Indoor Environmental Quality Management Ontology

Gabriel Jacoby-Cooper, Jihoon Chung and Kelsey Rook
{jacobg3, chungj11, rookk}@rpi.edu
Rensselaer Polytechnic Institute
Troy, NY USA 12180

Abstract

This project aims to develop an ontology that recommends a viable solution to improve indoor environmental quality (IEQ) for occupants and reduce energy use in a room. Buildings consume one-third of the world's energy and are some of the major energy consumers on the planet. In commercial and residential buildings, 46.2% of the energy is consumed for heating, cooling, ventilation, and lighting. Occupants use this energy for enhancing IEQ which is affected by many factors including temperature, humidity, airflow, air quality, etc.; however, it is difficult to find a suitable solution for the improvement because each building is under different environmental conditions, and every occupant has different clothing level and metabolic rate. In this project, we propose an ontology that suggests a viable solution to enhance IEQ and decrease energy use by combining several sets of knowledge: indoor environmental conditions, outdoor environmental conditions, and occupant profile. In future works, this ontology can be a basis to develop an industrial-scale IEQ management system by integrating 3D geometric models and thermodynamic simulation modules.

Introduction

According to reports written by the U.S. Energy Information Administration, commercial and residential buildings consumed 93% of electric energy in the end-use section in 2021[1], and 46.2% of energy use in buildings was for heating, cooling, ventilation, and lighting in 2014[2]. This energy is used for enhancing Indoor Environmental Quality (IEQ), which refers to a perceived experience of the building's indoor environment including thermal comfort, indoor air quality, acoustics, and control systems [3].

In a room, IEQ is affected by many factors: air temperature, mean radiant temperature, relative humidity, airflow, air quality, clothing, human activity, or an occupant's profile [4-5]. The problem is that different buildings are under different environmental conditions including weather, outdoor air quality, direction and location of the building, etc., and each occupant has different clothing and occupant profiles, which address their personal environmental preferences. Furthermore, potential solutions — air conditioners, electric heaters, window blinds, windows, doors, fans, etc. — have an influence on IEQ in different ways. For instance, an electric heater and a space heater both increase air temperature (at least in the right external conditions, which can be broadly considered in the knowledge base and the ontology by integrating weather API data); however, the electric heater doesn't affect humidity, unlike the space heater.

In this project, we aim to develop an ontology that finds a viable solution to improve IEQ for occupants while minimizing energy use in a room by combining several sets of knowledge: 1) indoor environmental conditions including air temperature, relative humidity, air speed, 2) outdoor environmental condition, such as outdoor air quality and daylight intensity, and 3) occupant profile including sex, height, weight, age, clothing level, and activity level.

A user will inform the IEQ management system of what quantifiable IEQ factors—thermal comfort and air quality—are currently causing them discomfort and to what degree, and the system will suggest the method for bringing those factors into an acceptable range. The user can manually enter their desired temperature and humidity ranges, or the system can infer them through the PMV model based on sensor data as well as other information that the user provides, including occupant profile descriptions.

As solutions to improve IEQ, several types of equipment affect thermal comfort in different ways: 1) fan increases air speed, 2) electric heater and space heater increase air temperature, 3) dehumidifier decreases humidity, 4) air conditioner decreases air temperature, and 5) window blinds decrease the air temperature. The following section will describe how the ontology can be used to find a viable solution and to improve IEQ.

Use Case

The goal of this ontology is to provide suggestions to improve IEQ in a room based on indoor and outdoor environments and occupant profiles. To evaluate IEQ, this ontology is based on the Predicted Mean Vote (PMV) model standardized by ISO and Air Quality Index (AQI) established by the US EPA. For the calculation, the PMV index requires air temperature, air speed, relative humidity, clothing level, and metabolic rate [6-7]; the metabolic rate requires activity intensity, age, sex, height, and weight [8]; the AQI is calculated based on concentration of ozone (O_3), particulate matter (PM), carbon monoxide (CO), sulfur dioxide (SO_2), and nitrogen dioxide (NO2) [9]. The scope of this use case is limited to a small room that one to three people can use. The target population of this application is individuals who regularly occupy the room. This use case is designed for users (specifically occupants of the building) or facility managers, and the language must be understandable to laypeople. If room occupants input their demographic information, the system is able to suggest a solution about what room components they should manipulate to increase/decrease IEQ parameters. If non-power-consuming components are available, it gives priority to them rather than power-consuming components to minimize energy consumption. This system cannot automatically manipulate opening/closing windows, HVAC systems, electric heaters, etc. In addition, this system doesn't include 3D geometries, fluid dynamics, and thermodynamic simulations to understand different effects depending on the locations of the room components. Therefore, it is unable to apply to large spaces where comfort factors, such as temperature and humidity, are different depending on the location of occupant seats.

To specify the scope of our ontology and essential functionality, we focused on several usage scenarios involving indoor and outdoor environmental conditions and occupants' demographic information. Based on their requirements from these scenarios, we further developed the key concepts and relations necessary in our ontology.

Further detailed information about the use case can be found in our use case document.

Technical Approach

We aim to create a system that, given a small room containing specified environment-affecting components as well as the demographic information for up to several occupants, will suggest an action to take that will increase the overall comfort of the occupants. Our ontology supports this reasoning by connecting a room and its components, occupants, and environment.

