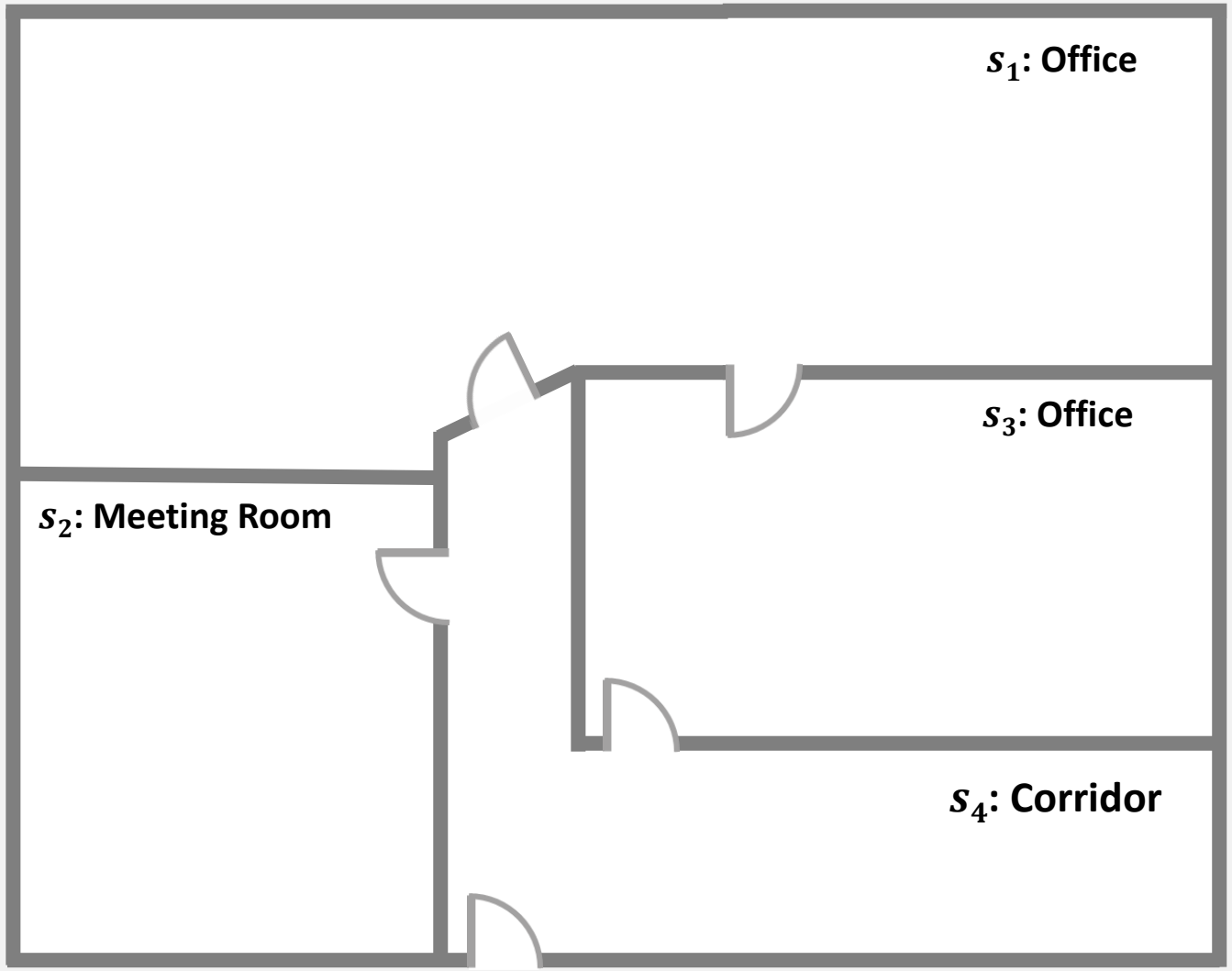
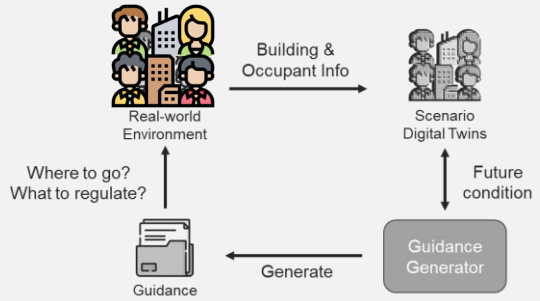


DigiGuide: Scenario Modeling





Coworking Office:

- Pay-as-you-go, allowing everyone to book by the hour or day

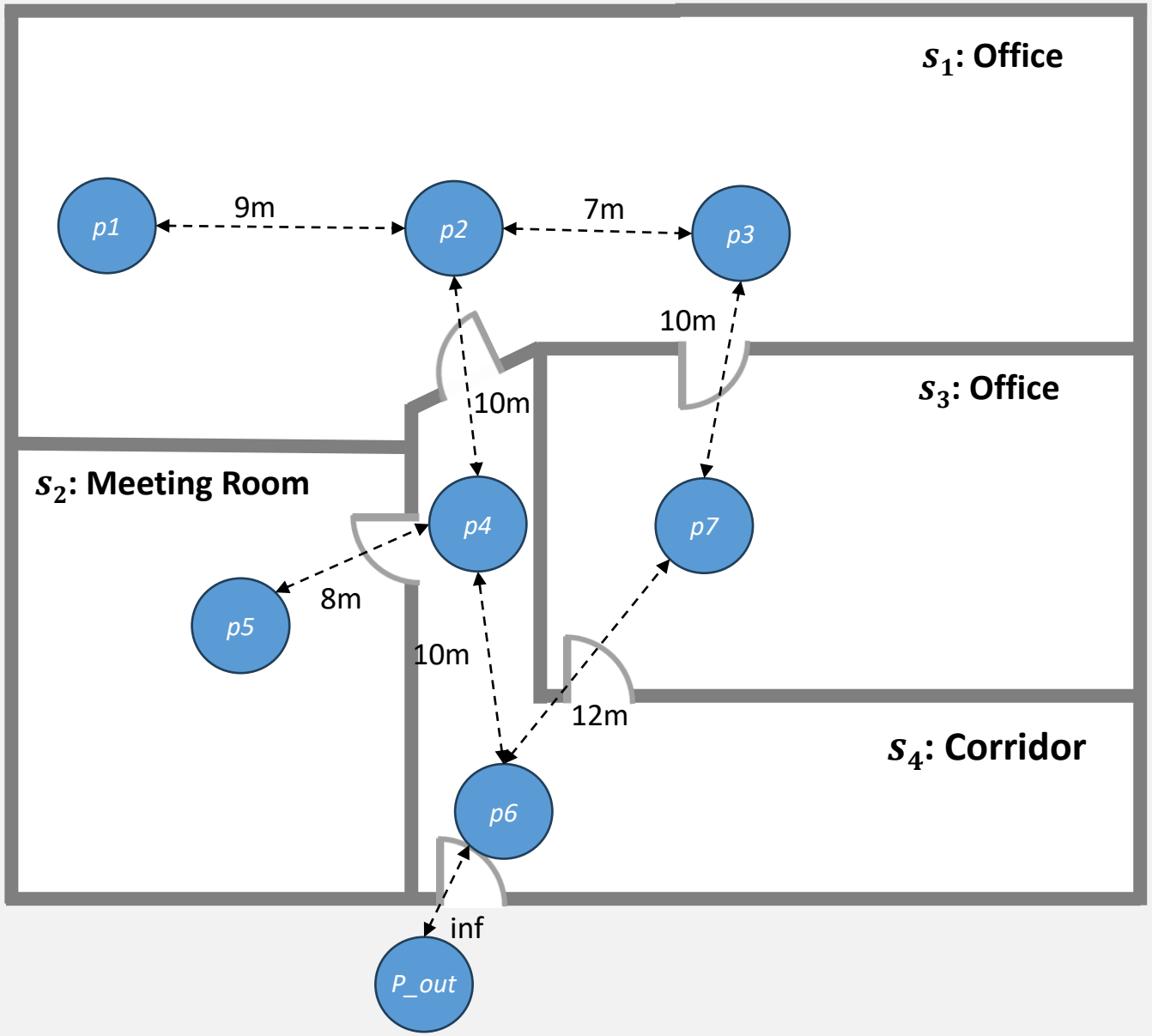
Building $\mathcal{B}$

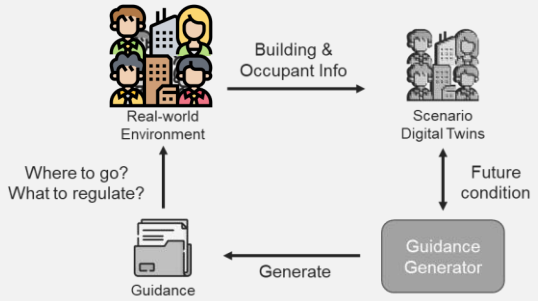
$$\mathcal{B} = (\mathcal{S}, \mathcal{P}, \mathcal{C}, \mathcal{U}, \mathcal{X}, \mathcal{E})$$

