Efficient Scheduling of Smart Building Energy Systems with AI Planning

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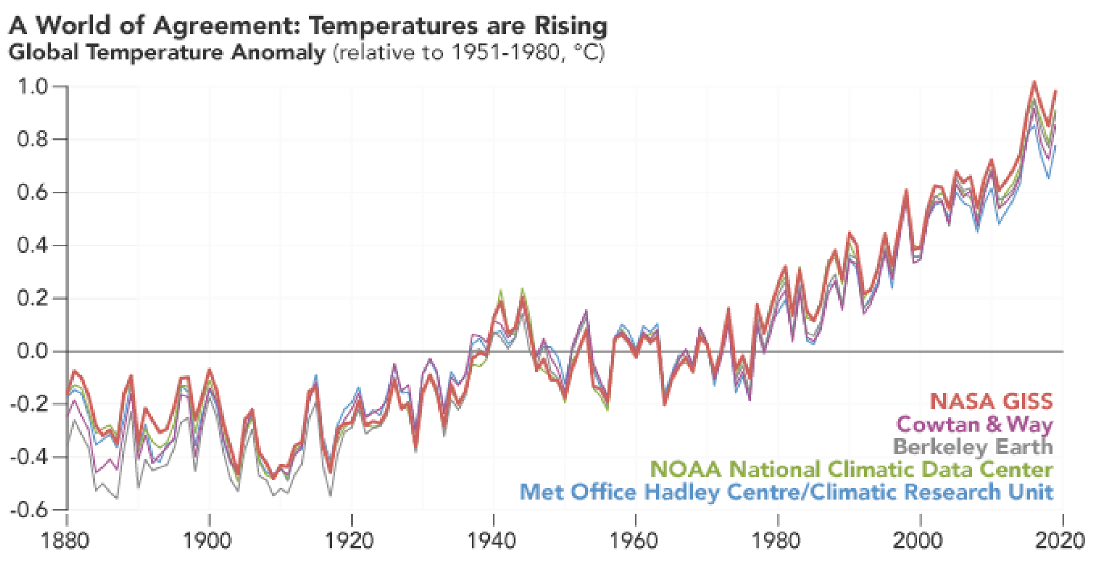
Buildings’ Energy Consumption

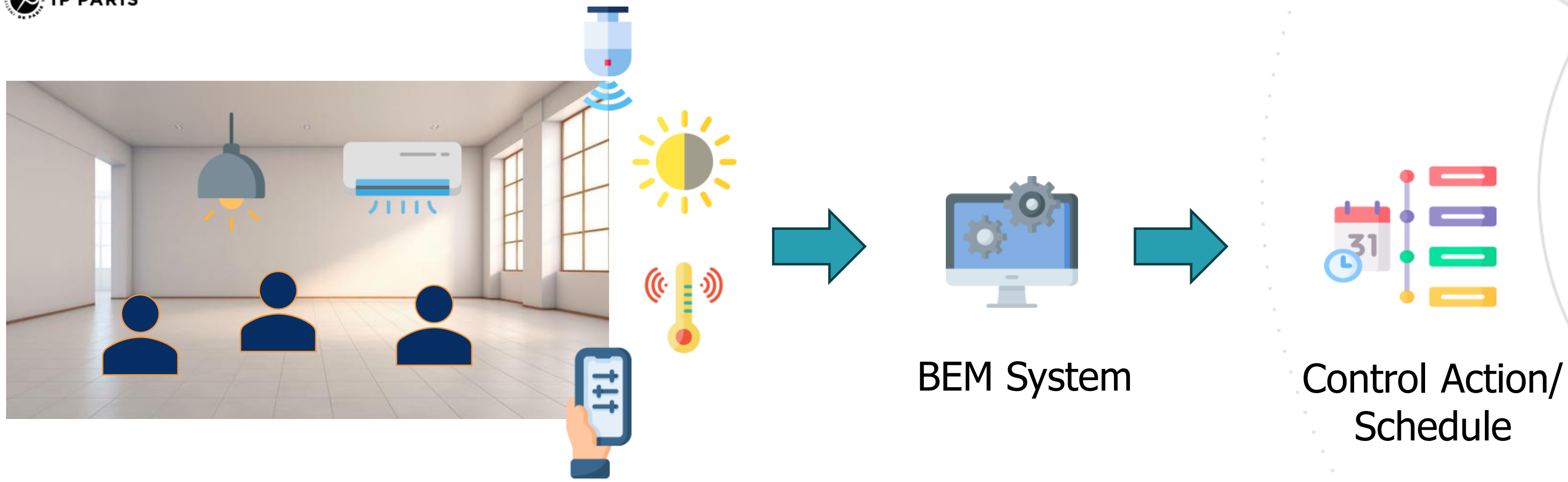
Average global temperature
has increased by at least **1.1°C**
since 2018 [1]


A World of Agreement: Temperatures are Rising
Global Temperature Anomaly (relative to 1951-1980, °C)

Building operations account for **30%** of global
final energy consumption and **26%** of global
energy-related emissions [2]

[1] World of Change: Global Temperatures 2022, NASA Earth Observatory.
[2] International Energy Agency(IEA), *Buildings*, 2022.

