Towards an Indoor Environmental Quality Management Ontology

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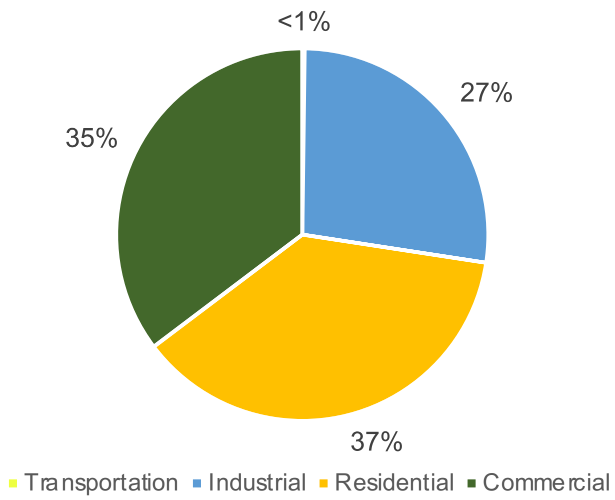
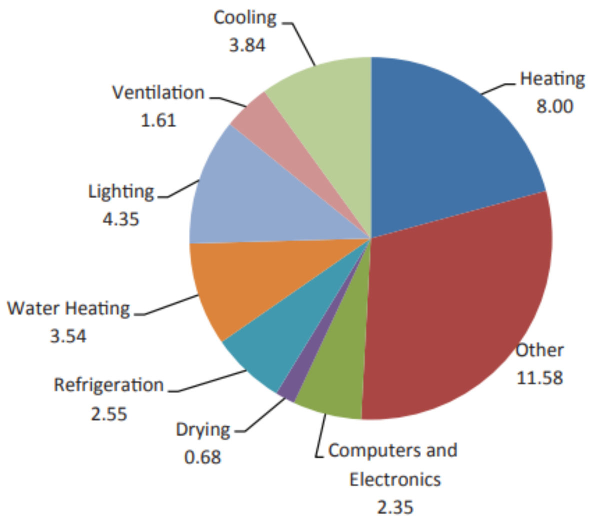
What is the Problem?

U.S. Electricity Consumption by Sector in 2013 [1]



2014 Residential and Commercial Building Primary Energy Use (Quads)[2]

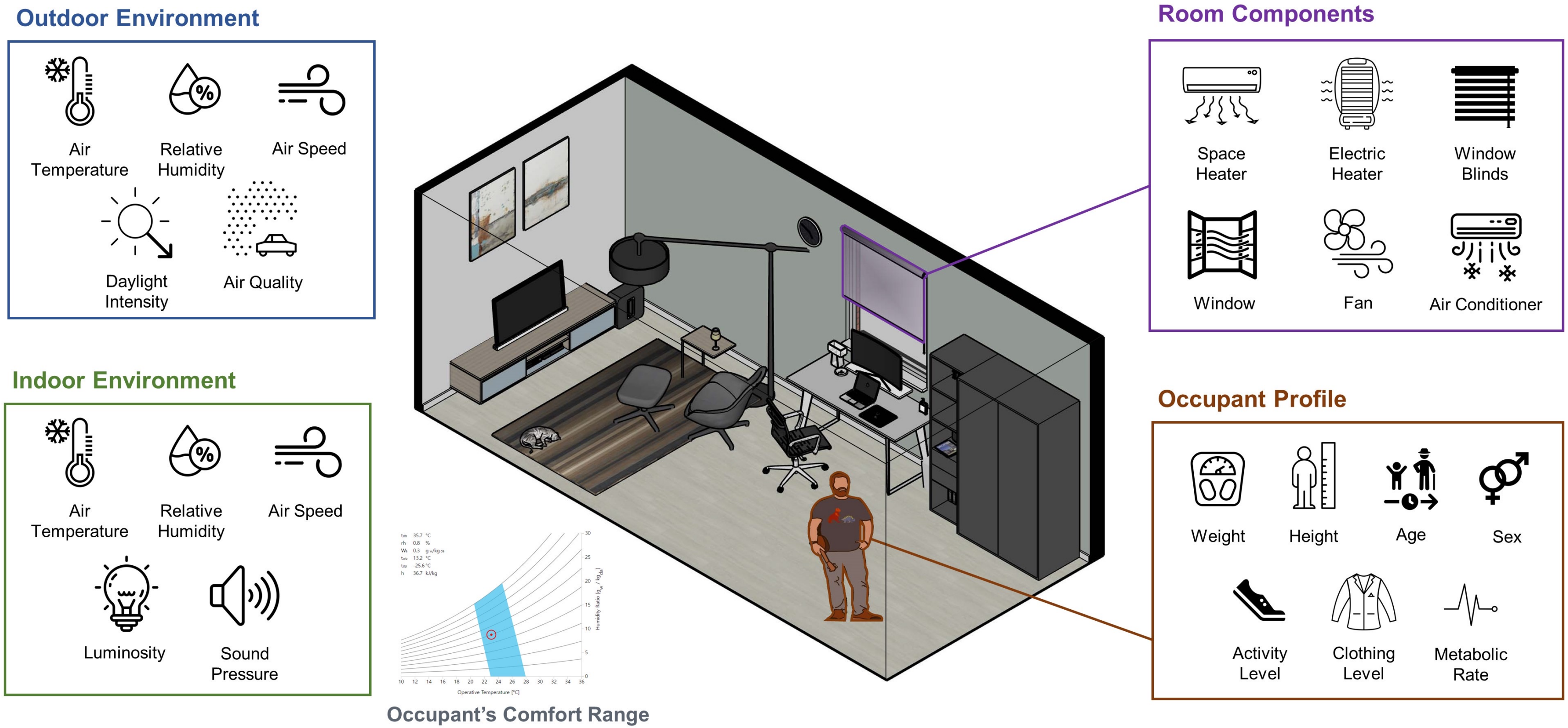


Energy use in Heating, Cooling, Ventilation, Lighting accounts for **46.2%**

[1] US Energy Information Administration. "Electricity Customers", available at https://www.epa.gov/energy/electricity-customers
[2] US Energy Information Administration. "Quadrennial Technology Review 2015", available at https://www.energy.gov/sites/prod/files/2017/03/f34/qtr-2015-chapter5.pdf

What is IEQ Management Ontology?