Space $\mathcal{S}$

$$s = (s_{id}, s_{type}, \mathcal{P}_s, \mathcal{C}_s)$$

DigiGuide: Scenario Modeling





Coworking Office:

Each space is separated to **Point of Interests (POI)**

Every two POIs can have **connections**

Building $\mathcal{B}$

$\mathcal{B} = (\mathcal{S}, \mathcal{P}, \mathcal{C}, \mathcal{U}, \mathcal{X}, \mathcal{E})$

Space $\mathcal{S}$

$s = (s_{id}, s_{type}, \mathcal{P}_s, \mathcal{C}_s)$

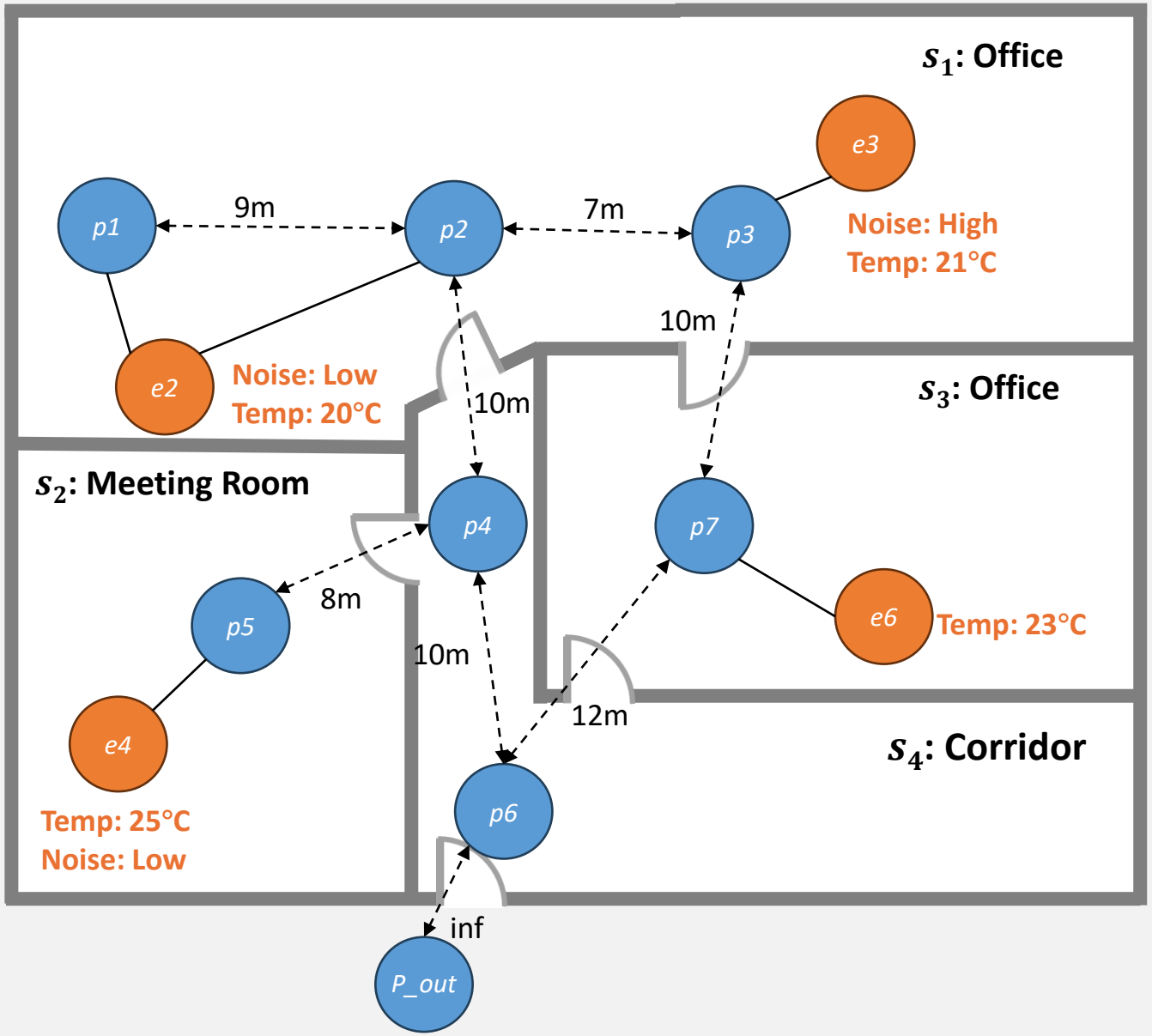
Connection $\mathcal{C}$

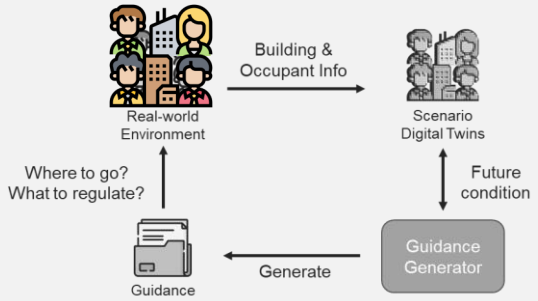
$c = (p_i, p_j, w)$

POI $\mathcal{P}$

$p = (p_{id}, p_{loc}, p_{size}, \mathcal{E}_p)$

DigiGuide: Scenario Modeling





Coworking Office:

Every POI has **environment observations**

Building $\mathcal{B}$

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Connection $\mathcal{C}$

$c = (p_i, p_j, w)$

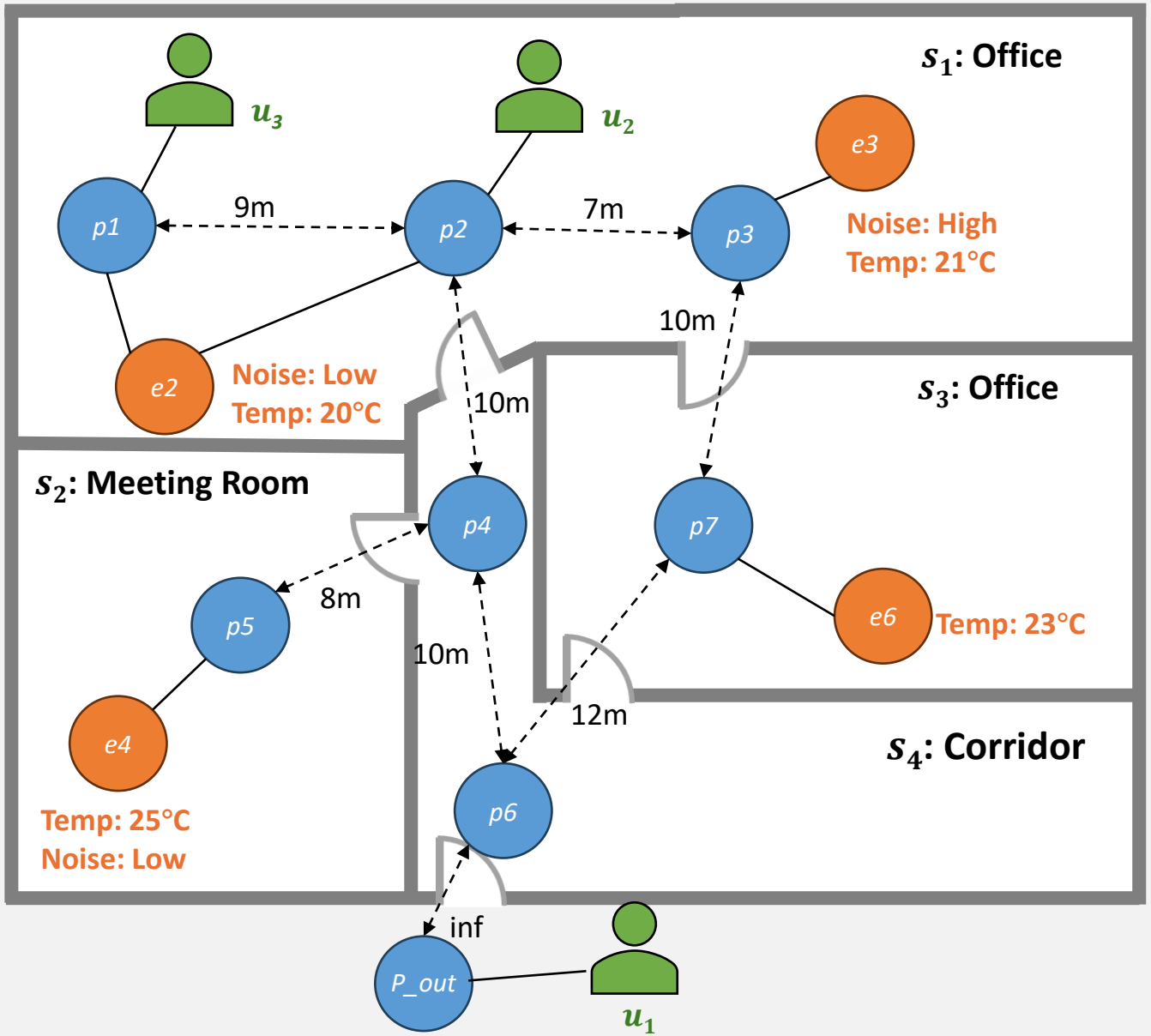
POI $\mathcal{P}$

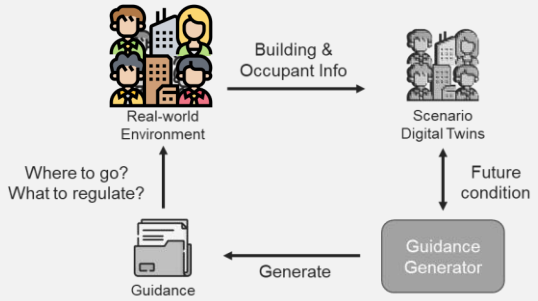
$p = (p_{id}, p_{loc}, p_{size}, \mathcal{E}_p)$

Environmental Feature $\mathcal{E}$

$e = (e_{id}, e_{type}, eval, obs)$

DigiGuide: Scenario Modeling





Coworking Office:

People can be **inside or outside the building**

Building $\mathcal{B}$

$\mathcal{B} = (\mathcal{S}, \mathcal{P}, \mathcal{C}, \mathcal{U}, \mathcal{X}, \mathcal{E})$

Space $\mathcal{S}$

$s = (s_{id}, s_{type}, \mathcal{P}_s, \mathcal{C}_s)$

Occupant $\mathcal{U}$

$u = (u_{id}, u_{loc}, \mathcal{R}_u, x)$

Connection $\mathcal{C}$

$c = (p_i, p_j, w)$

POI $\mathcal{P}$

$p = (p_{id}, p_{loc}, p_{size}, \mathcal{E}_p)$

Environmental Feature $\mathcal{E}$

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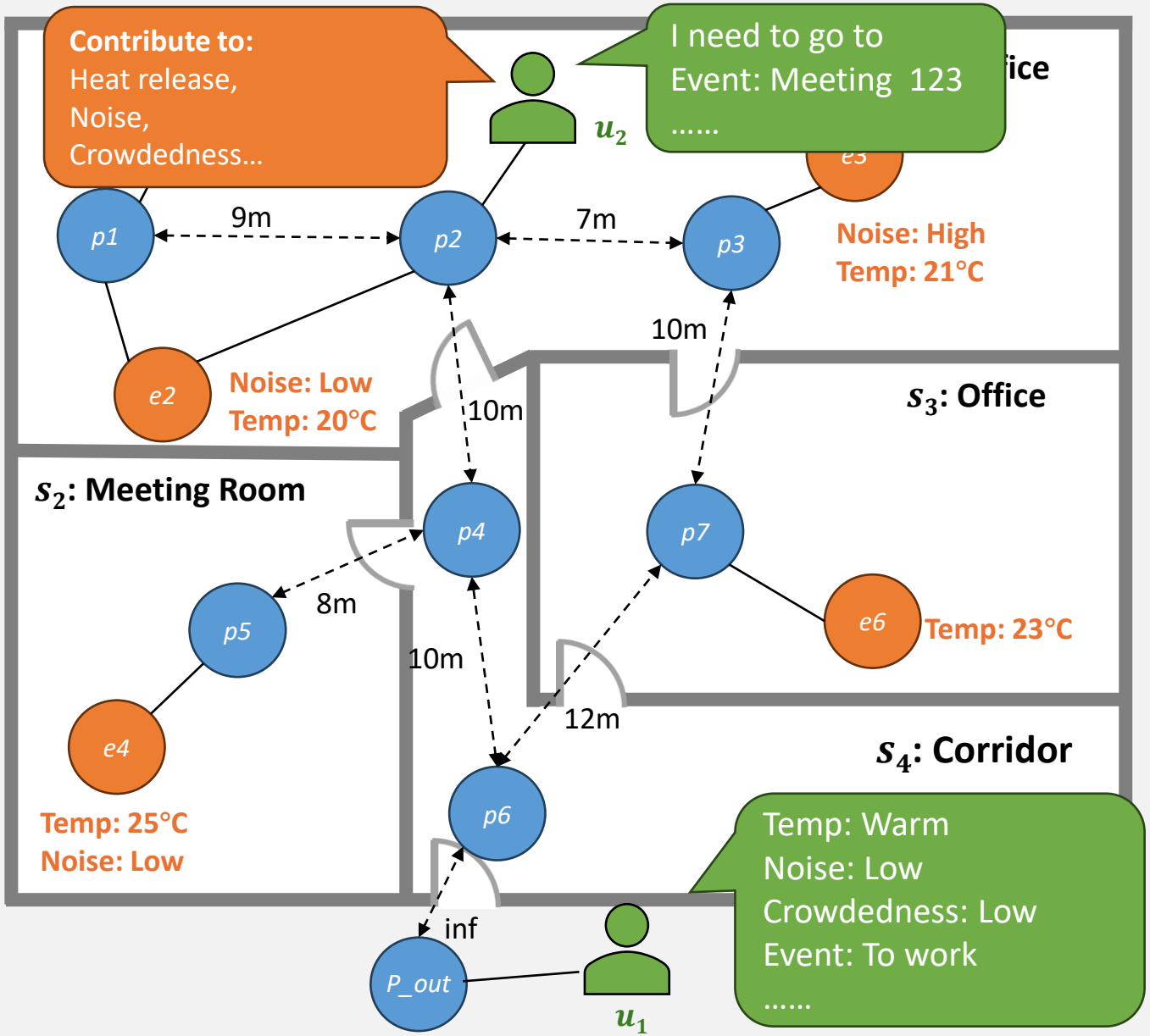
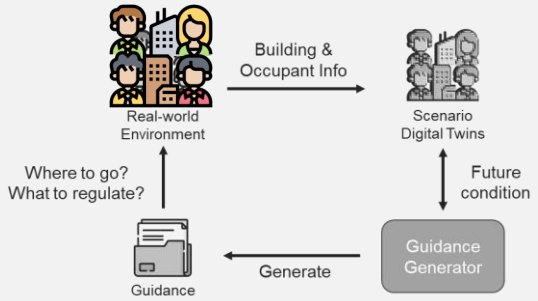
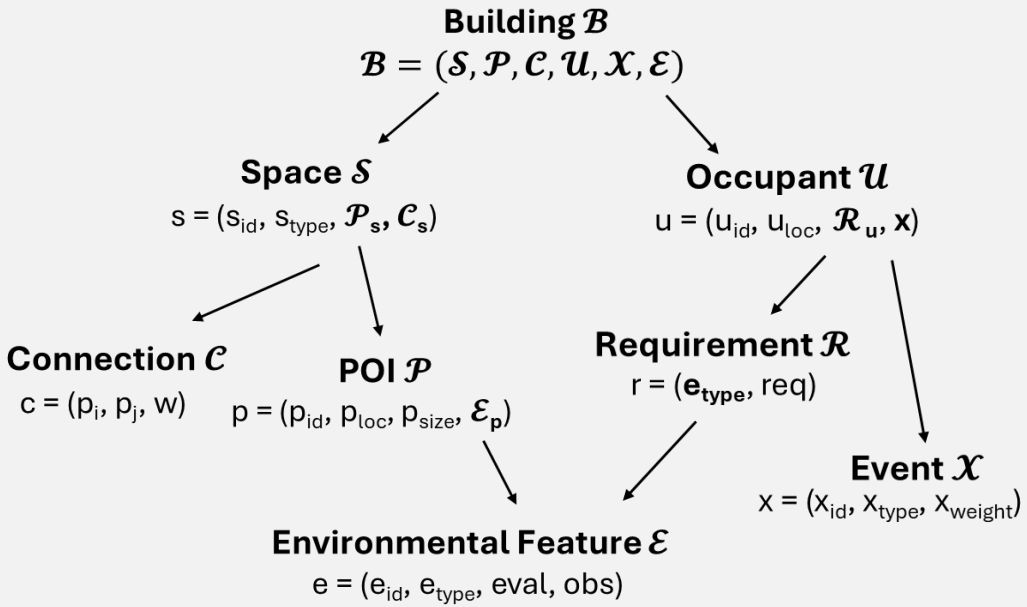