Building Energy Management Systems

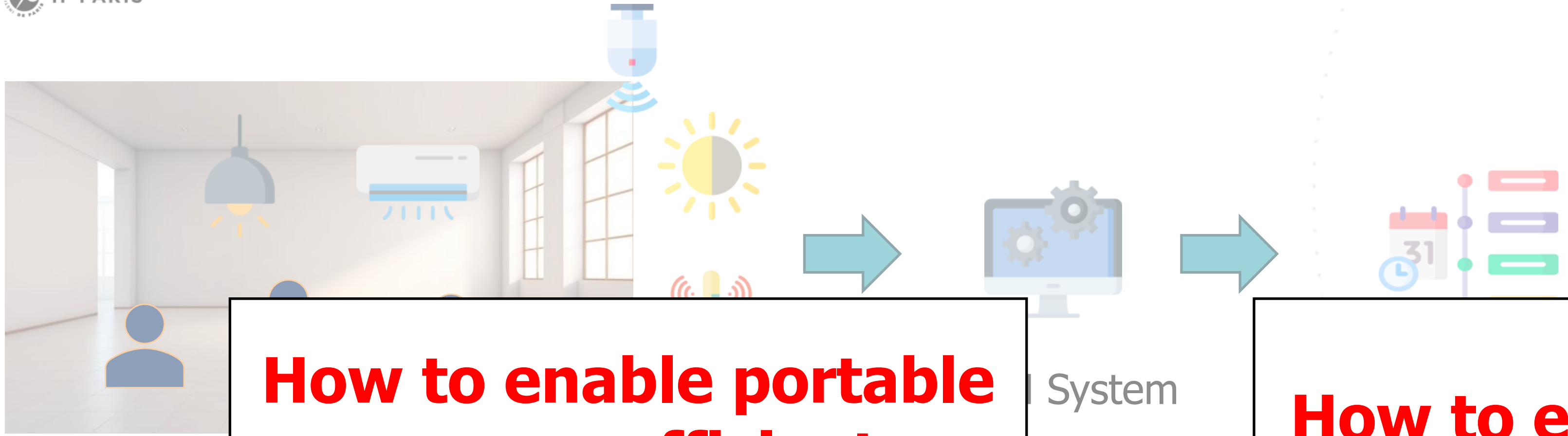

BEM System

Control Action/
Schedule

- ML techniques (NN, KNN, SVM) are used for predicting temperature, cooling load and comfort level to optimize HVAC control [1, 2, 3].
- MPC leverages RL to predict outcome of certain control actions and optimize HVAC energy usage [4, 5].
- AI Planning is used to for scheduling lighting operations based on occupant behavior prediction [6].

[1] G. Demirezet et al. IJER. 2020.
[2] P. Aparicio-Ruiz et al. Annals of Operations Research. 2020.
[3] D. J. Koschwitz et al. Energy. 2018.
[4] J. Arroyo et al. Applied Energy. 2022.
[5] A. T. Nguyen. Energy and Buildings. 2024.
[6] I. Georgievski et al.PMC. 2017

Building Energy Management Systems



How to enable portable energy-efficient solutions for cross-building optimization?

How to enable fast and easy adaptation in dynamic situations?

- ML techni … ing temperat … optimize …
- MPC lever … ol actions ar …
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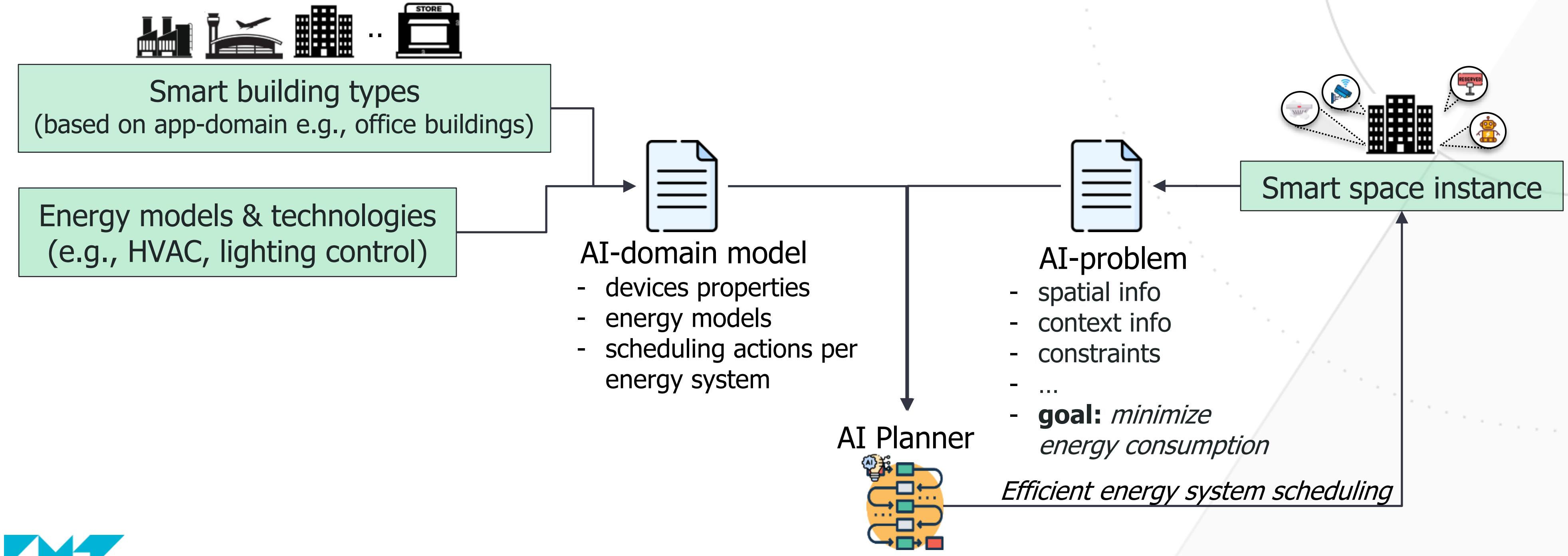
Solution Overview