* IEQ: Indoor Environmental Quality



Overview of Project

Problem:

- Occupants’ indoor comfort is affected by too many factors, including indoor and outdoor environment
- Each occupant has different clothing and characteristics and differently feel comfortable under the same indoor environment
- Potential solutions — air conditioners, electric heaters, window blinds, etc. — have an influence on IEQ in different ways

Scope:

- **The scope of this use case is limited to a small room that one to four people can use.**
- In the case of low IEQ, **this ontology can suggest a solution to improve IEQ by increasing or decreasing environmental parameters**.
- This system cannot automatically manipulate opening/closing windows, turning on/off HVAC systems, etc.
- **This system doesn’t include 3D geometries, fluid dynamics, and thermodynamic simulations to understand precise effects of room components depending on their locations**.
- The system cannot apply to large spaces where indoor environmetnal parameters differ depending in different points

What: **IEQ management ontology to recommend how to manipulate room components for improving IEQ in a room and minimizing building energy use**

Why: Commercial and residential buildings consumed 93% of electric energ in the end-use section in 2021, and 46.2% of energy use in buildinygs was for heating, cooling, ventilation, and lighting in 2014. This energy is used for enhancing Indoor Environmental Quality.

How: An ontology was developed based on the Predicted Mean Vote (PMV) model and Air Quality Index (AQI) to quantify IEQ and suggest viable solutions.