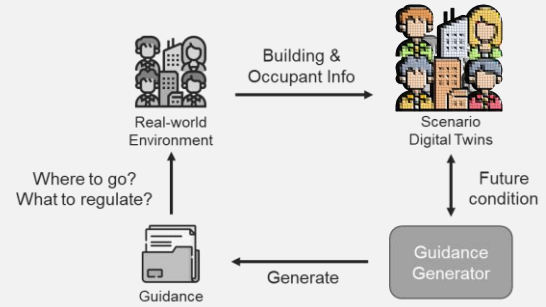
Coworking Office:

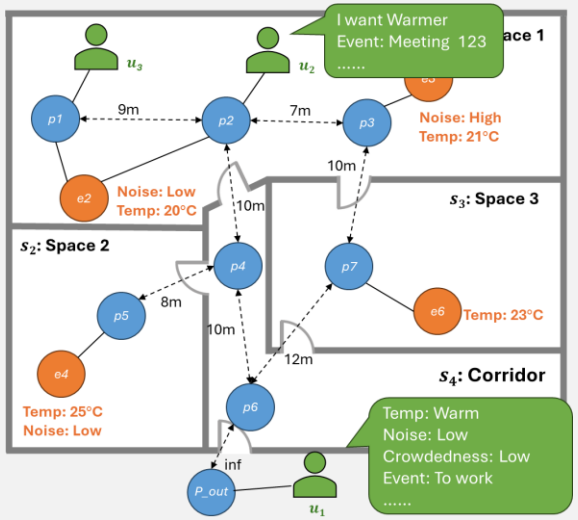
People provide comfort needs:

- Preferences – thermal preference
- Requirements – room type



DigiGuide: A DT-based Occupant Guiding System





DigiGuide

DT Modeling → Trend Predictor

- Creates **simulation models**
- **Analyzes historical records** for future prediction

Estimates Future condition:
- People's **location**
- Future **indoor environment**
- Possible **outcome**

Scenario Setup

Co-zyBench [1]

Occupant Digital Twins | Co-simulation Middleware | Building Digital Twin

Energy & Thermal comfort ⟷ Customizable Metrics

e.g., Crowdedness discomfort

Extendable Co-simulations

e.g., Crowdedness Level:

$$crowdness = \frac{occupant\ number}{capacity}$$

[1] Ma et al., PerCom, 2024

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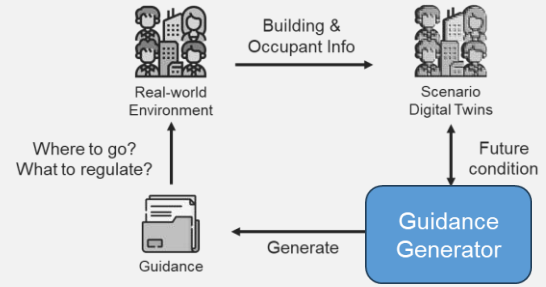
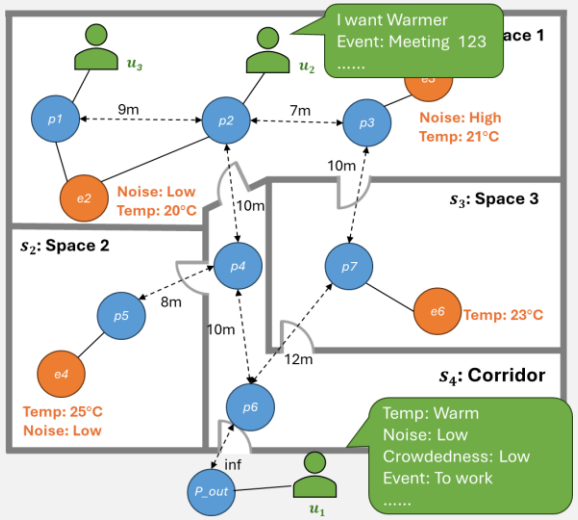
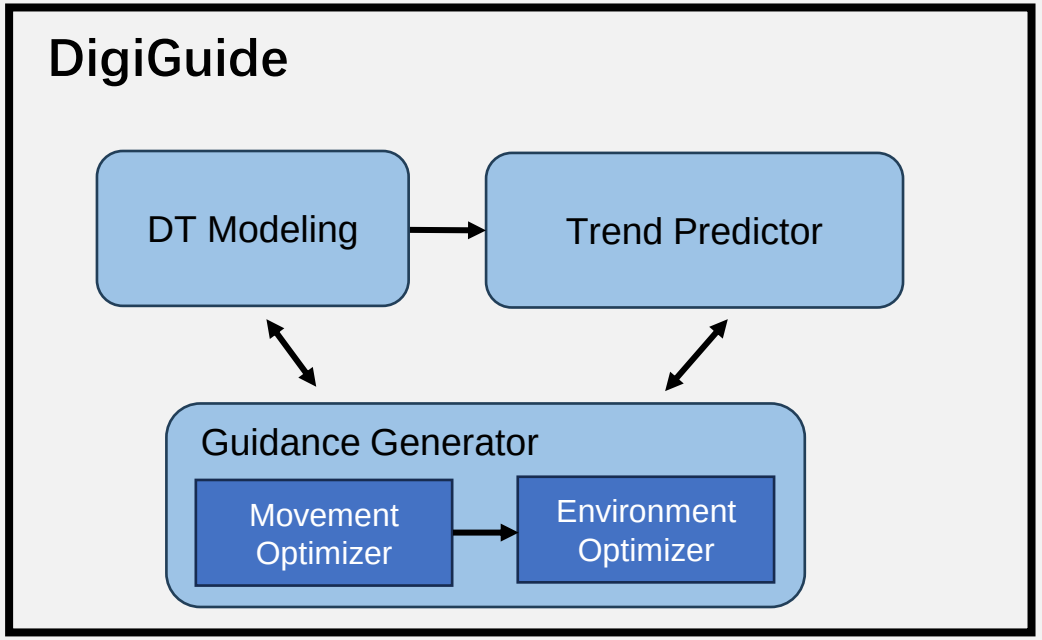
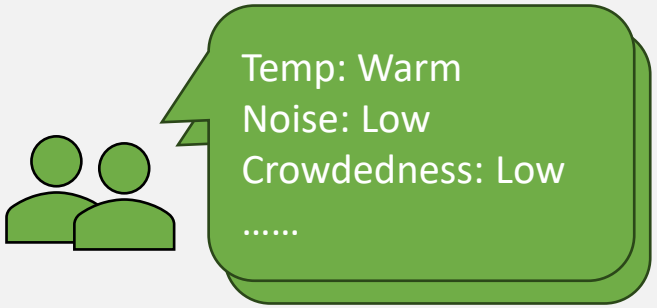