..

Smart building types
(based on app-domain e.g., office buildings)

Energy models & technologies
(e.g., HVAC, lighting control)

AI-domain model
- devices properties
- energy models
- scheduling actions per energy system

AI-problem
- spatial info
- context info
- constraints
- …
- **goal:** *minimize energy consumption*

Smart space instance

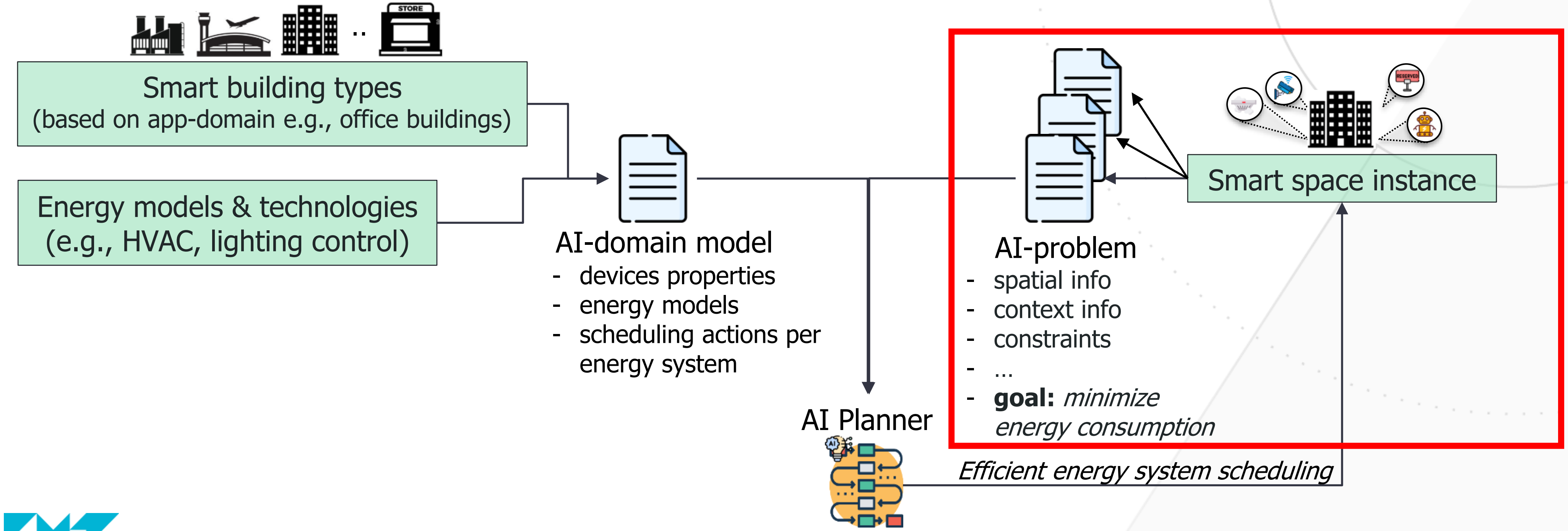
AI Planner

Efficient energy system scheduling

Solution Overview

Portability ⟶ pairing the same domain file with multiple problem files

Adaptation ⟶ re-planning requires only updating the problem file



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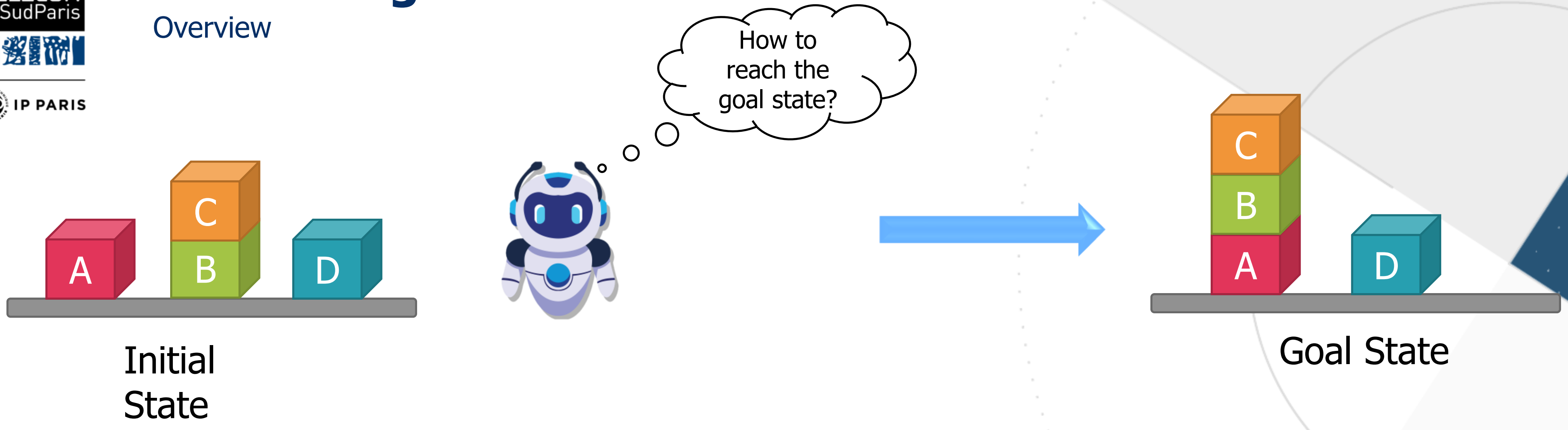
Efficient energy system scheduling