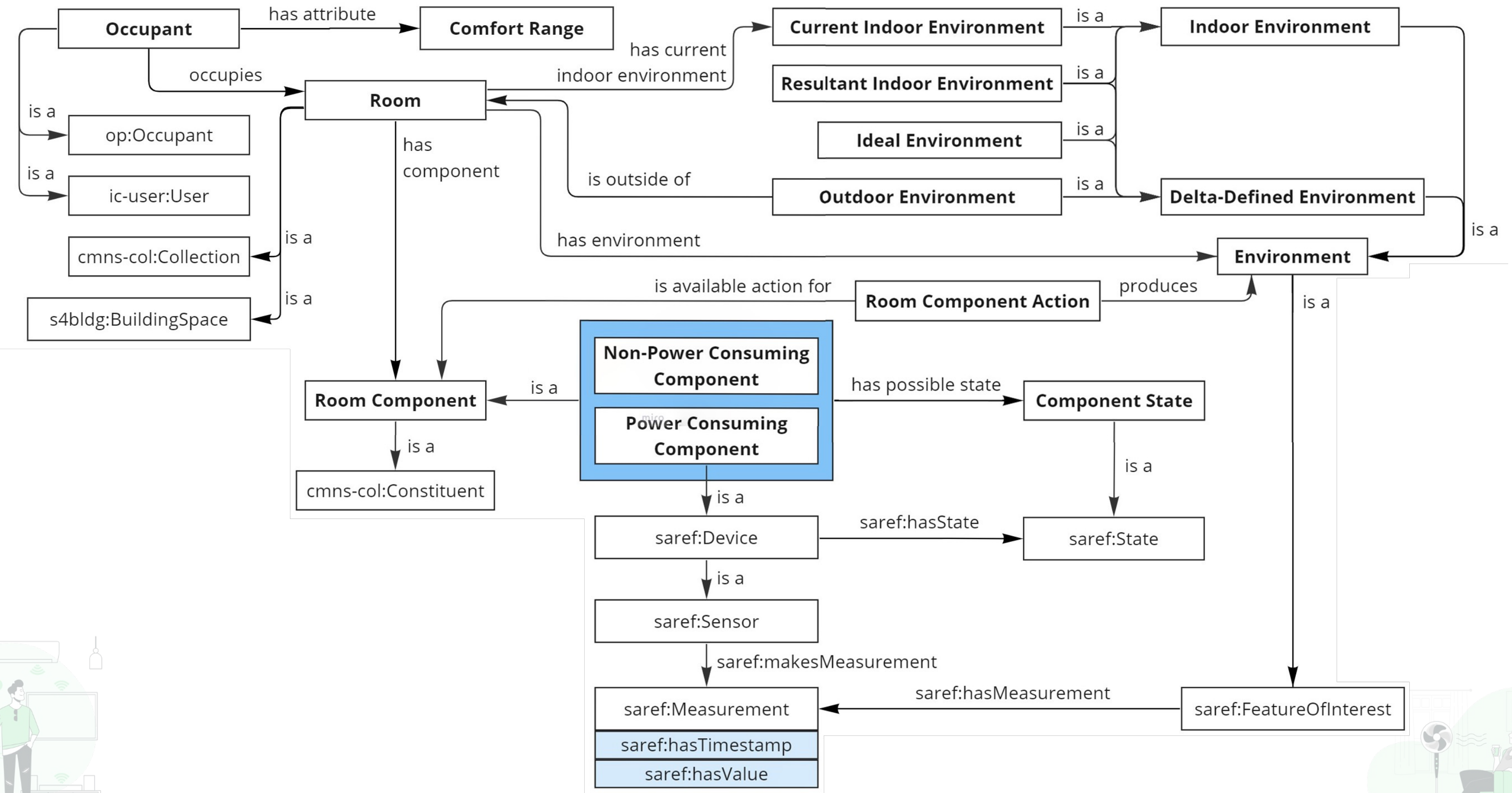
Related Works

Category	Description	Limitations	References
Energy Management	Mainly identifies inefficient energy consumption patterns and provides advice to improve energy efficiency in buildings	Considers only energy consumption, and doesn't concern occupants' comfort	Shah et al. [3], Lork et al. [4], Wicaksono et al. [5], Pruvost et al. [6], Tomašević et al. [7], Li and Hong [8], Hong et al. [9], and Hong et al. [10]
Post-Occupancy Evaluation	Mainly assess requirements of the building standards, such as LEED, BREEAM, or the WELL building standard, after occupants have used for some time period	Doesn't consider occupants' information for evaluating their comfort	Zhao et al. [11] and Zhao and Yang [12]
Indoor Environmental Quality	Mainly evaluate indoor air quality, occupants' thermal comfort, visual comfort, and acoustic comfort	Doesn't consider different occupants' information or suggest any action to meet their comfort requirements	Nolich et al. [13], Adeleke and Moodley [14], Spoladore et al. [15], Chen et al. [16], Spoladore et al. [17], Nguyen et al. [18], and Esnaola-Gonzalez et al. [19]

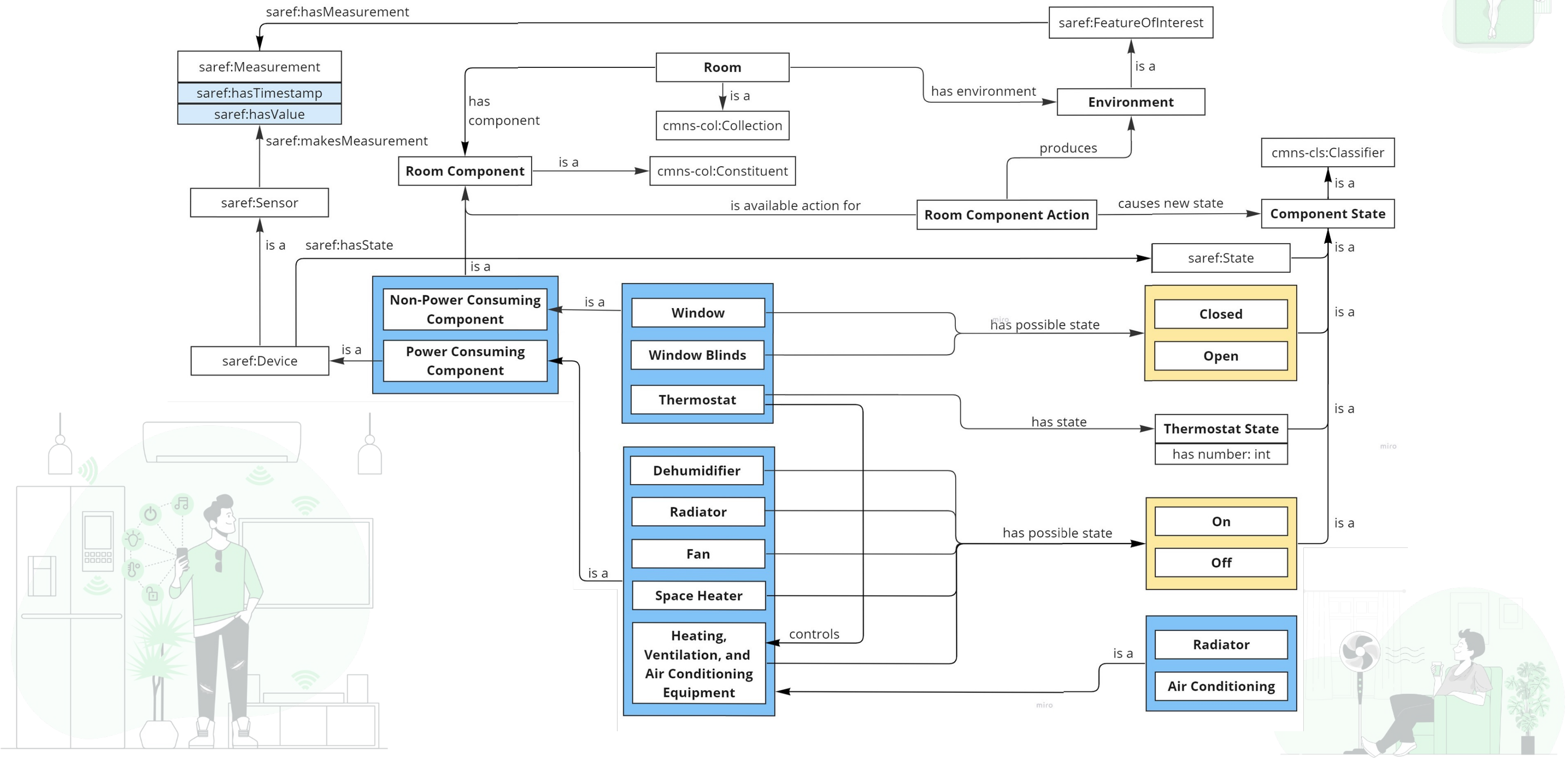
Related Works

Concepts	Our IEQ ontology	RoomFort [15]	Adeleke and Moodley [14]	Nolich et al. [13]	EEPSA [19]
Temperature & Humidity	**O**	O	O	O	O
Air Speed	**O**	X	X	X	X
Luminosity	**O**	O	X	O	O
Air Quality	**O**	O	O	X	O
Occupant Profile	**O** (age, gender, sex, weight, and height)	X	X	O (age and gender)	X
Multiple Occupants	**O**	X	X	X	X
Activity Level	**O** (quantified activity level)	O (“relax” or “concentration”)	X	O (“sleeping”, “reading”, or “light”)	O
Energy Consumption	**O** (Only considering power-consuming/non-power-consuming component)	X	X	O	O
Suggesting Actions	**O** (for power-consuming/non-power-consuming component)	X	O (Only for HVAC)	X	X