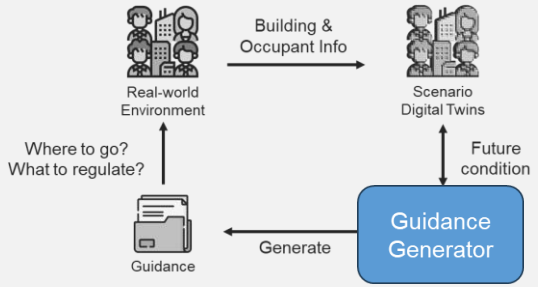


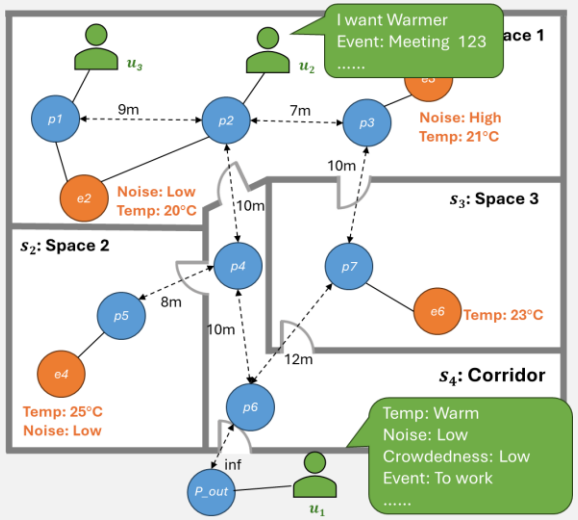
Movement Guidance

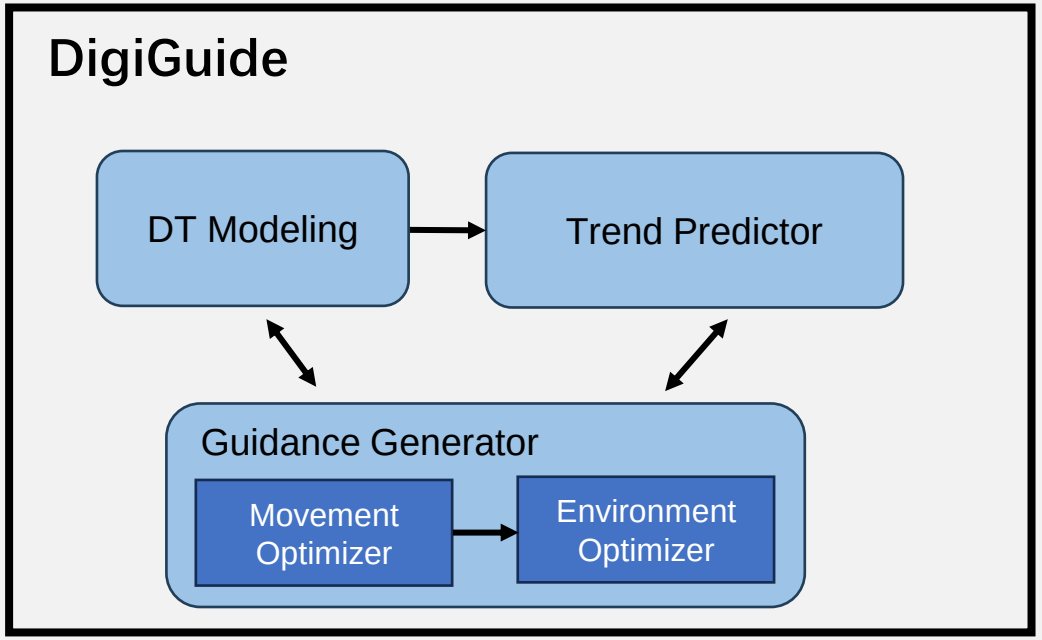
Evaluation

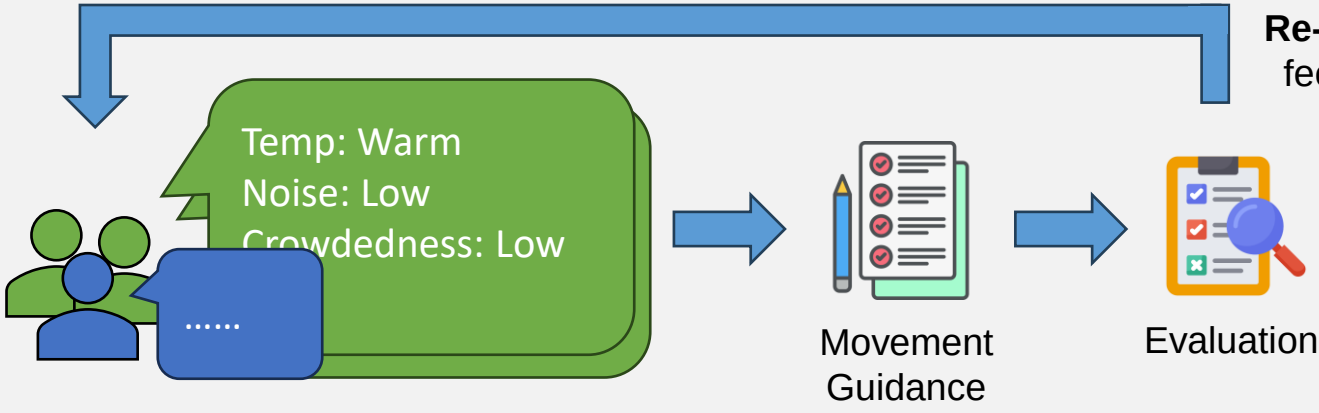
Performance on occupant comfort and energy