AI Planning

Overview



Initial State

How to reach the goal state?

Goal State

> Automated Planning is an area of artificial intelligence where the task is to **choose** and arrange **actions** in order **to achieve some goal**.

Application Domains

- Robotics [1]
- Web services composition [2], [3]
- Orchestration of IoT applications [4]

[1] A. Kattepur, B. Purushothaman. Cognitive Computation and Systems. 2020.
[2] S. Qi, X. Tang, D. Chen. IEEE CGC. 2012
[3] G. Zou, Y. Chen, Y. Yang, R. Huang, Y. Xu. ntl. Conf.on Cloud Computing and Virtualization.
[4] U. Bellur, N. Narendra, and S. Mohalik. IEEE Services. 2017

AI Planning for Efficient Scheduling of Energy Systems

A Planning Domain Σ is a state transition system that contains:

- A finite set of **states** of the system S (temperature setpoint, luminosity level)
- A set of **actions** α to be performed by an agent (increase max. plug load, set HVAC setpoint)
- A **state transition function** $\gamma: S \times A \rightarrow S$
- A **cost** function $C: S \times A \rightarrow [0, \infty)$ (energy consumption, comfort level)

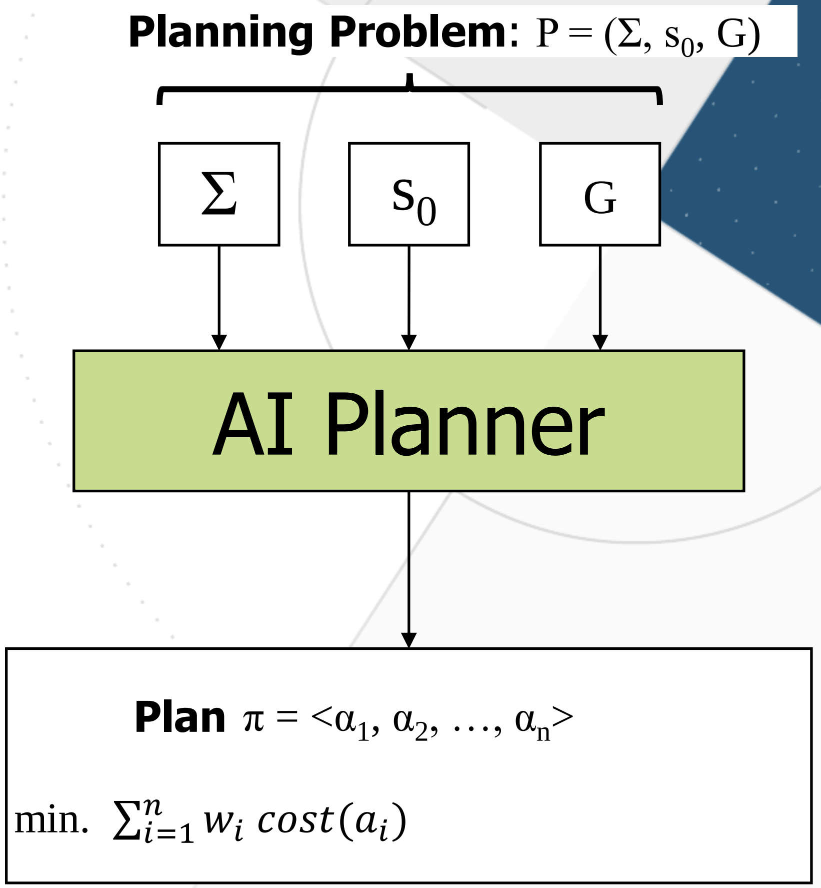
Initial State s_0

- $occ_{r_i}(t)$
- $\theta^{in}_{r_i}(t),\ \theta^{out}(t)$
- $\varphi_{r_i}(t)$

π

Goal State

- $\theta^{in}_{r_i} \geq \theta_{min}$
- $\theta^{in}_{r_i} \leq \theta_{max}$
- $\varphi_{r_i} \geq \varphi_{min}$



Planning Problem: $P = (\Sigma, s_0, G)$

Plan $\pi = <\alpha_1, \alpha_2, \ldots, \alpha_n>$

min. $\sum_{i=1}^{n} w_i \, cost(a_i)$

AI Planning for Efficient Scheduling of Energy Systems

Planning problems are expressed using the Planning Domain Definition Language (PDDL), an action-centered language that provides a standard syntax to describe actions by their parameters, preconditions, and effects.