Ontology Overview

Figure 1 shows how the most important high-level resources are connected in our ontology. Central to our project is a *Room*, which has *Room Components*— objects in the room that have some effect on the room's environment— and one or more *Occupants*, which have various characteristics from which we may calculate a comfort range. *Room components* are either power-consuming or non-power-consuming, with priority given to actions that use *Non-Power Consuming Components* during action recommendations. Each *Room Component* has multiple possible *Component States* and *Component Actions*; each action produces a new *component state*, as well as a different *Environment*. Additionally, each *Room* has one or more associated environments, including *Indoor Environments*, which refer to the *Current Indoor Environment* and some set of possible indoor environments, and *Delta-Defined Environments*, which are Environments defined by their difference from some other Environments. The *Current Indoor Environment* is defined in absolutes, while *Resultant Indoor Environments* are also *Delta-Defined Environments.* One *Ideal Environment* should exist, representing some environment that satisfies the comfort needs of the occupants as closely as possible. An *Outdoor Environment* is some environment associated with an *Indoor Environment* such that there is some influence on the *Indoor Environment* that can be exerted by opening a *Window*. (A future expansion might extend the modeling of indoor-outdoor influence to air conditioners or other relevant room components.) This *Outdoor Environment* is expressed as the difference from the *Current Indoor Environment*, as its effect on the *Indoor Environment* is dependent on whether it has a negative or positive difference from the *Indoor Environment*'s attributes.

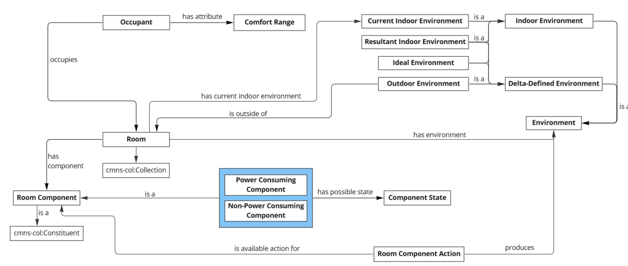

Figure 1: Ontology Overview Diagram

Room Component

Figure 2 shows, in more detail, what *Room Components* are considered in our system as well as their possible states. Each *Room Component Action* is associated with a particular *Room Component*, causes the component to have a new *Component State*, and produces a new *Environment*— specifically a *Resultant Environment*, defined in terms of the change the *Room Component Action* produces.

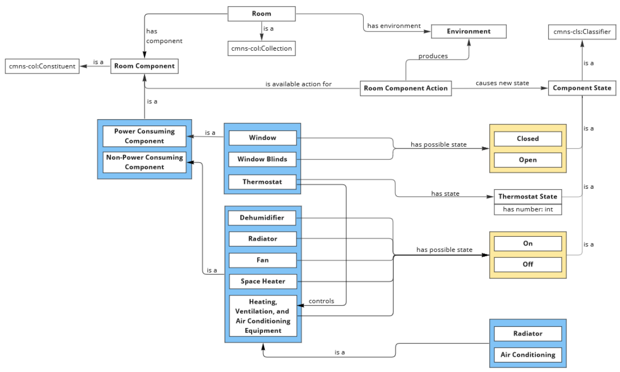

Figure 2: Room Component Diagram

Environment

Figure 3 reiterates the various subclasses of *Environment* created in our ontology, as well as a clarification of the attributes each type of *Environment* should have. The *Current Indoor Environment* is defined in absolute terms of air speed, relative humidity, and air temperature. The *Outdoor Environment* associated with an *Indoor Environment* has its air speed, humidity, and temperature defined in relative terms, but also has two absolute attributes, air quality, and daylight intensity, which are so defined because of the assumption that the default *Indoor Environment* air quality is Good, and lack of daylight will never affect air speed and humidity, or decrease indoor temperature. The remainder of *Outdoor Environment* attributes, as well as *Resultant* and *Ideal Indoor Environment* attributes, are, for the scope of this project, described in general terms as having a *Positive* or *Negative* difference from the *Current Indoor Environment*.

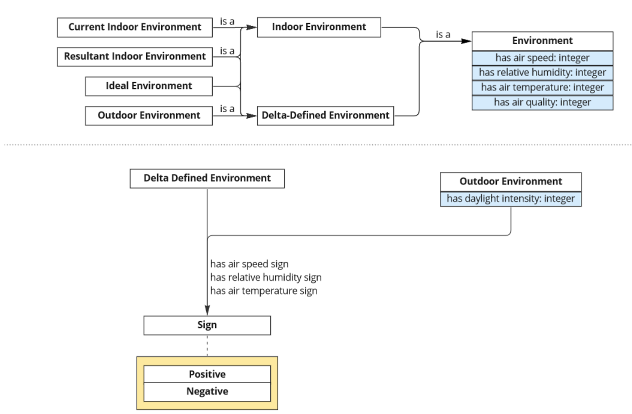

Figure 3: Environment Diagram

Outdoor Air Quality

Figure 4 shows how our ontology models the relationship between outdoor and indoor air quality, which is a special case: while turning some components on and off will be one-to-one with an increase or decrease in some environment attribute, actions that allow an *Outdoor Environment* to start or stop affecting the *Current Indoor Environment* depend on the status of the *Outdoor Environment* to determine what the *Resultant Indoor Environment* will be. To infer such a result, we use a specific *Outdoor Affected Action*, which takes into account some *Outdoor Environments* to produce a *Resultant Indoor Environment* with an inferred *Air Quality Level*.

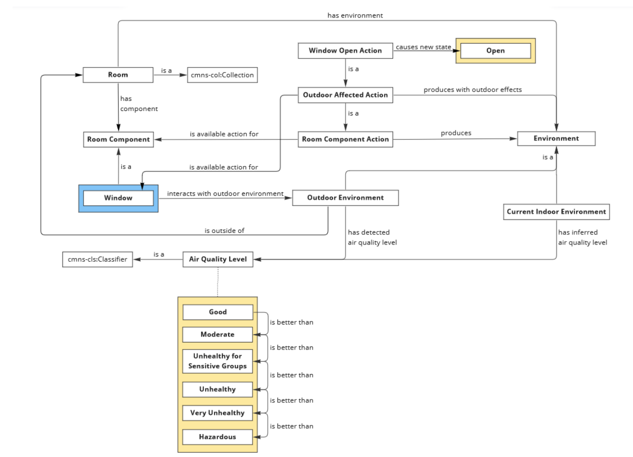

Figure 4: Air Quality Diagram

Occupants

Figure 5 shows the attributes associated with an Occupant in our ontology. Each Occupant occupies exactly one room and has associated data attributes from which their ideal environments can be calculated, externally to the ontology, in multiple optional ways.