DigiGuide: A DT-based Occupant Guiding System



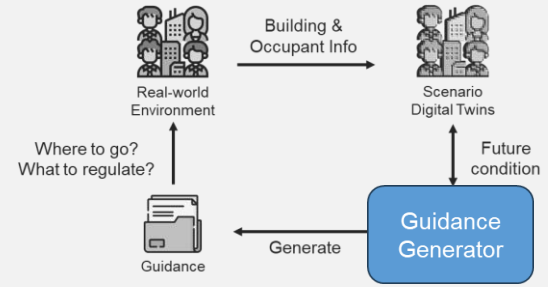


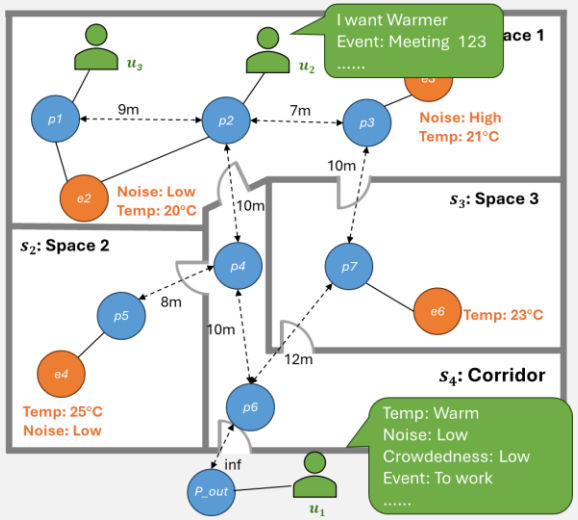


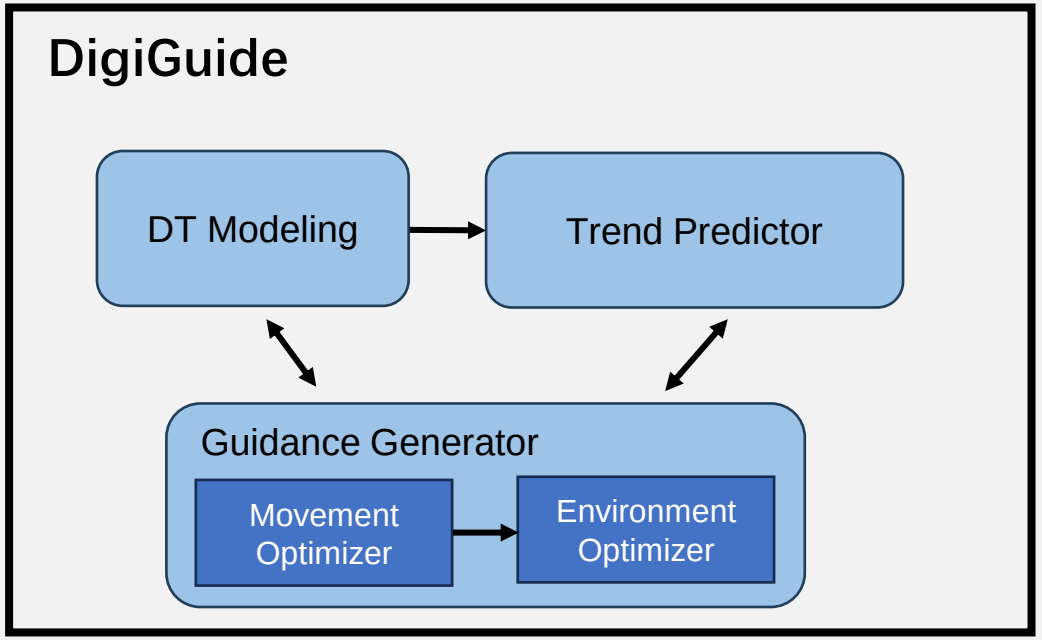


Re-guide who would feel uncomfortable (with penalty)

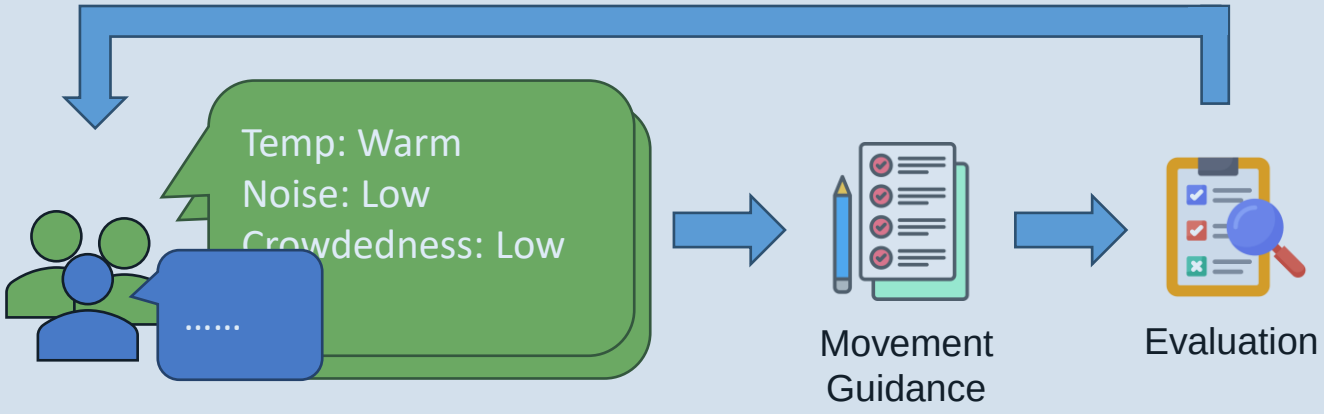
DigiGuide: A DT-based Occupant Guiding System



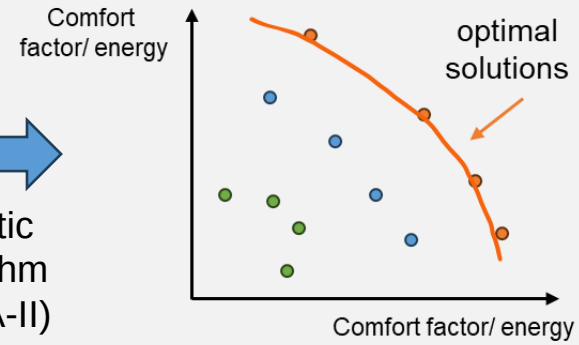




Multi-objective Optimization Problem



Genetic Algorithm (NSGA-II)



u1 -> p1,
u2 -> p3,
u3 -> p1,
……

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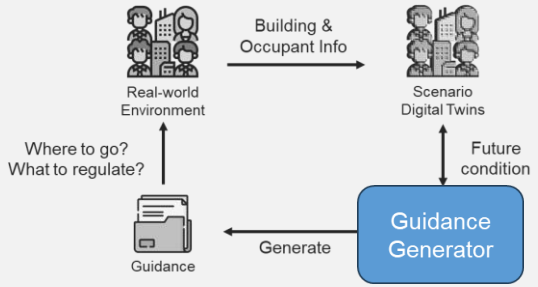

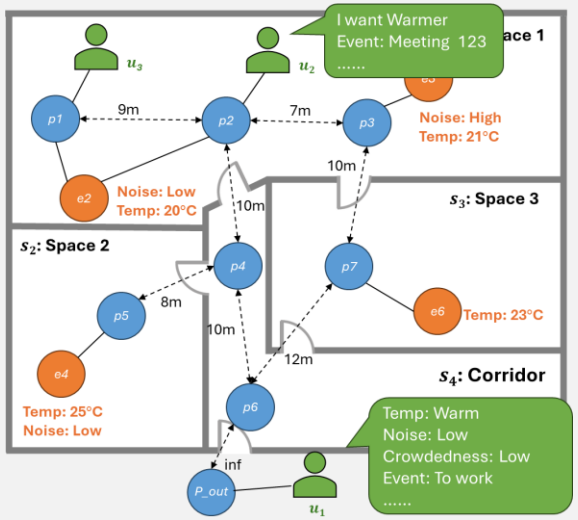

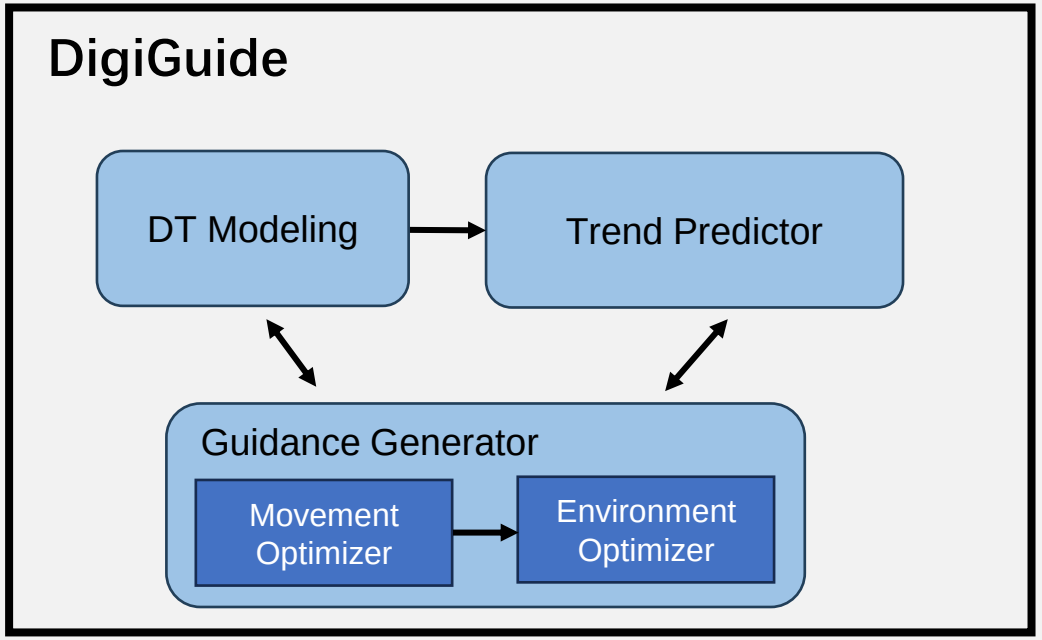

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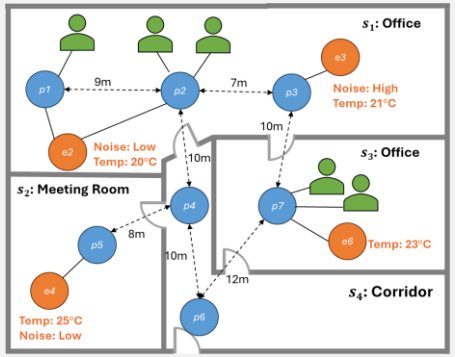
Movement Guidance & Evaluation



Future Scenario

- Analyze the preferences of all occupant in each place
- Regulate the environment to maximize the overall comfort.

