Indoor Environmental Quality Management Ontology

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Abstract

This project aims to develop an ontology that recommends a viable solution to improve indoor environmental quality (IEQ) for occupants and reduces 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 general solution to improve IEQ while decreasing energy usage because each building is under different environmental conditions, and every occupant has different clothing insulation and a different metabolic rate. In this project, we propose an ontology that suggests a viable solution to enhance IEQ and decrease energy usage by combining several sets of knowledge: indoor environmental conditions, outdoor environmental conditions, and occupant profiles. In future work, this ontology could serve as the foundation on top of which to develop an industrial-scale IEQ management system by integrating 3D geometric models and thermodynamic simulation modules.

Introduction

According to reports from the U.S. Energy Information Administration (US EIA), commercial and residential buildings were responsible for 72% of electric energy in 2013 [1], and 46.2% of energy use in buildings was consumed for heating, cooling, ventilation, and lighting in 2014 [2]. This energy is used to enhance 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 given room, IEQ is affected by many factors: air temperature, mean radiant temperature, relative humidity, airflow, air quality, clothing, human activity, and occupant information such as age, sex, height, and weight [4-5]. The problem is that different buildings are under different environmental conditions including weather, outdoor air quality, orientation and location of the building, *etc.*, and each occupant has a unique combination of tolerance levels and daily clothing choices, which affect their personal environmental preferences. Furthermore, potential solutions—air conditioners, electric heaters, window blinds, windows, doors, fans, *etc.*—have differing influences on IEQ. 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, and air speed, 2) outdoor environmental conditions, such as air quality and daylight intensity, and 3) occupant information including sex, height, weight, age, clothing insulation, and activity level.

A user will inform the IEQ management system of the quantifiable IEQ factors—thermal comfort and air quality—that are currently causing them discomfort and to what degree and the system will suggest a 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 Predicted Mean Vote (PMV) model based on sensor data as well as other information that the user provides, including occupant profile descriptions.

The types of equipment we consider affect thermal comfort in different ways: 1) fans increase air speed, 2) electric heaters and space heaters increase air temperature, 3) dehumidifiers decrease humidity, 4) air conditioners decrease air temperature and relative humidity, and 5) window blinds decrease the air temperature. The following section will describe how ontology can be used to find a viable solution and 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 utilizes the PMV model standardized by International Organization for Standardization (ISO) and Air Quality Index (AQI) established by the United States Energy Information Administration (US EPA). Calculating the PMV index requires air temperature, air speed, relative humidity, clothing insulation, and metabolic rate [6-7]; the metabolic rate calculation requires activity intensity, age, sex, height, and weight [8]; the AQI is calculated based on the concentration of ozone (O3), particulate matters (PM), carbon monoxide (CO), sulfur dioxide (SO2), 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 used must be understandable to laypeople. If room occupants input their demographic information, the system can suggest a solution in the form of a list of room components they should manipulate to increase/decrease IEQ parameters. If non-power-consuming components are available, they are prioritized over power-consuming components to minimize energy consumption. This system is not currently designed to manipulate windows, HVAC systems, electric heaters, *etc. automatically.* In addition, 3D geometries, fluid dynamics, and thermodynamic simulations to understand different effects depending on the locations of the room components were deemed out-of-scope given the relatively short time frame of the project. Therefore, applications that reflect large spaces where comfort factors, such as temperature and humidity, were also deemed out-of-scope.

To constrain the coverage of the ontology, we focused on several usage scenarios involving indoor and outdoor environmental conditions and occupants' demographic information. Based on the requirements and competency questions that we extracted from these usage scenarios, we further developed the key concepts and relations necessary in our ontology.

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, occupant profiles, and indoor and outdoor environmental parameters. The primary parameters that this system acts on are environmental measurements taken by available sensors.

Ontology Overview

Figure 1 shows the relationships between the most important high-level resources 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.

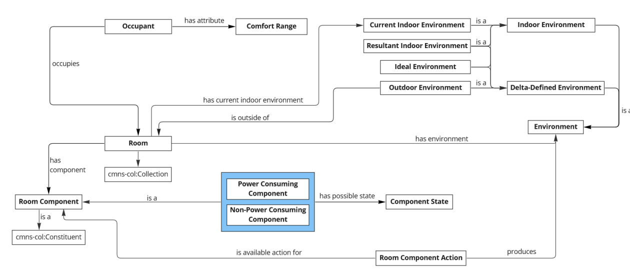

Figure 1: Ontology Overview Diagram

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.