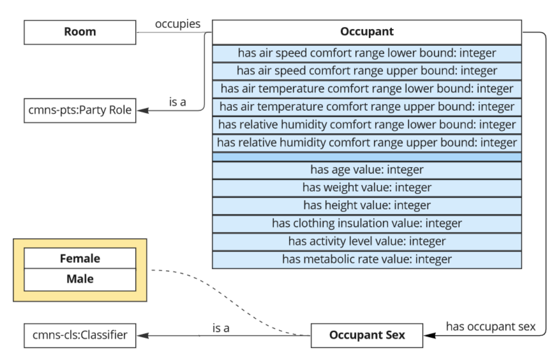

Figure 5: Occupant Diagram

Justification

The ontology is structured primarily to support specific types of queries and secondarily to model the domain in a more general manner. The prioritization of supporting specific queries means that some of the modeling choices diverge from what would otherwise be most intuitive to a human domain expert. For example, we declare a *"produces with outdoor effects"* object property that relates a *Room Component Action* (the subject) to a *Resultant Indoor Environment* (the object). We say that a *Room Component Action produces with outdoor effects* a *Resultant Indoor Environment* when the action is an *Outdoor-Affected Action*, meaning that some aspect of the relevant *Outdoor Environment* affects the *Resultant Indoor Environment*. Although this object property doesn't intuitively map to any single relation in the real world-a human would probably say that the relevant *Room Component* interacts with the outdoor environment, rather than the production of the *Resultant Indoor Environment*-it permits that the reasoner infers properties about the *Resultant Indoor Environment* based on the detected properties of the relevant *Outdoor Environment*.

Evaluation

For the scope of this project, we designed five competency questions to evaluate the developed ontology. The questions mainly focused on asking a strategy to enhance occupants' comfort by changing given indoor and outdoor environmental parameters. These are complex problems because the occupants' comfort depends not only on indoor environmental parameters but also on occupant profiles. Furthermore, its solution can be different depending on available room components and outdoor environmental parameters as well as the indoor environment.

To demonstrate the ability of our ontology, we performed the assessments by constructing SPARQL queries and verifying the answer to each question. Note that this evaluation is carried out only for assessing the ability to answer the questions through manual inputs, and it does not cover the capability of an IEQ management system using this ontology. Moreover, because ontology reasoners cannot perform arithmetic or numeric comparison, we assume that users either directly input their comfort range or allow it to be calculated using a PMV equation (see Appendix A) but that's all external to the ontology. In this context, 'metabolic rate' indicates the energy produced per unit skin surface area of an individual, which is equal to 58.2W/m². This value depends on an individual's age, sex, weight, height as well as activity level, and it can be estimated based on equations (see Appendix B) 'clo' is a unit indicating the thermal insulation provided by clothing assembles. One 'clo' is equal to 0.155 m2·°C/W [10]. In this project, we assume that users manually input their activity and clothing level based on the standardized data table established by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE, see Appendix C and D).

Competency Question 1

Question: How to meet all requirements of the multiple occupants' comfort ranges in an office room? There are three occupants who prefer temperatures in the range of 73°F to 77°F, 74°F to 78°F, and 75° to 78°F, respectively. All other factors are already ideal. The outdoor temperature is 18°F. The current HVAC thermostat setting is 75°F, which is the current indoor temperature. An electric space heater is available but is currently switched off.

With the latest additions to our main ontology, some of these queries now require nontrivial reasoning. This means that they must be executed in "Snap SPARQL Query" instead of Protégé's built-in SPARQL query feature. Additionally, we're still investigating a problem with running Pellet on our ontology, so we recommend that you activate HermiT before executing a query.

```
SELECT DISTINCT ?roomComponent ?newState WHERE {
    ?roomComponent iem:isComponentOf ind:Question2Room .
    ?roomComponent iem:hasAvailableAction ?action .
    ?action iem:causesNewState ?newState .
    ?action iem:produces ?resultantEnvironment .
    ?resultantEnvironment
iem:hasAirTemperatureSign ?airTemperatureSign .
    ind:Question2EnvironmentTarget
iem:hasAirTemperatureSign ?airTemperatureSign .
}
```

This query shouldn't return any results because in the relevant competency question, the current environment is already ideal. Therefore, no actions need to be suggested or taken.

Example result:

?roomComponent	?newState

Competency Question 2

Question: How should IEQ parameters, such as temperature, humidity, airflow, etc., be changed to make the multiple occupants feel comfortable in a living room during summer? The occupants' profile is a 26-year-old son typing something on his laptop (metabolic rate: 1.1, Long-sleeve coveralls, t-shirt: 0.72 clo, the blue area in Figure 5), a 59-year-old mother dancing (metabolic rate: 3.4, Long-sleeve coveralls, t-shirt: 0.72 clo, the grey area in Figure 5), and a 32-year-old daughter cleaning the house (metabolic rate: 2.7, Long-sleeve coveralls, t-shirt: 0.72 clo, the purple area in Figure 5). The outdoor weather is 89°F, relative humidity is 70%, and outdoor air quality index is 34, 'Good'. Indoor temperature is 85°F and relative humidity is 67%. A fan and a dehumidifier are available.