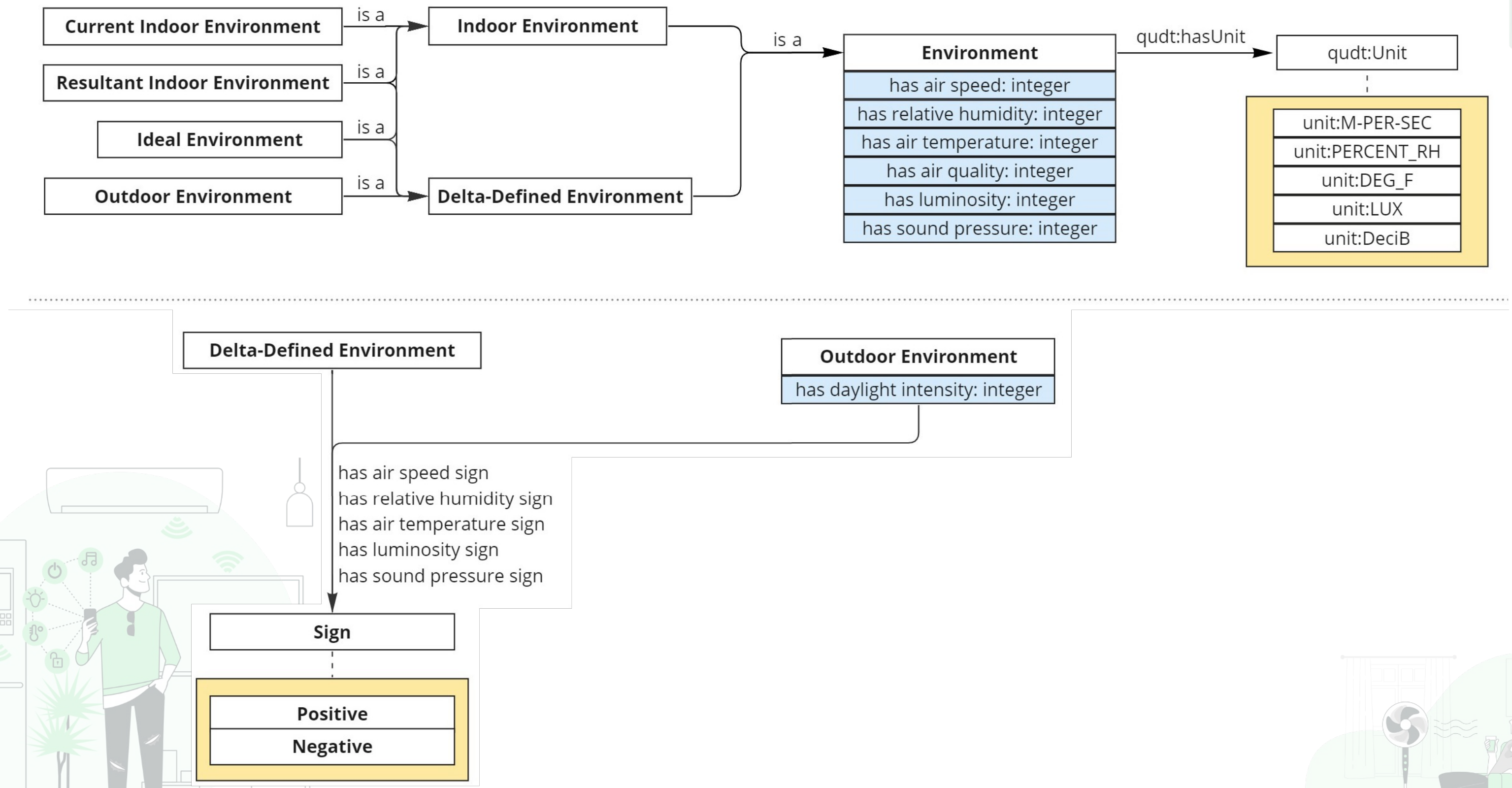
Conceptual Model: High-Level Diagram

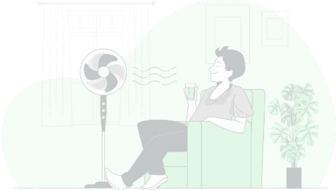


Conceptual Model: Room Component Diagram

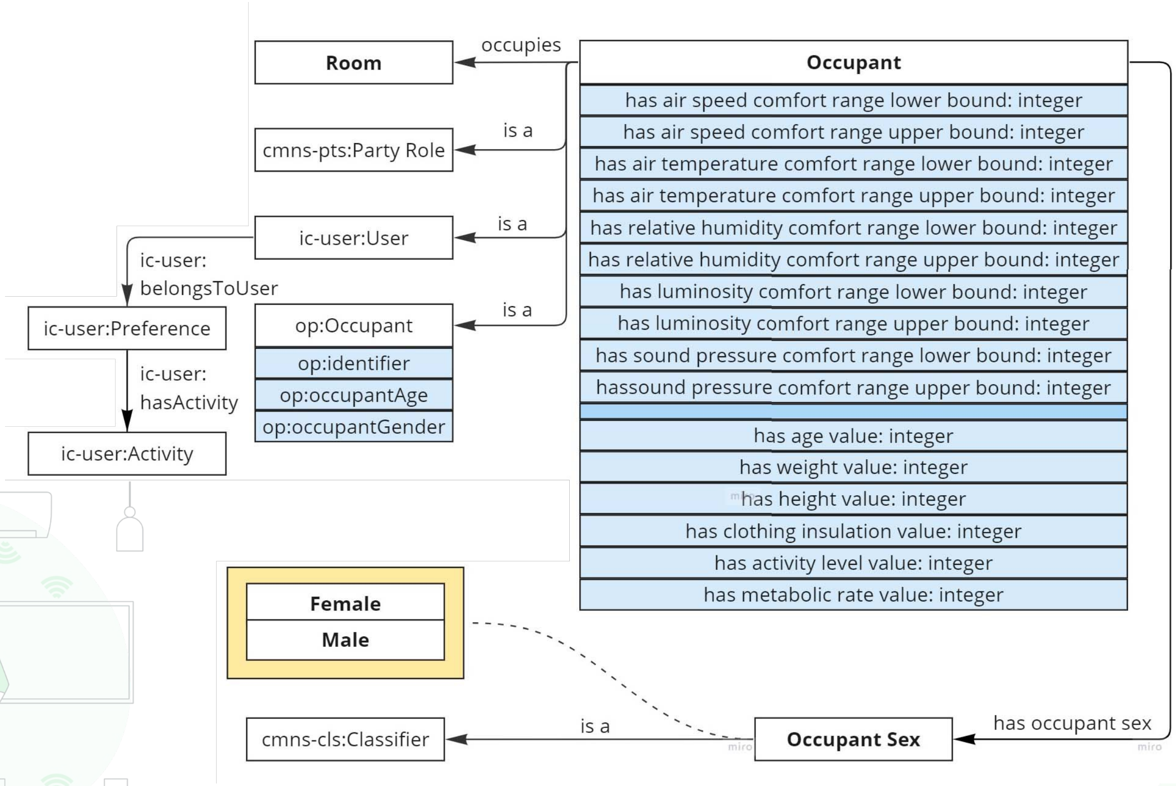


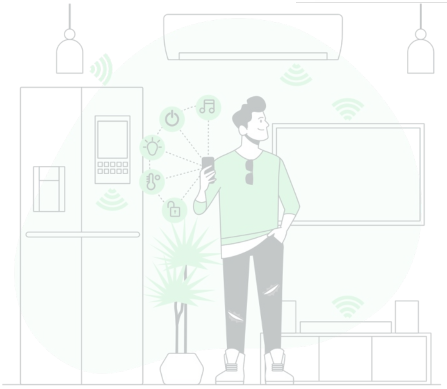
Conceptual Model: Environment Diagram

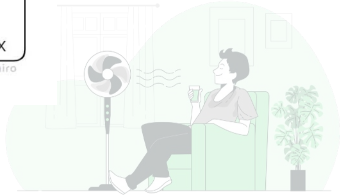




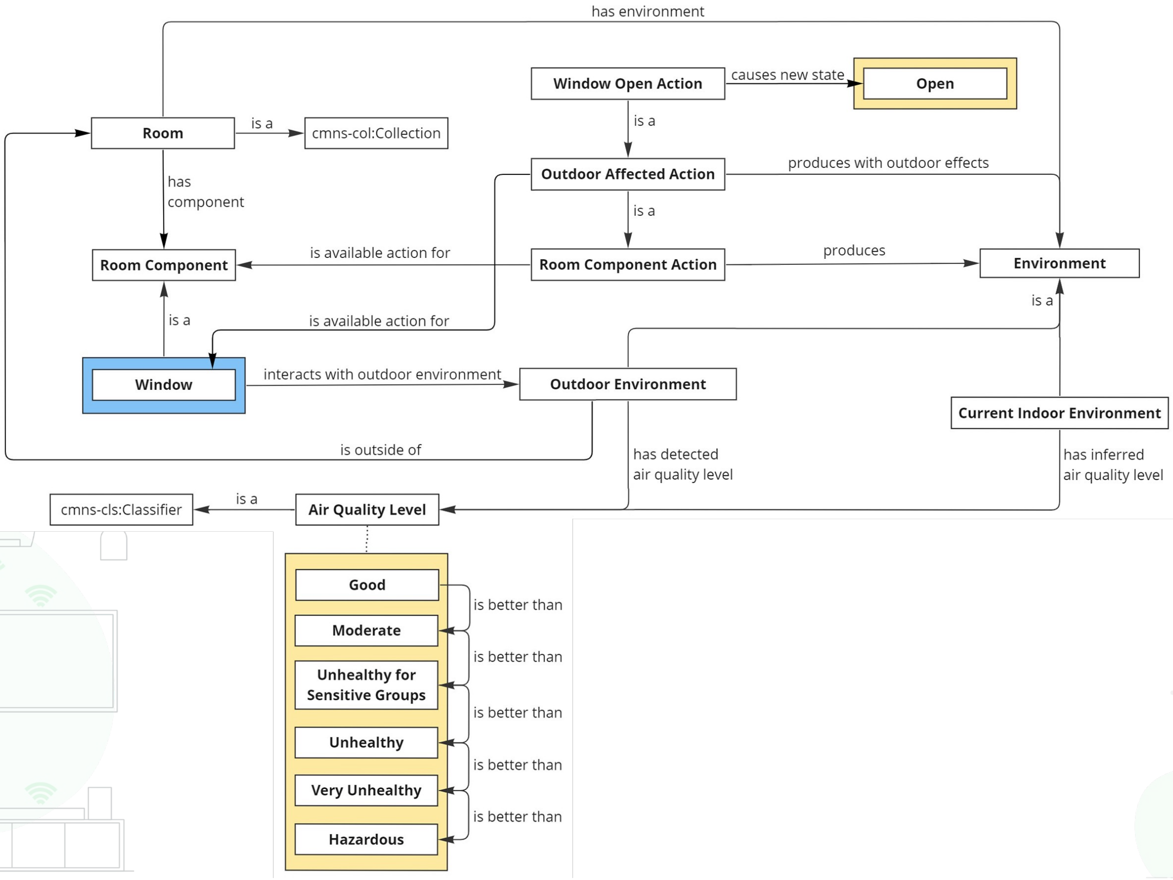
Conceptual Model: Occupant Diagram



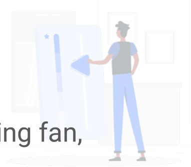




Conceptual Model: Air Quality Diagram



Competency Question 4



- Indoor air temperature: 85℉
- Indoor relative Humidity: 67%
- Indoor air speed: 0.8m/s
- Available room components: window blinds, ceiling fan, window (opened), dehumidifier

Question: **What IEQ parameters, such as temperature, humidity, airflow, etc., make the multiple occupants feel comfortable in a living room during summer?**

Parameters:

Occupant 1) Daughter (Blue area)
26-year-old female
typing something on her laptop (metabolic rate: 1.1)
Long-sleeve coveralls, t-shirt (0.72 clo)
Comfort range of temperature/humidity: 78~86℉, 0~38%

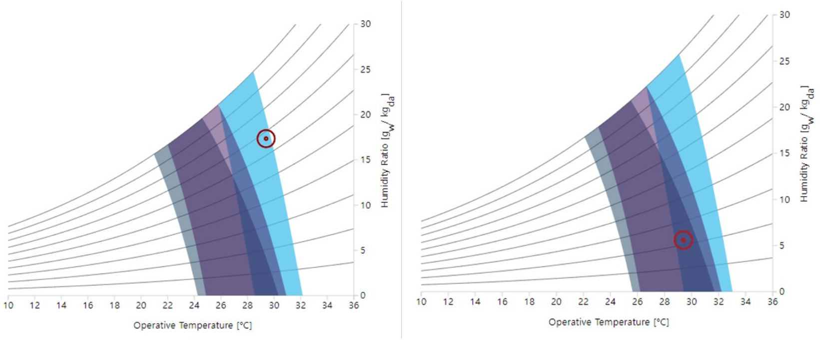