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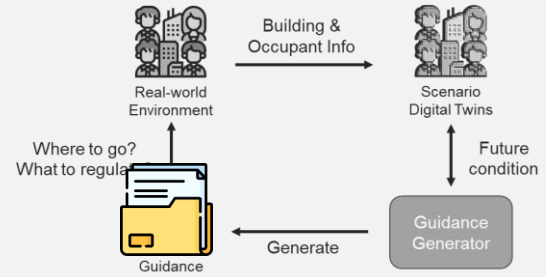
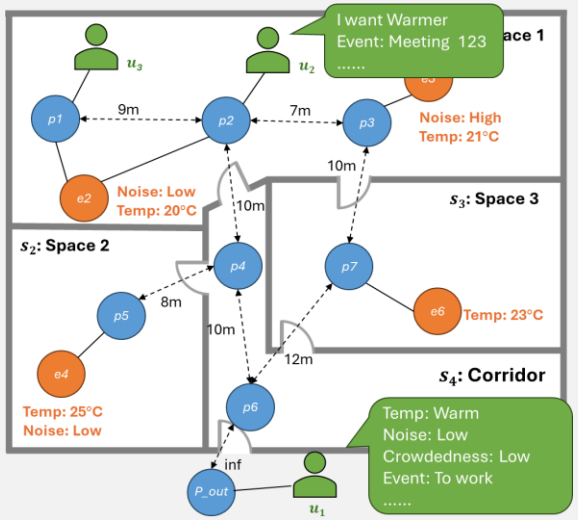
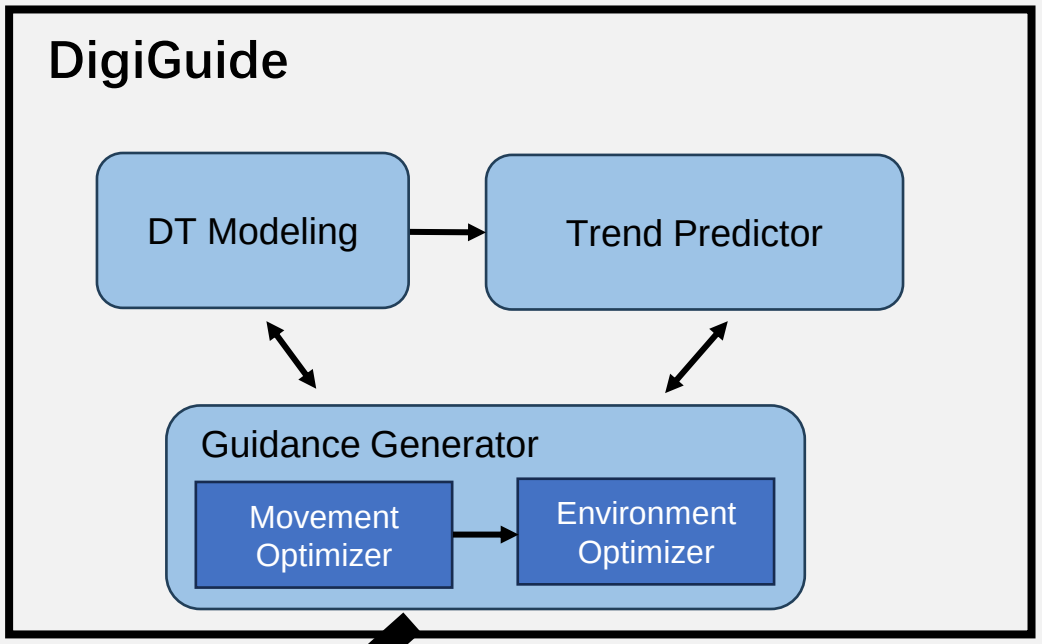
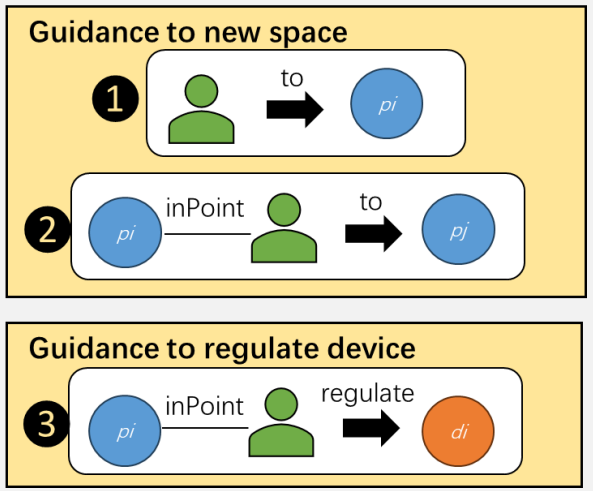








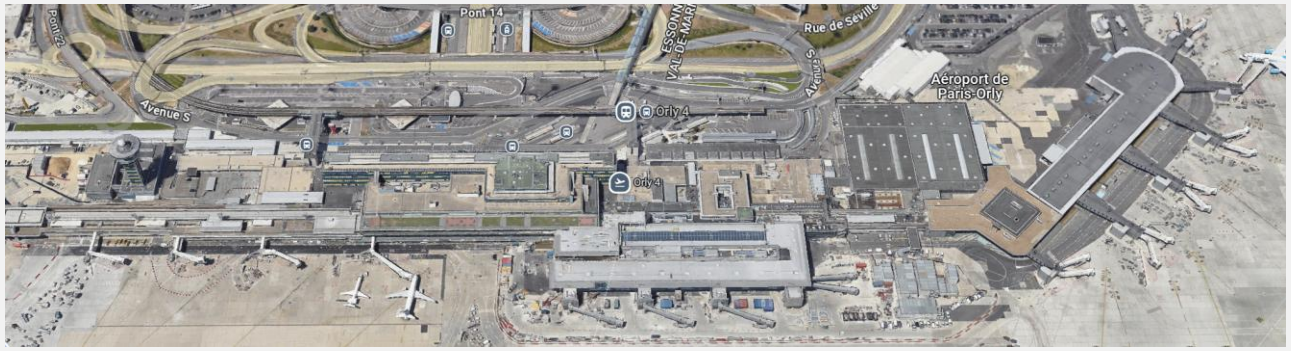
1. Gu
2.

- Does guiding people perform better on comfort and energy performance?
- How our solution (DT + Genetic Algorithm) performs than others?

3. Generate **control actions** to regulate indoor environment

Experimental Setup – Simulation of Two Large Scale Scenarios

Drahi-X Innovation Center, France



Orly International Airport Terminal 4, France

- 2 floors with 127 office rooms in different sizes, 8 meeting rooms.
- 160 occupants work and have meetings every workday.
- People have various comfort needs:
  - **Thermal comfort**
  - **Crowdedness**
  - **Noise level**
  - **Walk distance**

- 3 floors with 16 boarding gates, 40 waiting areas, 3 lounge rooms
- 100 flights with 100-200 people per day
- Comfort preferences:
  - **Thermal comfort**
  - **Crowdedness**
  - **Noise level**
  - **Distance to the boarding gate**

Experimental Setup – Baselines

Movement Optimizer – Generate Movement Guidance:

- **BL**: Realistic people movement without guidance.
- **WS**: Weighted-Sum approach base on the current environment.
- **GA**: Our solution with DT and genetic algorithm

Environment Optimizer – Generate Environmental Control Actions:

- **Maj**: Adjusts environment based on the majority of current occupants' preferences.
- **Drift**: Applies initial adjustment, then gradually shifts settings toward energy-saving targets.