Domain file

```
(:action temperature_setting_cooling_21
   :parameters (?o -occupancy)
   :precondition (and (>=(time) 0)
                      (=(occupancy_type ?o) 1) (>(temperature_outside)
                      (max_temperature)) (>=(number_occupants ?o) 4)
                      (<=(number_occupants) 6))
   :effect (and (assign (temperature_setting) 21)
                (increase (energy_consumption) 6000)))

(:action light_setting_500
   :parameters (?o -occupancy ?ws -window_shading)
   :precondition (and (>=(time)0)
                      (=(occupancy_type ?o) 2) (not (open ?ws))
   :effect (and (assign (temperature_setting) 21)
               (increase (energy_consumption) 6000)))
…
```

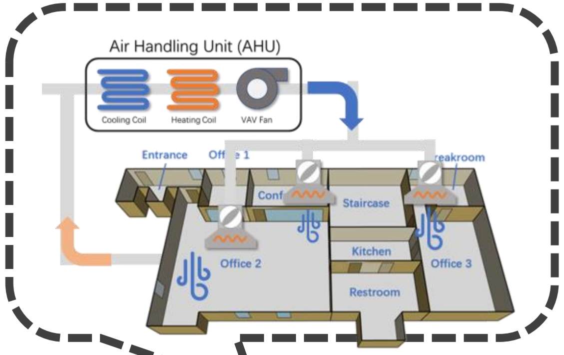
Problem file

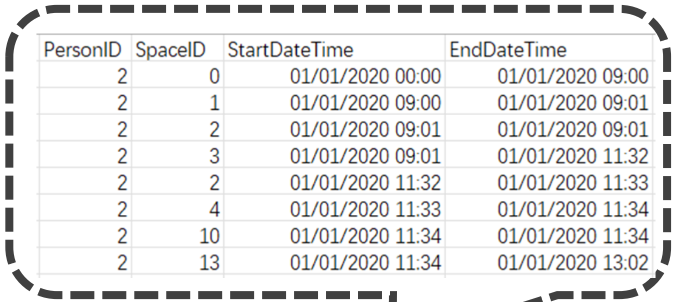
```
(:objects
   printing energymanagement … topic_all  - Topic
   app1 app2 app3 app4 … app_all - Application)
(:init
   (=(temperature_outside) 27)
   (=(temperature_inside) 27)
   (=(energy_consumption) 0)
   (=(min_temperature) 20)
   (=(max_temperature) 23)
   (=(number_occupants ?o) 2))
(:goal (all_done)
       (>=(temperature_inside) 20)
       (<=(temperature_inside) 24)))
(:metric minimize (energy_consumption))
```

```
0.0010: (TEMPERATURE_SETTING_21 O1) [D:1.0000; C:0.1000]
0.0012: (TURN_COOLING_ON R1) [D:1.0000; C:5500.0000]
1.0013: (HVAC_IS_COOLING R1) [D:1.0000; C:4000.0000]
2.0015: (HVAC_COOLING_OFF R1) [D:1.0000; C:0.1000]
3.0017: (TURN_COOLING_ON R1) [D:1.0000; C:5500.0000]
…
```

Experimental Setup

- Gross **office area**: 268 m^2
- The HVAC is implemented as VAV (Variable Air Volume)
- **18 individuals** with different rooms share the office space
- **Location**: Paris, France
- **Climate Zone**: Climat 4A-Mixed Humid (ASHRAE)
- **Time of Year**: June -> August
- Weather reports from 2007 – 2021 [4]





PersonID	SpaceID	StartDateTime	EndDateTime
2	0	01/01/2020 00:00	01/01/2020 09:00
2	1	01/01/2020 09:00	01/01/2020 09:01
2	2	01/01/2020 09:01	01/01/2020 09:01
2	3	01/01/2020 09:01	01/01/2020 11:32
2	2	01/01/2020 11:32	01/01/2020 11:33
2	4	01/01/2020 11:33	01/01/2020 11:34
2	10	01/01/2020 11:34	01/01/2020 11:34
2	13	01/01/2020 11:34	01/01/2020 13:02

EnergyPlus [1]

Building Digital Twin

Co-zyBench [2]

Occupant Digital Twin

SmartSPEC [3]

- Indoor Temperature
- Outdoor Temperature
- Occupant number

- HVAC control schedule
- ON/OFF control & setpoint

AI Planner Runtime Environment

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[1] EnergyPlus, https://energyplus.net/