Occupant 2) Mother (Grey area)
59-year-old female
dancing (metabolic rate: 3.4)
Long-sleeve coveralls, t-shirt (0.72 clo)
Comfort range of temperature/humidity: 69~80℉, 0~38%

Occupant 3) Son (Purple area)
32-year-old male
cleaning the house (metabolic rate: 2.7)
Long-sleeve coveralls, t-shirt (0.72 clo)
Comfort range of temperature/humidity: 70~82℉, 0~38%

Sample Answer from Ontology: Turn on the fan and dehumidifier

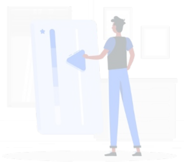
Reasoning:

The three people have gaps in comfort ranges of temperature and humidity due to the different activity levels, and the current air temperature and relative humidity are only in the daughter's comfort zone. If the air speed is 1.6m/s and the relative humidity is 22%, IEQ will meet the three people's comfort requirements. Thus, turning on the dehumidifier and fan is more appropriate.



Psychrometric Chart before turning on equipment (left, air-speed: 0.8m/s, humidity: 67%) and after turning on (right, air-speed: 1.5m/s, humidity: 22%)

Competency Question 4



SPARQL Query

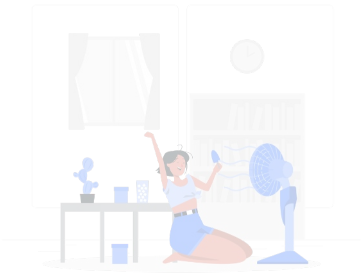
```