Combine them together:

- BL-Maj, BL-Drift, WS-Maj, WS-Drift, **GA-Maj, GA-Drift**

Experiment Results

Co-working Open Space Performance

	BL-Maj	BL-Drift	WS-Maj	WS-Drift	GA-Maj	GA-Drift
Energy (kwh)	1852.81	1807.83	1810.77	1759.52	1768.39	**1725.66**
Crowd (lvl)	**0.55**	**0.55**	1.34	1.32	0.92	0.95
Acoustic (lvl)	0.13	0.13	1.17	1	0.11	**0.1**
Thermal (TSV)	1.37	1.48	0.74	0.99	**0.69**	0.86
Distance (m)	60.12	60.12	**25.34**	23.16	38.75	40.41

25% decline

Airport Performance

Metric	BL-Maj	BL-Drift	WS-Maj	WS-Drift	GA-Maj	GA-Drift
Energy (kwh)	125.25	122.21	122.41	121.91	116.64	**108.64**
Crowd (lvl)	0.43	0.43	**0.08**	0.09	0.1	0.1
Acoustic (lvl)	**0.8**	**0.8**	1.09	1.14	0.95	0.94
Thermal (TSV)	0.29	0.31	0.32	0.33	**0.18**	0.19
Distance (m)	466.78	463.78	**273.54**	273.79	336.55	336.55

GA achieves an average of

- **18.2% lower discomfort** and **8.6% lower energy consumption** than BL
- **11.7% lower discomfort** with **5.7% less energy** compared to WS

Maj compares to **Drift**

- Drift reduces energy consumption by **2-4%**
- Drift leads to comfort decline

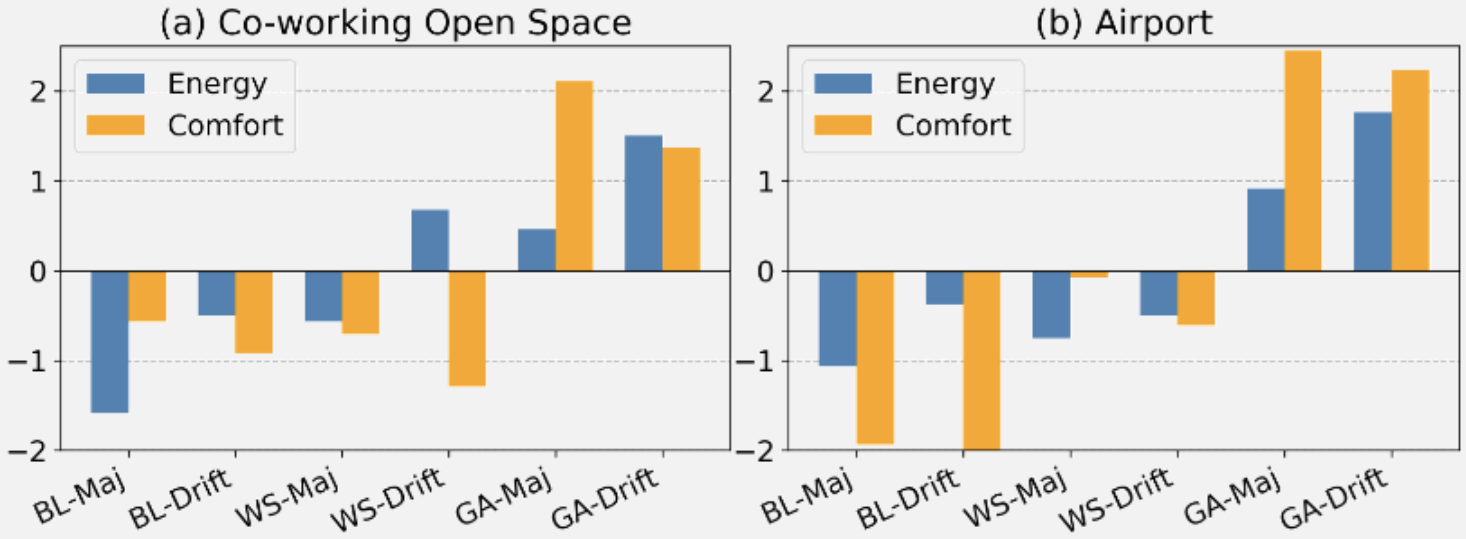
Experiment Results - Energy vs. Comfort

Negated Z Score: $Z' = -Z = -\frac{x - \mu}{\sigma}$

Mean value

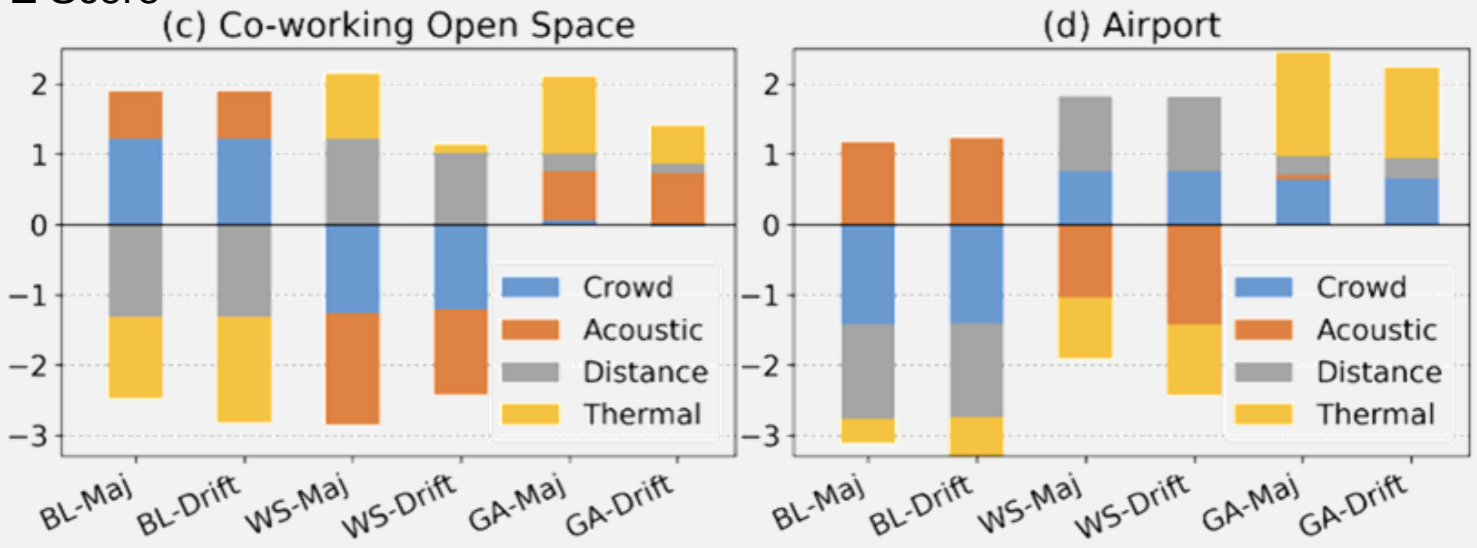
Standard Deviation

How much the value is above or below the mean value (larger is better)



GA has positive values for both energy and comfort in both scenarios.

Experiment Results – Comfort Balance



GA has positive values for all comfort factors – not sacrifice others for specific comfort factor

GA has the largest accumulated value – achieve the best comfort performance in general.

Conclusion & Future Work

DigiGuide: A novel occupant guiding system combining Digital Twins and Genetic Algorithms to optimize occupant comfort and energy.

- Generates guidance for both occupant movement and environmental control
- Optimizes multiple comfort needs of all people and energy consumption
- Considers future dynamism using Digital Twins
- Support various comfort needs by modeling multiple-optimization problem

This work is open-source and available on GitHub
https://github.com/satrai-lab/DigiGuide

GitHub

Thank You!

jun_ma@telecom-sudparis.eu