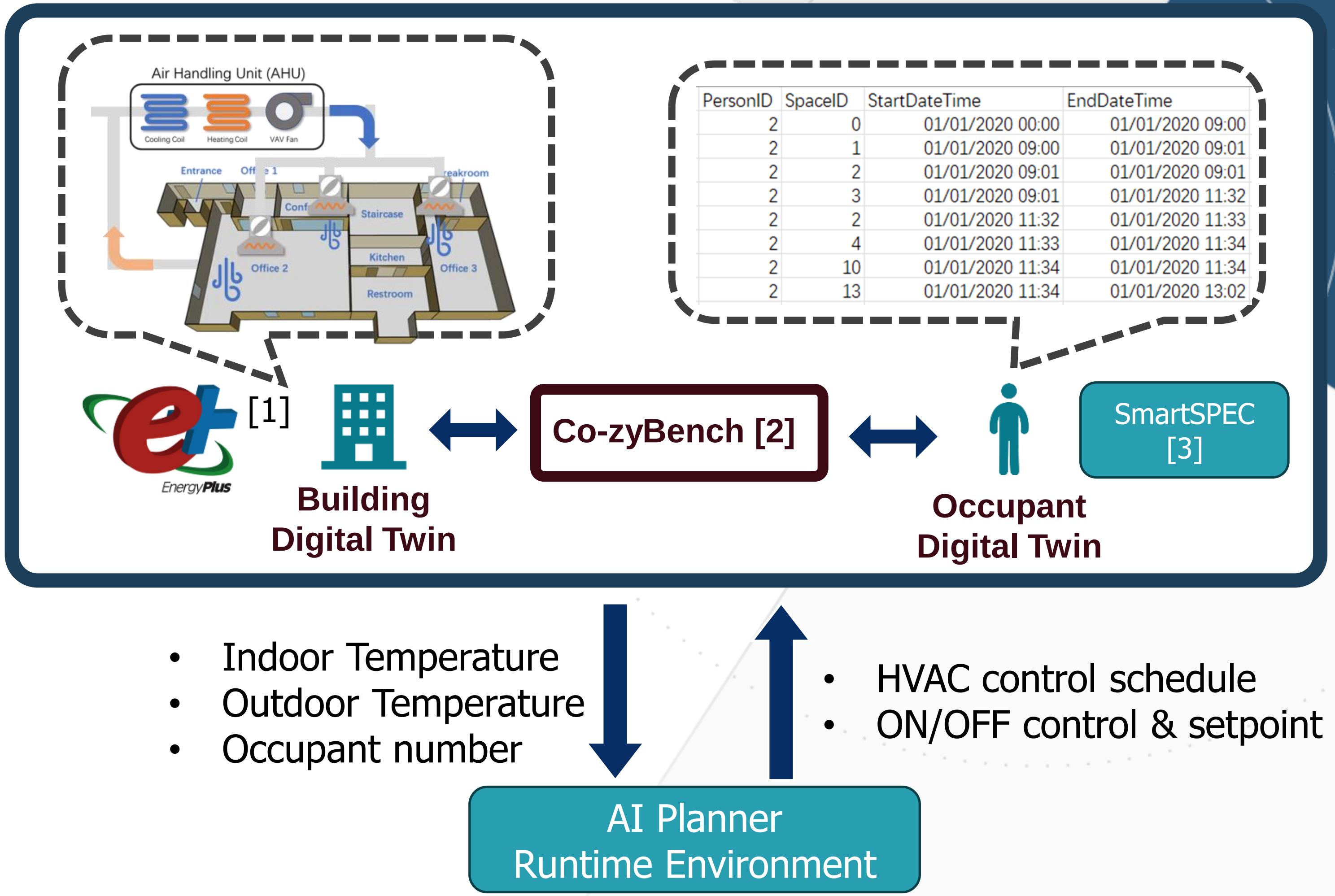
[2] J. Ma et al. "Co-zybench: Using co-simulation and digital twins to benchmark thermal comfort provision in smart buildings." *PerCom*. 2024.

[3] A. Chio et al. "Smartspec: Customizable smart space datasets via event-driven simulations." *PerCom*. 2022.

[4] D. B. C Lawrite et al. "Development of Global Typical Meteorological Years (TMYx)". 2019

Experimental Setup

- The AI planner generates daily HVAC schedules from 8:00 to 20:00.
- Actions may be performed every 30 mins.
- **Thermal comfort** range: 21 - 24° C.
- **Goal**: minimize energy consumption, while keeping thermal comfort range.
- **Re-planning**:
    - Temperature change > 3° C
    - Occupation fluctuation >= 3