SELECT DISTINCT ?airSpeedRoomComponent ?airSpeedNewState ?relativeHumidityRoomComponent
?relativeHumidityNewState WHERE {
            ?airSpeedRoomComponent iem:isComponentOf ind:Question4Room .
            ?airSpeedRoomComponent iem:hasAvailableAction ?airSpeedAction .
            ?airSpeedAction iem:causesNewState ?airSpeedNewState .
            ?airSpeedAction iem:produces ?airSpeedResultantEnvironment .
            ?airSpeedResultantEnvironment iem:hasAirSpeedSign ?airSpeedSign .
            ind:Question4EnvironmentTarget iem:hasAirSpeedSign ?airSpeedSign .

            ?relativeHumidityRoomComponent iem:isComponentOf ind:Question4Room .
            ?relativeHumidityRoomComponent iem:hasAvailableAction ?relativeHumidityAction .
            ?relativeHumidityAction iem:causesNewState ?relativeHumidityNewState .
            ?relativeHumidityAction iem:produces ?relativeHumidityResultantEnvironment .
            ?relativeHumidityResultantEnvironment iem:hasRelativeHumiditySign ?relativeHumiditySign .
            ind:Question4EnvironmentTarget iem:hasRelativeHumiditySign ?relativeHumiditySign .
}
```