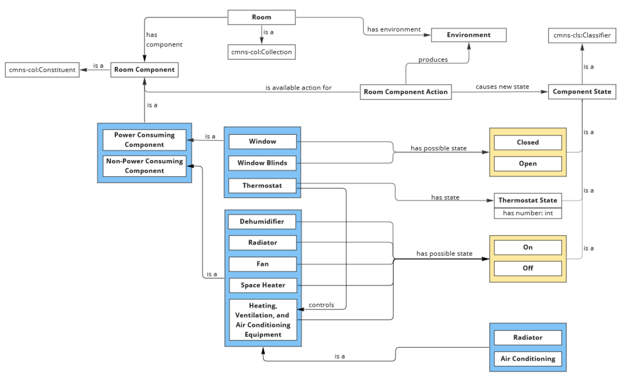

Figure 2: Room Component Diagram

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*.

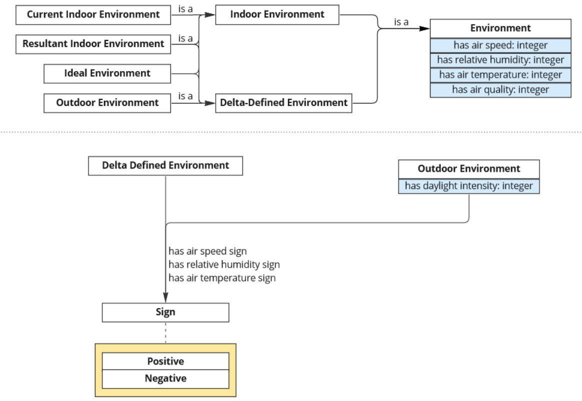

Figure 3: Environment Diagram

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*.

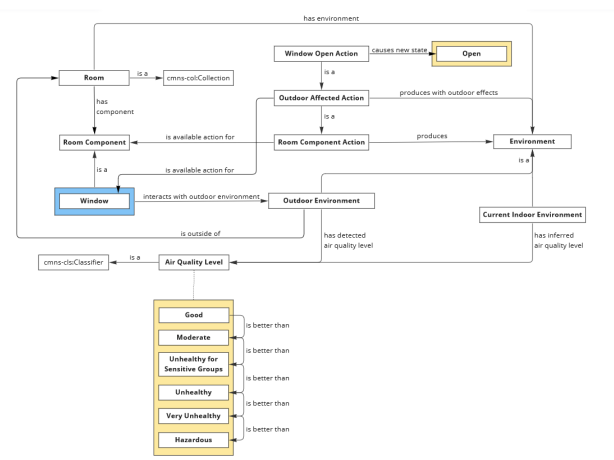

Figure 4: Air Quality Diagram

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.

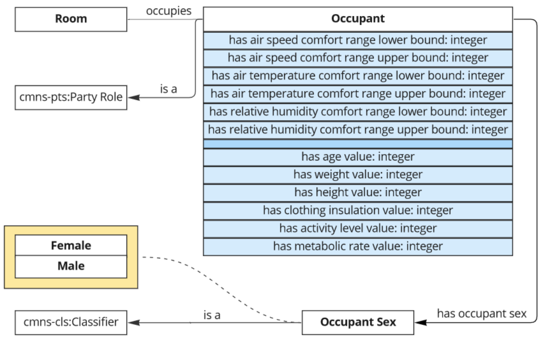

Figure 5: Occupant Diagram

Justification

The ontology is structured primarily to support specific types of queries and secondarily to model the domain in a general manner. The prioritization of supporting specific queries means that some of the modeling choices diverge from what would 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 the reasoner to infer 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 efficacy of the ontology. The questions mainly focus on asking for 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 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 does not cover the capability of an IEQ management system using this ontology. Moreover, because the description logic reasoners we use cannot perform arithmetic or numeric comparison, we assume that users either directly input their comfort range or permit that it be calculated using a PMV equation (see Appendix A) externally to the ontology. (Note, however, that a hybrid environment that incorporates the application of rules or the integration of custom code—which was out-of-scope for this project—would indeed be able to perform the requisite numeric comparison. See the "Limitations" section of this paper for further discussion.) Additionally, we assume that users manually input their activity level and clothing insulation based on the standardized data table established by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE, see Appendix C and D). This table provides the metabolic rate for a corresponding activity and the insulation value for a garment so that the users can easily find them. For instance, the metabolic rate of sleeping is 0.7; clothing insulation of trousers with a short-sleeve shirt is 0.57 clo. 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). The 'clo' indicates the unit of the thermal insulation provided by particular garments. One 'clo' is equal to 0.155 m2·°C/W [10].