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AI Planner
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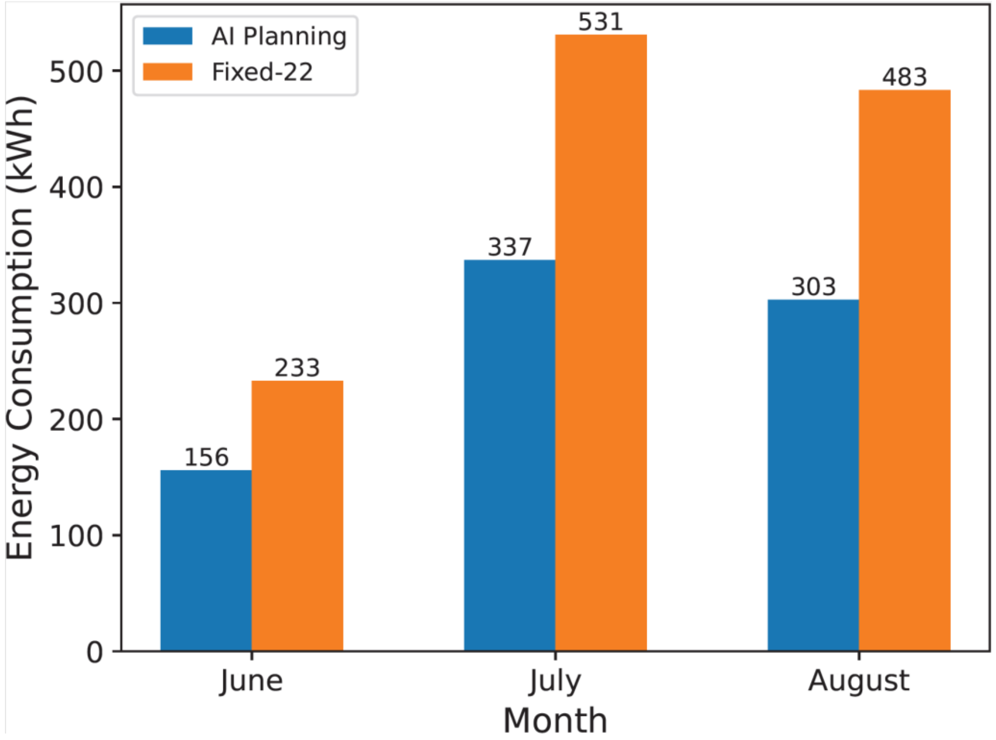
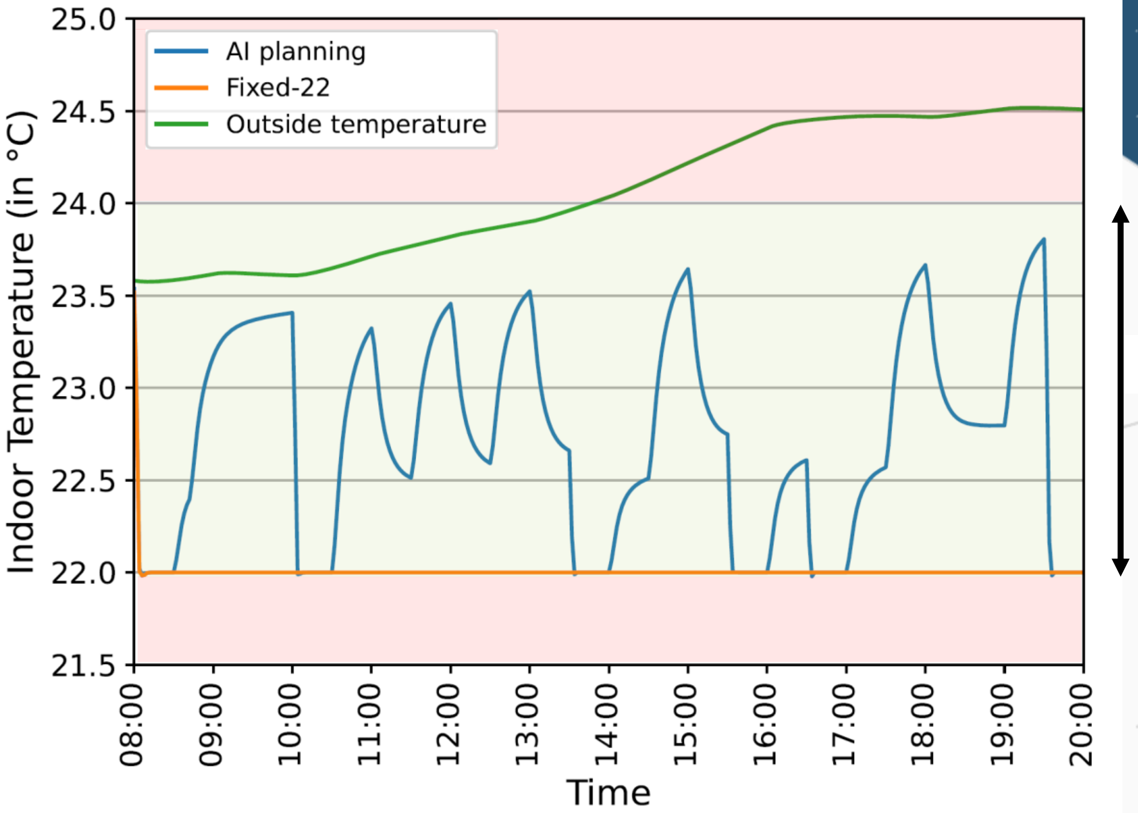
Experimental Results