This query looks for two different actions: one to change the air temperature and one to change the relative humidity. Each action must be available for a particular room component that's, in turn, part of the room individual that's associated with the relevant competency question. The actions are selected by ensuring that they produce respective resultant environments with the same environment attribute delta signs as the target environment.

```
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:

?airSpeedRoomComponent	?airSpeedNewState	?relativeHumidityRoomComponent	?relativeHumidityNewState
ind:Question4Fan	iem:On	ind:Question4Dehumidifier	iem:On

Competency Question 3

Question: In a small gym, three people are working out. 22-year-old male Jason walking on a treadmill lifting 45kg bars (metabolic rate: 4.0, wearing shorts & short-sleeve shirt: 0.36 clo, the blue area in Figure 6), 44-year-old male Bob seated with heavy limb movement (metabolic rate: 2.2, wearing typical summer indoor clothing: 0.5 clo, the grey area in Figure 6), and 52-year-old female Sarah walking on a treadmill with 3 mph (metabolic rate: 3.8, wearing a short-sleeve shirt: 0.57 clo, the purple area in Figure 6). How should IEQ parameters, such as temperature, humidity, airflow, etc., be changed to make the multiple occupants feel comfortable in a gym? Indoor air-speed is 0.3m/s, outdoor air-speed is 2m/s, and outdoor air quality index is 38, 'Good'. An air conditioner is available, and windows are closed.

This query looks for a single action to change the air speed. The action must be available for a particular room component that's, in turn, part of the room individual that's associated with the relevant competency question. The action is selected by ensuring that it produces a resultant environment with the same air speed environment attribute delta sign as the target environment. The query also requires that the resultant environment have a "good" air quality level, which is inferred by the reasoner from the fact that opening a window must produce a resultant environment with the same air quality level as the relevant outdoor environment.

```
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

Competency Question 4

Question: In a room, only one occupant sits on a chair. Is this occupant feel comfortable? The occupant has a preferred temperature range of 72°F to 80°F and a preferred humidity range of 28% to 40%. The room temperature is 75°F and the relative humidity is 55%.

This query corresponds with competency question 6. Given a specific room, it returns the occupants whose corresponding comfort ranges include the environment values and who therefore currently feel comfortable. Since there are no currently comfortable occupants in competency question 6, this query intentionally returns no results.

```
SELECT ?occupant WHERE {
    ?occupant iem:occupies ind:Question6Room .
    ?occupant
iem:hasAirTemperatureComfortRangeLowerBound ?airTemperatureLowerBou
nd .
    ?occupant
iem:hasRelativeHumidityComfortRangeLowerBound ?relativeHumidityLowerB
ound .
    ?occupant
iem:hasAirTemperatureComfortRangeUpperBound ?airTemperatureUpperBou
nd .
    ?occupant
iem:hasRelativeHumidityComfortRangeUpperBound ?relativeHumidityUpperB
ound .
    ind:Question6EnvironmentCurrent
iem:hasAirTemperatureValue ?airTemperatureValue .
    ind:Question6EnvironmentCurrent
iem:hasRelativeHumidityValue ?relativeHumidityValue .
    FILTER(?airTemperatureValue <= ?airTemperatureUpperBound) .
    FILTER(?airTemperatureValue >= ?airTemperatureLowerBound) .
    FILTER(?relativeHumidityValue <= ?relativeHumidityUpperBound) .
    FILTER(?relativeHumidityValue >= ?relativeHumidityLowerBound) .
}
```

Since there are no currently comfortable occupants in competency question 6, this query intentionally returns no results.

Example result:

?occupant

Competency Question 5

Question: In a small office space with three occupants, who are currently comfortable? Occupant 1 has a preferred temperature range of 64°F to 68°F, prefers lower humidity (25% to 35%), and enjoys a light breeze (1 m/s to 2 m/s). Occupant 2 has a preferred temperature range of 70°F to 75°F, is comfortable in varied humidity (30% to 40%), and likes a light to moderate breeze (1 m/s to 3 m/s). Occupant 3 has a preferred temperature range of 68°F to 74°F, is comfortable in most humidity settings (30% to 50%), and prefers no breeze (0 m/s to 1 m/s). The office temperature is 70°F, the relative humidity is 30%, and the air speed is 2 m/s.

This query corresponds with competency question 7. Given a specific room, it returns the occupants whose corresponding comfort ranges include the environment values and who therefore currently feel comfortable.

```
SELECT ?occupant WHERE {
    ?occupant iem:occupies ind:Question7Room .
    ?occupant
iem:hasAirSpeedComfortRangeLowerBound ?airSpeedLowerBound .
    ?occupant
iem:hasAirTemperatureComfortRangeLowerBound ?airTemperatureLowerBou
nd .
    ?occupant
iem:hasRelativeHumidityComfortRangeLowerBound ?relativeHumidityLowerB
ound .
    ?occupant
iem:hasAirSpeedComfortRangeUpperBound ?airSpeedUpperBound .
    ?occupant
iem:hasAirTemperatureComfortRangeUpperBound ?airTemperatureUpperBou
nd .
    ?occupant
iem:hasRelativeHumidityComfortRangeUpperBound ?relativeHumidityUpperB
ound .
    ind:Question7EnvironmentCurrent
iem:hasAirTemperatureValue ?airTemperatureValue .
    ind:Question7EnvironmentCurrent
iem:hasAirSpeedValue ?airSpeedValue .
    ind:Question7EnvironmentCurrent
iem:hasRelativeHumidityValue ?relativeHumidityValue .
    FILTER(?airTemperatureValue <= ?airTemperatureUpperBound) .
    FILTER(?airTemperatureValue >= ?airTemperatureLowerBound) .
    FILTER(?airSpeedValue <= ?airSpeedUpperBound) .
    FILTER(?airSpeedValue >= ?airSpeedLowerBound) .
    FILTER(?relativeHumidityValue <= ?relativeHumidityUpperBound) .
    FILTER(?relativeHumidityValue >= ?relativeHumidityLowerBound) .
}
```

Example result:

?occupant
Question7Occupant2

Discussion

Key Features

Our ontology is designed such that queries can discover available actions that produce the ideal indoor environment and that meet various acceptability criteria. It's available as an RDF file on our website: https://indoor-environment-manager--rpi-ontology-engineering.netlify.app/oe2022/indoor-environment-manager/

Value of Semantics

We use semantics to infer how to change indoor environmental parameters to meet the comfort requirements of multiple occupants. For instance, our ontology can infer air speed should be increased, decreased, or be unchanged based on the different comfort ranges of three occupants. Additionally, the semantics can be utilized to infer whether particular actions are "acceptable" given a set of general rules and heuristics. For example, theontology is designed such that a reasoner can infer that opening a window produces a resultant indoor environment with the same air quality level as the relevant outdoor environment. A query might then restrict the set of actions that it returns to just those that produce a "good" or "moderate" indoor air quality level. Resultant indoor environments are predicted, not detected in the real world, so a query on a regular database without semantics wouldn't be able to filter out actions that cause unacceptable indoor air quality levels because the necessary information wouldn't be present in the database.