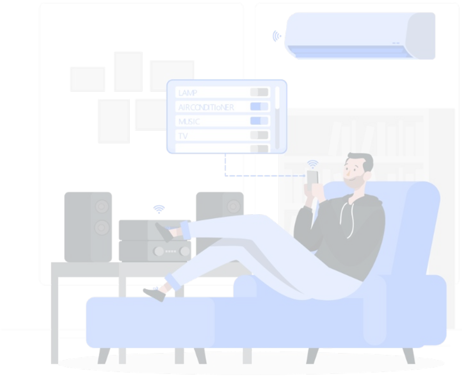
Example Result

?airspeed RoomComponent	?airSpeedNewState	?relativeHumidity RoomComponent	?relativeHumidity NewState
ind:Question4Fan	iem:On	ind:Question4Dehumidifier	iem:On

Multiple Metrics

- A single query can find combinations of multiple actions
  - Each action affects exactly one IEQ metric
- Query is written with desired metrics in mind
- Some limitations…
  - Doesn’t support multi-metric actions
  - Doesn’t support multiple actions for the same metric





Competency Question 5

Question: What IEQ parameters, such as temperature, humidity, airflow, etc., make the multiple occupants feel comfortable in a gym?

Parameters:

Occupant 1) Jason (Blue area)
22-year-old male
walking on a treadmill lifting 45kg bars (metabolic rate: 4.0)
wearing shorts & short-sleeve shirt (0.36 clo)
Comfort range of air speed: 0.5~2.8m/s

Occupant 2) Bob (Grey area)
44-year-old male
seated with heavy limb movement (metabolic rate: 2.2)
wearing typical summer indoor clothing (0.5 clo)
Comfort range of air speed: 0.3~3.8m/s

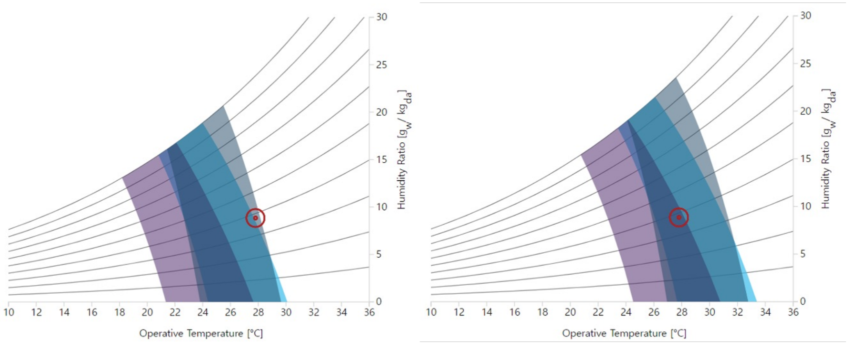
Occupant 3) Sarah (Purple area)
52-year-old female
walking on a treadmill with 3 mph (metabolic rate: 3.8)
wearing a short-sleeve shirt (0.57 clo)
Comfort range of air speed: 1.3~4m/s

- Outdoor air speed: 2m/s
- Outdoor air quality index: 38, “Good”
- Indoor air speed: 0.3m/s
- Available room components: air conditioner, window

Sample Answer from Ontology: Open the windows

Reasoning:

Only Bob feels comfortable in the gym. Outdoor air-speed (2m/s) is faster than indoor air-speed (0.3m/s). In addition, outdoor air quality is good, and opening windows (NonPowerConsumingComponent) can be a better option than turning on the air-conditioner (PowerConsumingComponent) in terms of energy use. If the window is opened, and the air-speed becomes 1.6m/s, all the occupants can feel comfortable



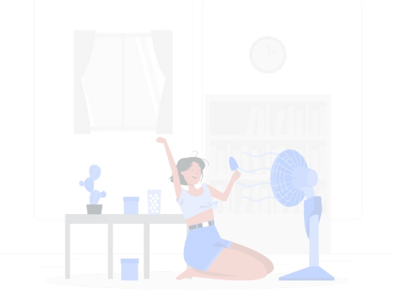
Psychrometric Chart before Opening Windows (left, air-speed: 0.3m/s) and after Opening Windows (right, air-speed: 1.6m/s)

Competency Question 5

SPARQL Query

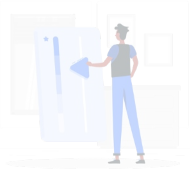
```
SELECT DISTINCT ?airSpeedRoomComponent ?airSpeedNewState WHERE {
            ?airSpeedRoomComponent iem:isComponentOf ind:Question5Room .
            ?airSpeedRoomComponent iem:hasAvailableAction ?airSpeedAction .
            ?airSpeedAction iem:causesNewState ?airSpeedNewState .
            ?airSpeedAction iem:produces ?airSpeedResultantEnvironment .
            ?airSpeedResultantEnvironment iem:hasAirQualityLevel iem:AirQualityLevelGood .
            ?airSpeedResultantEnvironment iem:hasAirSpeedSign ?airSpeedSign .
            ind:Question5EnvironmentTarget iem:hasAirSpeedSign ?airSpeedSign .
}
```