Up to 35% savings in energy consumption



Total energy consumption per month

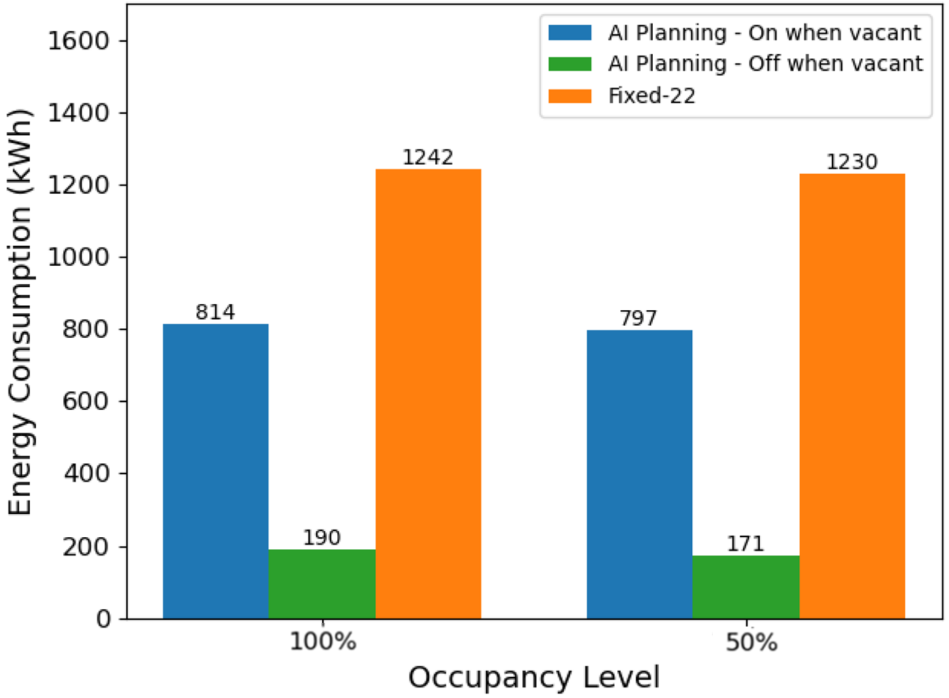


thermal comfort range

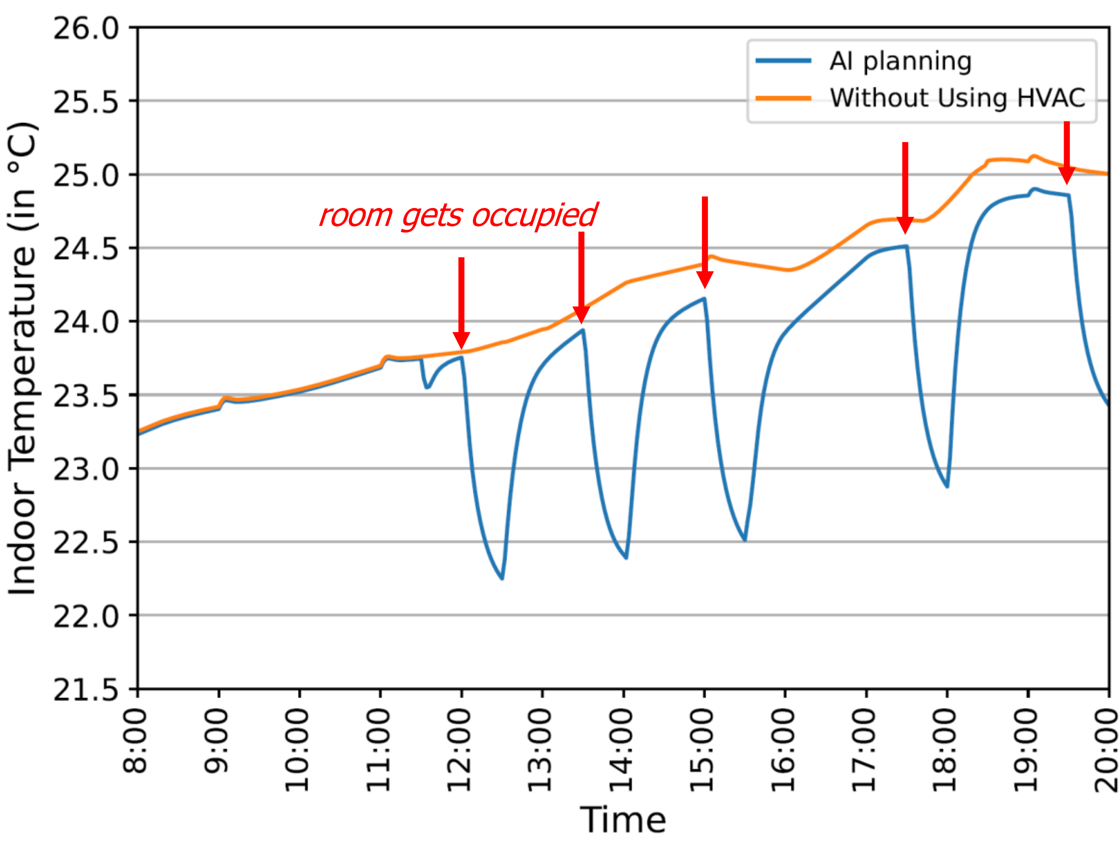
Temperature variations throughout the day

Experimental Results: Energy-Constrained Setting

Up to 77% savings in energy consumption



Total energy consumption per occupancy level



Indoor temperature variations throughout the day

Key Takeaways and Future Directions

- We propose an AI planning-based approach for efficient scheduling of energy systems.
- **AI planning techniques** are used to schedule energy systems operations and adapt such schedules in dynamic situations.
- The experimental results show that our can **reduce energy consumption of HVAC systems by up to 30**% and adapt to different situations.
- Expand our approach to include **various optimization needs** of building administrators and **compliance with country regulations**.
- Implement our approach in **real-life settings** involving hydropower plants in the context of the Di-Hydro EU project[1].

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[1] https://dihydro-project.eu

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