Limitations

Firstly, the most significant limitation of our model is its reliance purely on "sign-based" deltas for air temperature, air speed, and relative humidity. For instance, an ideal indoor environment must be declared in terms of a positive or negative delta from the current indoor environment for each of the three IEQ metrics, and reasoning on precise numeric values is unsupported. Secondly, this ontology cannot consider the interrelation between air temperature, relative humidity, air speed, clothing level, and metabolic rate. For example, an occupant's comfort ranges of air temperature and relative humidity depend on air speed, clothing level, and metabolic rate; however, our current ontology cannot capture this relationship. Thirdly, our model assumes that indoor environmental parameters are uniform for all locations in a room; however, it can suggest an improper solution if the size of the room is large and the distribution of the air temperature is uneven. Future work, which we discuss in a later section of this paper, could include improving the fidelity of the model to be able to reason with qualitative "buckets" or even precise numeric values, but there are significant unsolved challenges to doing this.

Websites

Detailed information can be found on our website. The website contains information pertaining to all the aspects of this project, such as use case documents, terminology lists, conceptual model diagrams, ontology files, SPARQL queries, presentations, and weekly reports. Furthermore, all the previous versions of the artifacts are available on the website.

Relative Work

Over the two decades, in Architecture, Engineering, Construction, Owner, and Operation (AECOO) industries, ontology technologies have been applied to improve building performance or indoor environmental quality. After comparatively analyzing 17 articles, we classified the related works into three categories: energy management, post-occupancy evaluation (POE), and indoor environmental quality (IEQ).

The energy management ontologies mainly aim to improve energy efficiency in buildings. Shah et al. [11] developed an ontology for managing home electrical appliances, which is compatible with Suggested Upper Merged Ontology (SUMO). Lork et al. [12] suggested an ontology for energy optimization in buildings by classifying energy consumption into efficient and inefficient categories. Wicaksono et al. [13] and Pruvost et al. [14] proposed an ontology-based expert system to identify potential efficiency risks and provide users with advice based on the analysis of real-time building operational data. Tomašević et al. [15] proposed an ontology-based facility data model for increasing interoperability among energy management subsystems in accordance with the ISO 50001 standard. Li and Hong [16] developed an EFOnt which is an ontology for providing schemas for building energy flexibility applications and a standardized tool for co-developing knowledge. All the ontologies in this category only dealt with energy efficiency in buildings without occupant's comfort. In the case of Hong et al. [17-18], a framework was developed to represent energy-related occupant behavior consisting of a driver of the behavior, an occupant's need, the occupant's action, and a building system. The main purpose of this framework is to provide standardized data for building simulation tools, and it didn't include concepts for suggesting an action to improve the occupants' comfort in a room.

The POE ontologies evaluate buildings after they have been used for some time based on building assessment standards, such as Leadership in Energy and Environmental Design (LEED), Building Research Establishment Environmental Assessment Method (BREEAM), or WELL building standard. These ontologies concern extensive assessment categories including energy, environment, and occupant comfort; however, they don't consider different occupants' profiles or suggest any action to deal with their discomfort issues [19-20].

The ontologies in IEQ category mainly concern indoor air quality, occupants' thermal comfort, visual comfort, and acoustic comfort. Nolich et al. [21] developed an ontology-based decision-making system for cruise cabin comfort considering passengers' profiles and activities. Adeleke and Moodley [22] suggested an ontology for monitoring indoor air quality and thermal comfort and controlling HVAC systems. Spoladore [23] developed RoomFort ontology to personalize indoor air quality, thermal comfort, and luminous comfort based on guests' needs and activities. Chen et al. [24] proposed an ontology to determine a thermal and acoustic comfort index based on Building Information Modeling (BIM) technology and WELL Building Standard. Spoladore et al. [25] developed Knowledge-Base Home (KBHOme) containing users' health and physical status, and living environment. These five ontologies mainly focused on indoor human comfort but did not include energy consumption concepts. This ontology allows to infer a set of appliances to help elderly or impaired people. Some ontologies concerned both IEQ and building energy use. Nguyen et al. [26] suggested an ontology to classify multiple users' activities in multiple areas based on sensor measurements for building energy and comfort management. Esnaola-Gonzalez et al. [27]

developed Energy Efficiency Prediction Semantic Assistant (EEPSA) ontology to assist data analysts in energy efficiency and thermal comfort in buildings.

In conclusion, based on the analysis of the related works, 17 research articles were categorized into three areas: energy management, POE, and IEQ. The ontologies in the first category were designed to identify inefficient energy consumption patterns and provide advice to improve efficiency; however, they didn't concern occupants' comfort. The POE ontologies mainly focused on meeting the requirements of the building standards; but, they didn't consider different occupants' profiles or suggest actions for improving their indoor comfort. The five ontologies in the IEQ category contained indoor human comfort concepts but didn't concern energy consumption. The other two ontologies included both concepts; however, they didn't consider multiple occupant profiles and suggest any action to enhance their indoor comfort. Multiple occupant profile concepts are necessary to understand their indoor comfort because all occupants have different thresholds for human comfort due to their different metabolic rates and clothing levels, and it is more complex to find the intersection of multiple occupants' comfort ranges than just one's comfort range. Moreover, viable actions for improving comfort should be suggested based on their profiles as well as available room components. In this paper, we focus on developing an ontology that provides advice to improve indoor environmental quality and reduce energy consumption based on occupants' profiles and room components.