Example Result

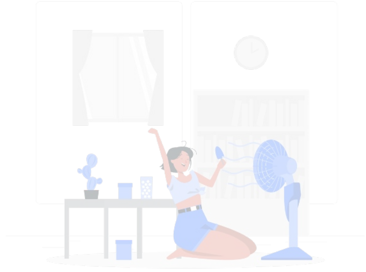


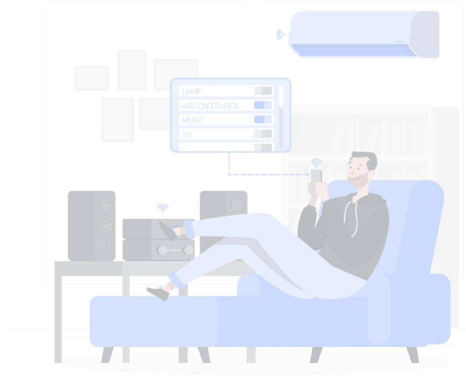
?airSpeedRoomComponent	?airSpeedNewState
ind:Question5Window	iem:Open

Heuristics

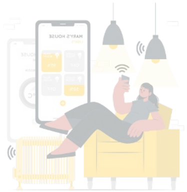


- Reasoning lets us filter out bad suggestions per declared criteria
  - For example, the fact that opening a window is a bad suggestion when there's hazardous air quality outside can be deduced by a reasoner
- Some heuristics could be written into the queries
  - For example, actions could be sorted by energy usage

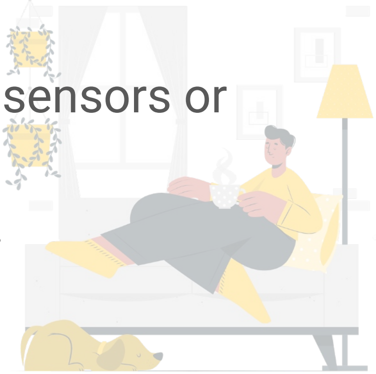




Value of Semantics



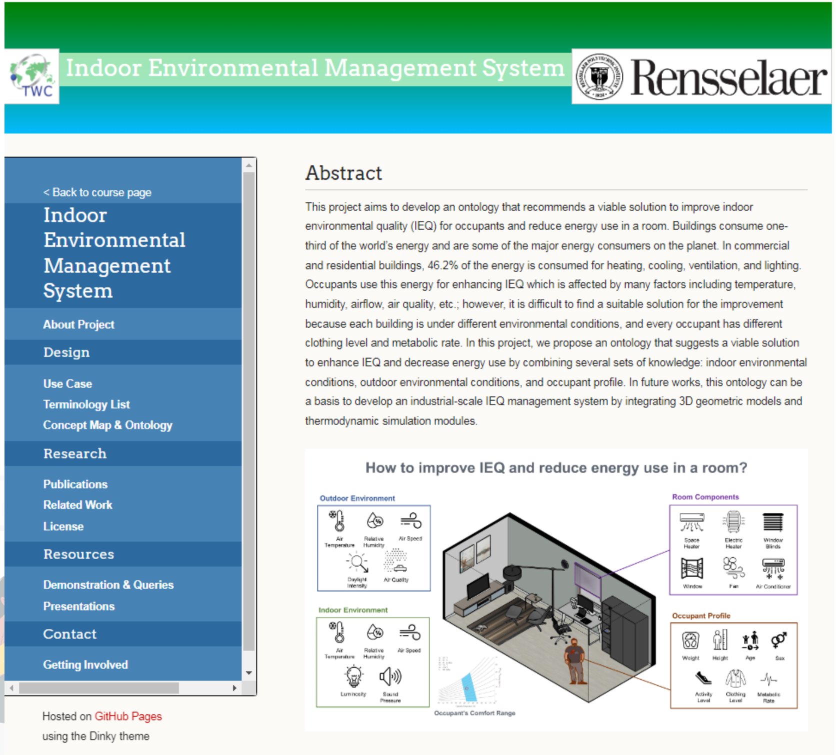
- Enable reasoning
  - Infer new knowledge about resultant/predicted environments
  - Filter out “bad” action suggestions based on declared rules
  - Example: Predict that if the outdoor air quality is “unhealthy”, then opening a window will make the indoor air quality “unhealthy” too, so don’t suggest that the user open a window
  - Easily extensible with new rules and heuristics (both “client” and “server”)
- Extensibility: reducing burden of adoption in smart buildings that already use other ontologies
- Robustness: handling incomplete inputs gracefully from IoT sensors or occupants
- Provenance: explaining why a particular action is suggested.



Conclusion

- Contribution
  - The proposed ontology suggests viable solutions for enhancing occupants’ comfort considering indoor and outdoor environmental conditions and occupant profiles.
  - Unlike the related works, this ontology includes multiple occupant profile concepts to meet their different comfort requirements.
- Limitation
  - **Ideal indoor environment must be declared in terms of a positive or negative delta from the current indoor environment**, and reasoning on precise numeric values is unsupported.
  - **Cannot consider the interrelation between parameters of thermal comfort**, such as air temperature, relative humidity, air speed, clothing insulation, and activity level
  - This model assumes that indoor environmental parameters are uniform for all locations in a room, so it could potentially suggest an improper solution if the size of the room is large and the distribution of the air temperature is uneven
- Future Work
  - Current reasoning system using signs will be **expanded to consider precise numeric values** computed outside of the ontology rather than positive or negative delta signs
  - **The ontology will incorporate geometric and thermodynamic reasoning for supporting multiple “sub-environments” and should be able to make suggestions** considering spatial information and thermodynamic simulation, such as moving a fan to be closer to a certain person with lower temperature preferences.

Website for More Detailed Information



URL: https://bit.ly/3RS3Xq7

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