Future Work

This semester, we developed an ontology for improving IEQ in a room based on indoor and outdoor environments and occupant profiles. This ontology suggests turning on/off, pulling up/down or opening/closing room components, in order to increase or decrease environmental parameters. To make this project feasible and doable during the semester, we pivoted the scope of the project several times. Firstly, we excluded acoustic and visual comfort concepts from the scope of IEQ to enhance the feasibility. Secondly, 3D geometries and thermodynamic parts were excluded due to their computational complexity. Thirdly, we excluded energy consumption and cost concepts because they required equipment specifications and thermodynamic knowledge. Fourthly, we excluded the PMV calculation in the ontology because we found that Protege didn't support mathematical calculation. Finally, we changed the bucket-based reasoning into sign-based reasoning to make the ontology simpler. After several pivots, we could specify the feasible scope of this project and implement the essential functionality of the ontology. Future work would further develop the ontology to enable the PMV-centered suggestion by considering the interrelation between air temperature, relative humidity, and air speed. Moreover, the excluded scope would be contained for achieving the ultimate goal of this project, which is to improve IEQ including indoor air quality, sound, and visual comfort.

Conclusion

In this project, we developed an ontology that suggests viable solutions for enhancing IEQ in a room considering indoor environmental conditions, outdoor environmental conditions, and occupant profiles. If non-power-consuming components are available, the ontology places a higher priority on them to reduce building energy use. To specify the scope of this project and the essential functionality, we described usage scenarios and competency questions. Based on them, we designed conceptual models focusing on room components, indoor/outdoor environment, and outdoor air quality. Finally, we developed ontology and verify the functionality by answering the competency questions using SPARQL queries. In the future, we further develop to implement PMV-centered suggestions by considering the interrelation between air temperature, relative humidity, and air speed. This ontology can be a basis to develop an industrial-scale of IEQ management system by integrating 3D geometric models and thermodynamic simulations modules.

Acknowledgments

We greatly appreciate our professors Deborah McGuinness' and Elisa Kendall's help and insight during the development of our Indoor Environmental Management System Ontology. Thank you to Jade Franklin and Sola Shirai for providing feedback on our artifacts and presentations. Furthermore, we are thankful to professor Dennis Shelden for sharing his insight with us as a domain expert.

References

[1] US Energy Information Administration. "U.S. energy consumption by source and sector, 2021", available at https://www.eia.gov/totalenergy/data/monthly/pdf/flow/total-energy-spaghettichart-2021.pdf

[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

[3] ASHRAE Terminology. "indoor environment quality (IEQ)", available at https://xp20.ashrae.org/terminology/index.php?term=indoor%20environment%20quality%20(IEQ)

[4] Luo, Maohui, Zhe Wang, Kevin Ke, Bin Cao, Yongchao Zhai, and Xiang Zhou. "Human metabolic rate and thermal comfort in buildings: The problem and challenge." Building and Environment 131 (2018): 44-52.
[5] Hasson, Rebecca E., Cheryl A. Howe, Bryce L. Jones, and Patty S. Freedson. "Accuracy of four resting metabolic rate prediction equations: effects of sex, body mass index, age, and race/ethnicity." Journal of Science and Medicine in Sport 14, no. 4 (2011): 344-351.
[6] Tartarini, F., Schiavon, S., Cheung, T., Hoyt, T., (2020). “CBE Thermal Comfort Tool: online tool for thermal comfort calculations and visualizations”. SoftwareX 12, 100563.
[7] International Organization for Standardization. (2005). “Ergonomics of the thermal environment — Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria (ISO 7730)”. available at https://www.sis.se/api/document/preview/907006/
[8] Hasan, M. H., Alsaleem, F. M., & Rafaie, M. (2016). “Sensitivity analysis for the PMV thermal comfort model and the use of wearable devices to enhance its accuracy”. International High Performance Buildings Conference. Paper 200.
[9] US Energy Information Administration. “Technical Assistance Document for the Reporting of Daily Air Quality – the Air Quality Index (AQI)”, available at https://www.airnow.gov/sites/default/files/2020-05/aqi-technical-assistance-document-sept2018.pdf
[10] Standard, A. S. H. R. A. E. (2017). Standard 55–2017 thermal environmental conditions for human occupancy. Ashrae: Atlanta, GA, USA., available at https://hogiaphat.vn/upload/docs/ASHRAE55-version2017.pdf
[11] Shah, N., Chao, K. M., Zlamaniec, T., & Matei, A. (2011, June). Ontology for home energy management domain. In International Conference on Digital Information and Communication Technology and Its Applications (pp. 337-347). Springer, Berlin, Heidelberg.
[12] Lork, C., Choudhary, V., Hassan, N. U., Tushar, W., Yuen, C., Ng, B. K. K., ... & Liu, X. (2019). An ontology-based framework for building energy management with IoT. Electronics, 8(5), 485.
[13] Wicaksono, H., Dobreva, P., Häfner, P., & Rogalski, S. (2013, September). Methodology to develop ontological building information model for energy management system in building operational phase. In International Joint Conference on Knowledge Discovery, Knowledge Engineering, and Knowledge Management (pp. 168-181). Springer, Berlin, Heidelberg.
[14] Pruvost, H., Wilde, A., & Enge-Rosenblatt, O. (2023). Ontology-Based Expert System for Automated Monitoring of Building Energy Systems. Journal of Computing in Civil Engineering, 37(1), 04022054.
[15] Tomašević, N. M., Batić, M. Č., Blanes, L. M., Keane, M. M., & Vraneš, S. (2015). Ontology-based facility data model for energy management. Advanced Engineering Informatics, 29(4), 971-984.
[16] Li, H., & Hong, T. (2022). A semantic ontology for representing and quantifying energy flexibility of buildings. Advances in Applied Energy, 8, 100113.
[17] Hong, T., D'Oca, S., Turner, W. J., & Taylor-Lange, S. C. (2015). An ontology to represent energy-related occupant behavior in buildings. Part I: Introduction to the DNAs framework. Building and Environment, 92, 764-777.
[18] Hong, T., D'Oca, S., Taylor-Lange, S. C., Turner, W. J., Chen, Y., & Corgnati, S. P. (2015). An ontology to represent energy-related occupant behavior in buildings. Part II: Implementation of the DNAS framework using an XML schema. Building and Environment, 94, 196-205.
[19] Zhao, Y., Yang, Q., Fox, A., & Zhang, T. (2020, April). Ontology-based knowledge modeling of post-occupancy evaluation for green building. In IOP Conference Series: Earth and Environmental Science (Vol. 495, No. 1, p. 012076). IOP Publishing.
[20] Zhao, Y., & Yang, Q. (2021). Development of an ontology-based Semantic Building post-occupancy Evaluation Framework. International Journal of Metrology and Quality Engineering, 12, 19.
[21] Nolich, M., Spoladore, D., Carciotti, S., Buqi, R., & Sacco, M. (2019). Cabin as a home: a novel comfort optimization framework for IoT equipped smart environments and applications on cruise ships. Sensors, 19(5), 1060.
[22] Adeleke, J. A., & Moodley, D. (2015, September). An ontology for proactive indoor environmental quality monitoring and control. In Proceedings of the 2015 annual research conference on south African institute of computer scientists and information technologists (pp. 1-10).
[23] Spoladore, D., Arlati, S., Carciotti, S., Nolich, M., & Sacco, M. (2018). RoomFort: An ontology-based comfort management application for hotels. Electronics, 7(12), 345.
[24] Chen, W., Chena, K., Gan, V. J. L., & Cheng, J. C. P. (2019). A methodology for indoor human comfort analysis based on BIM and ontology. In ISARC. Proceedings of the International Symposium on Automation and Robotics in Construction (Vol. 36, pp. 1189-1196). IAARC Publications.
[25] Spoladore, D., Arlati, S., & Sacco, M. (2017). Semantic and virtual reality-enhanced configuration of domestic environments: the smart home simulator. Mobile Information Systems, 2017.
[26] Nguyen, T. A., Raspitzu, A., & Aiello, M. (2014). Ontology-based office activity recognition with applications for energy savings. Journal of Ambient Intelligence and Humanized Computing, 5(5), 667-681.
[27] Esnaola-Gonzalez, I., Bermúdez, J., Fernandez, I., & Arnaiz, A. (2021). EEPSA as a core ontology for energy efficiency and thermal comfort in buildings. Applied Ontology, 16(2), 193-228.

Appendix A. Equation of the Predicted Mean Vote (PMV) [7]

The PMV is an index that predicts the mean value of the votes of a large group of persons on the 7-point thermal sensation scale (see Table 1), based on the heat balance of the human body. Thermal balance is obtained when the internal heat production in the body is equal to the loss of heat to the environment.

Table 1: Seven-point thermal sensation scale

+3	Hot
+2	Warm
+1	Slightly warm
0	Neutral
-1	Slightly cool
-2	Cool
-3	Cold

$$
\begin{aligned}
PMW \;=\; & [0.303 \cdot exp(-\,0.036 \cdot M) + 0.028] \cdot \\
& \left\{(M - W) - 3.05 \cdot 10^{-3} \cdot [5733 - 6.99 \cdot (M - W) - P_a] - 0.42 \cdot [(M - W) - 58.15]\right\} \\
& \left\{-\,1.7 \cdot 10^{-5} \cdot M \cdot (5867 - P_a) - 0.0014 \cdot M \cdot (34 - t_a)\right\} \\
& \left\{-\,3.96 \cdot 10^{-8} \cdot f_{cl} \cdot [(t_{cl} + 273)^4 - (\underline{t}_r + 273)^4] + f_{cl} \cdot h_c \cdot (t_{cl} - t_a)\right\}
\end{aligned}
\tag{1}
$$

$$
\begin{aligned}
t_{cl} = \; & 35.7 - 0.028 \cdot (M - W) \\
& - I_{cl} \cdot \left\{3.96 \cdot 10^{-8} \cdot f_{cl} \cdot \left[(t_{cl} + 273)^4 - (\underline{t}_r + 273)^4\right] + f_{cl} \cdot h_c \cdot (t_{cl} - t_a)\right\}
\end{aligned}
\tag{2}
$$

$$
\begin{aligned}
h_c = & \left\{2.38 \cdot \left|t_{cl} - t_a\right|^{0.25} \; for \; 2.38 \cdot \left|t_{cl} - t_a\right|^{0.25} > 12.1 \cdot \sqrt{v_{ar}}\right\} \\
& or \left\{12.1 \cdot \sqrt{v_{ar}} \; for \; 2.38 \cdot \left|t_{cl} - t_a\right|^{0.25} < 12.1 \cdot \sqrt{v_{ar}}\right\}
\end{aligned}
\tag{3}
$$

$$
\begin{aligned}
f_{cl} = & \left\{1.00 + 1.290 \cdot I_{cl} \; for \; I_{cl} \le 0.078 m^2 \cdot K/W\right\} \\
& or \left\{1.05 + 0.645 \cdot I_{cl} \; for \; I_{cl} > 0.078 m^2 \cdot K/W\right\}
\end{aligned}
\tag{4}
$$

where

M is the metabolic rate, in watts per square meter (W/m2);
W is the effective mechanical power, in watts per square meter (W/m2);

I_{cl} is the clothing insulation, in square metres kelvin per watt (m2 · K/W);

f_{cl} is the clothing surface area factor;

t_a is the air temperature, in degrees Celsius (°C);

$\underline{t_r}$ is the mean radiant temperature, in degrees Celsius (°C);

v_{ar} is the relative air velocity, in meters per second (m/s);

P_a is the water vapor partial pressure, in pascals (Pa);

h_c is the convective heat transfer coefficient, in watts per square meter kelvin [W/(m2 · K)];

f_{cl} is the clothing surface temperature, in degrees Celsius (°C).

Appendix B. Metabolism Estimation based on Age, Sex, Weight, and Height [8]

$$Basal\ Metabolic\ Rate\ (BMR)\ = (\frac{10m}{1Kg} + \frac{6.25h}{1cm} - \frac{0.5a}{1year} + s)\frac{Kcal}{day}$$
(5)

where

m is the mass of the body (in kilograms);
h is the height of the body in cm;
a is the age in years;
s is a factor relating to sex, $s = \{+\ 5\ for\ males\ or\ -\ 161\ for\ females\}$.

$$Estimated\ Energy\ Requirement\ (EER)\ =$$

$$\{864 - 9.72 \cdot a(years) + PA \cdot (14.2 \cdot m(kg) + 503 \cdot h(meters))\ for\ males\}$$

$$or\ \{387 - 7.31 \cdot a(years) + PA \cdot (10.9 \cdot m(kg) + 660.7 \cdot h(meters))\ for\ females\} \quad (6)$$

where

PA is the physical activity level
$for\ male,\ PA = \{1,\ 1.0 < PAL < 1.4\ (Sedentary);\ 1.12,\ 1.4 < PAL < 1.6\ (Low\ active)\}$
$or\ \{1.27,\ 1.6 < PAL < 1.9\ (Active);\ 1.54,\ 1.9 < PAL < 2.5\ (Very\ active)\}$;
$for\ female,\ PA = \{1,\ 1.0 < PAL < 1.4\ (Sedentary);\ 1.14,\ 1.4 < PAL < 1.6\ (Low\ active)\}$
$or\ \{1.27,\ 1.6 < PAL < 1.9\ (Active);\ 1.45,\ 1.9 < PAL < 2.5\ (Very\ active)\}$

$$PAL\ = ((I - 1)\ [(1.15/0.9) \times DD\ (minutes)]/1440))/\ (BEE/[0.0175 \times 1440 \times w\ (kg)]) \quad (7)$$

where

I is the activity intensity;
D is the activity duration
$BEE = \{2933.8 \cdot a(years) + 456.4 \cdot h(meters) + 10.12 \cdot w(kg)\ for\ male\}$
$or\ \{2472.67 \cdot a(years) + 401.5 \cdot h(meters) + 8.6 \cdot w(kg)\ for\ female\}$

$$MET = \frac{EER}{BMR} \quad (8)$$

Appendix C. Metabolic Rates for Typical Tasks [10]

Activity	Metabolic Rate		
	Met Units	W/m^2	$Btu/h \cdot ft^2$
Resting			
Sleeping	0.7	40	13
Reclining	0.8	45	15
Seated, quiet	1.0	60	18
Standing, relaxed	1.2	70	22
Walking (on level surface)			
0.9 m/s, 3.2 km/h, 2.0 mph	2.0	115	37
1.2 m/s, 4.3 km/h, 2.7 mph	2.6	150	48
1.8 m/s, 6.8 km/h, 4.2 mph	3.8	220	70
Office Activities			
Reading, seated	1.0	55	18
Writing	1.0	60	18
Typing	1.1	65	20
Filing, seated	1.2	70	22
Filing, standing	1.4	80	26
Walking about	1.7	100	31
Lifting/packing	2.1	120	39
Driving/Flying			
Automobile	1.0 to 2.0	60 to 115	18 to 37
Aircraft, routine	1.2	70	22
Aircraft, instrument landing	1.8	105	33
Aircraft, combat	2.4	140	44
Heavy vehicle	3.2	185	59

Miscellaneous Occupational Activities			
Cooking	1.6 to 2.0	95 to 115	29 to 37
House cleaning	2.0 to 3.4	115 to 200	37 to 63
Seated, heavy limb movement	2.2	130	41
Machine work			
sawing (table saw)	1.8	105	33
light (electrical industry)	2.0 to 2.4	115 to 140	37 to 44
heavy	4.0	235	74
Handling 50 kg (100 lb) bags	4.0	235	74
Pick and shovel work	4.0 to 4.8	235 to 280	74 to 88
Miscellaneous Leisure Activities			
Dancing, social	2.4 to 4.4	140 to 225	44 to 81
Calisthenics/exercise	3.0 to 4.0	175 to 235	55 to 74
Tennis, single	3.6 to 4.0	210 to 270	66 to 74
Basketball	5.0 to 7.6	290 to 440	90 to 140
Wrestling, competitive	7.0 to 8.7	410 to 505	130 to 160

Appendix D. Clothing Insulation l_{cl} Values for Typical Ensembles [10]

Clothing Description	**Garments Included**	l_{cl}, clo
Resting	(1) Trousers, short-sleeve shirt	0.57
	(2) Trousers, long-sleeve shirt	0.61
	(3) #2 plus suit jacket	0.96
	(4) #2 plus suit jacket, vest, t-shirt	1.14
	(5) #2 plus long-sleeve sweater, t-shirt	1.01
	(6) #5 plus suit jacket, long underwear bottoms	1.30
Skirts/dresses	(7) Knee-length skirt, short-sleeve shirt (sandals)	0.54
	(8) Knee-length skirt, long-sleeve shirt, full slip	0.67
	(9) Knee-length skirt, long-sleeve shirt, half slip, long-sleeve sweater	1.10
	(10) Knee-length skirt, long-sleeve shirt, half slip, suit jacket	1.04
	(11) Ankle-length skirt, long-sleeve shirt, suit jacket	1.10
Shorts	(12) Walking shorts, short-sleeve shirt	0.36
Overalls/coveralls	(13) Long-sleeve coveralls, t-shirt	0.72
	(14) Overalls, long-sleeve shirt, t-shirt	0.89
	(15) Insulated coveralls, long-sleeve thermal underwear tops and bottoms	1.37
Athletic	(16) Sweat pants, long-sleeve sweatshirt	0.74
Sleepwear	(17) Long-sleeve pajama tops, long pajama trousers, short 3/4 length robe (slippers, no socks)	0.96