Competency Question 1

Question: How can we meet all requirements of 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 non-trivial reasoning. This means that the user must activate a reasoner before executing a query in "Snap SPARQL Query" instead of Protégé's built-in SPARQL query feature.

```
SELECT DISTINCT ?roomComponent ?newState WHERE {
    ?roomComponent iem:isComponentOf ind:Question1Room .
    ?roomComponent iem:hasAvailableAction ?action .
    ?action iem:causesNewState ?newState .
    ?action iem:produces ?resultantEnvironment .
    ?resultantEnvironment
iem:hasAirTemperatureSign ?airTemperatureSign .
    ind:Question1EnvironmentTarget
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 the 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:Question2Room .
    ?airSpeedRoomComponent iem:hasAvailableAction ?airSpeedAction .
    ?airSpeedAction iem:causesNewState ?airSpeedNewState .
    ?airSpeedAction iem:produces ?airSpeedResultantEnvironment .
    ?airSpeedResultantEnvironment iem:hasAirSpeedSign ?airSpeedSign .
    ind:Question2EnvironmentTarget iem:hasAirSpeedSign ?airSpeedSign .

    ?relativeHumidityRoomComponent iem:isComponentOf
ind:Question2Room .
    ?relativeHumidityRoomComponent
iem:hasAvailableAction ?relativeHumidityAction .
    ?relativeHumidityAction
iem:causesNewState ?relativeHumidityNewState .
    ?relativeHumidityAction
iem:produces ?relativeHumidityResultantEnvironment .
    ?relativeHumidityResultantEnvironment
iem:hasRelativeHumiditySign ?relativeHumiditySign .
    ind:Question2EnvironmentTarget
iem:hasRelativeHumiditySign ?relativeHumiditySign .
}
```

Example result:

?airSpeedRoomComponent	?airSpeedNewState	?relativeHumidityRoomComponent	?relativeHumidityNewState
ind:Question4 Fan	iem:On	ind:Question4 Dehumidifier	iem:On

Competency Question 3

Question: In a small gym, three people are working out. 22-year-old male Jason is walking on a treadmill and lifting 45 kg bars (metabolic rate: 4.0, wearing shorts & short-sleeve shirt: 0.36 clo, the blue area in Figure 6), 44-year-old male Bob is seated and conducting heavy limb movements (metabolic rate: 2.2, wearing typical summer indoor clothing: 0.5 clo, the gray area in Figure 6), and 52-year-old female Sarah is walking on a treadmill at 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? The indoor air speed is 0.3m/s, the outdoor air speed is 2m/s, and the outdoor air quality index is 38, 'Good'. An air conditioner is available, and all 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 is, in turn, part of the room individual that's associated with the relevant competency question. An 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:Question3Room .
    ?airSpeedRoomComponent iem:hasAvailableAction ?airSpeedAction .
    ?airSpeedAction iem:causesNewState ?airSpeedNewState .
    ?airSpeedAction iem:produces ?airSpeedResultantEnvironment .
    ?airSpeedResultantEnvironment iem:hasAirQualityLevel
iem:AirQualityLevelGood .
    ?airSpeedResultantEnvironment iem:hasAirSpeedSign ?airSpeedSign .
    ind:Question3EnvironmentTarget 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. Does 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 4. 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 4, this query intentionally returns no results.

```
SELECT ?occupant WHERE {
    ?occupant iem:occupies ind:Question4Room .
    ?occupant
iem:hasAirTemperatureComfortRangeLowerBound ?airTemperatureLowerBou
nd .
    ?occupant
iem:hasRelativeHumidityComfortRangeLowerBound ?relativeHumidityLowerB
ound .
    ?occupant
iem:hasAirTemperatureComfortRangeUpperBound ?airTemperatureUpperBou
nd .
    ?occupant
iem:hasRelativeHumidityComfortRangeUpperBound ?relativeHumidityUpperB
ound .
    ind:Question4EnvironmentCurrent
iem:hasAirTemperatureValue ?airTemperatureValue .
    ind:Question4EnvironmentCurrent
iem:hasRelativeHumidityValue ?relativeHumidityValue .
    FILTER(?airTemperatureValue <= ?airTemperatureUpperBound) .
    FILTER(?airTemperatureValue >= ?airTemperatureLowerBound) .
    FILTER(?relativeHumidityValue <= ?relativeHumidityUpperBound) .
    FILTER(?relativeHumidityValue >= ?relativeHumidityLowerBound) .
}
```

Example result:

?occupant

Competency Question 5

Question: In a small office space with three occupants, who is 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 5. 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:Question5Room .
    ?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:Question5EnvironmentCurrent
iem:hasAirTemperatureValue ?airTemperatureValue .
    ind:Question5EnvironmentCurrent
iem:hasAirSpeedValue ?airSpeedValue .
    ind:Question5EnvironmentCurrent
iem:hasRelativeHumidityValue ?relativeHumidityValue .
    FILTER(?airTemperatureValue <= ?airTemperatureUpperBound) .
    FILTER(?airTemperatureValue >= ?airTemperatureLowerBound) .
    FILTER(?airSpeedValue <= ?airSpeedUpperBound) .
    FILTER(?airSpeedValue >= ?airSpeedLowerBound) .
    FILTER(?relativeHumidityValue <= ?relativeHumidityUpperBound) .
    FILTER(?relativeHumidityValue >= ?relativeHumidityLowerBound) .
}
```

Example result:

?occupant
Question5Occupant2

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/ontology.html

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 that air speed should be increased, decreased, or unchanged based on the different comfort ranges of three occupants. Additionally, semantics can be utilized to infer whether particular actions are "acceptable" given a set of general rules and heuristics. For example, the ontology 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 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. One notable consequence of this is that multiple actions that affect the same IEQ metric can't be "summed" to produce a single delta of greater or lesser magnitude.

This limitation is due to the inability of standard RDF reasoners like Pellet and HermiT to make inferences from all but the most trivial of quantitative relations. 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, perhaps by employing a rule engine, but there are significant unsolved challenges to doing this.

Secondly, this ontology cannot consider the interrelation between air temperature, relative humidity, air speed, clothing insulation, and metabolic rate. For example, an occupant's comfort ranges of air temperature and relative humidity depend on air speed, clothing insulation, and metabolic rate; however, our current ontology cannot fully capture this relationship.

Thirdly, our 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.

The second and third limitations are the results of scoping decisions made at the beginning of the ontology development process. We don't currently foresee any specific technical hurdles that would preclude the expansion of the ontology to overcome these limitations in the future.

Websites

Detailed information can be found on our website. This website contains information pertaining to all 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.

Related Work

Over the past two decades, the Architecture, Engineering, Construction, Owner, and Operation (AECOO) industries have applied ontology technologies to improve building performance and 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).

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 the Suggested Upper Merged Ontology (SUMO). Lork et al. [12] suggested an ontology for energy optimization in buildings that classifies 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 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 deal only with energy efficiency in buildings without considering occupant 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 doesn'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 the WELL building standard. These ontologies are concerned with 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].

Related ontologies in the IEQ category mainly consider 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 the 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 the WELL Building Standard. Spoladore et al. [25] developed Knowledge-Base Home (KBHome), a set of ontologies containing users' health status, physical status, and living environment. This ontology can suggest a set of appliances to help elderly or impaired people. These five ontologies focus primarily on indoor human comfort but do not include energy consumption concepts. On the other hand, some ontologies have incorporated both IEQ and building energy use. For example, 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 the Energy Efficiency Prediction Semantic Assistant (EEPSA) ontology to assist data analysts in improving energy efficiency and thermal comfort in buildings.

In conclusion, based on the analysis of the aforementioned 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 don't concern occupants' comfort. The POE ontologies mainly focused on meeting the requirements of the building standards; but, they don'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 final two ontologies included both concepts; however, they don't consider multiple occupant profiles or suggest any action to enhance their indoor comfort. Multiple occupant profile concepts are necessary to fully maximize indoor comfort because occupants typically have different comfort thresholds due to their different metabolic rates and clothing insulations, and finding parameters that optimize the comfort of multiple occupants with different profiles is a much more complex problem than considering the comfort ranges of a single occupant. 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 available room components.

Future Work

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 to increase or decrease environmental parameters. To make this project feasible and doable during a single semester, we pivoted the scope of the project several times. First, we excluded acoustic and visual comfort concepts from the scope of the IEQ system to enhance feasibility. Second, 3D geometries and thermodynamic parts were excluded due to complexity of implementation. Third, we excluded energy consumption and cost concepts because they required equipment specifications and thermodynamic knowledge. Fourth, we excluded the PMV calculation in the ontology because Protégé does not conveniently support mathematical calculation. Finally, we switched from bucket-based reasoning to sign-based reasoning to simplify the ontology. 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.

As mentioned previously in our discussion of limitations, future work necessitates that our current system of reasoning using signs be expanded to consider more granular changes in parameters by either properly re-implementing our "bucket" system or considering precise numeric values. Numbers could be handled with a rule engine or computed completely outside of the ontology; the capabilities of OWL/RDF to supplement arithmetic would need to be explored further while implementing this crucial feature. Similarly, the current version of the ontology is capable of reasoning about how opening a window affects indoor parameters only in relation to air quality. Related logic should be put in place to reason about the effects of other outdoor parameters on the related indoor space.

Adding geometric reasoning is not as crucial as supporting more extensive numerical reasoning, but it would greatly increase the utility of our system. Our current scope is restricted to small rooms where the available parameters will not differ drastically in different points around the room. To be practical in a large office space, or more effective in the average residential home that has several interconnected rooms, our ontology must support multiple “sub-environments” and reason about what areas of an environment room components can affect. Additionally, such a system should be able to make suggestions like moving a fan or radiator to be closer to a certain person or even to suggest that a person with lower temperature preferences move their workstation to an area with higher airflow, for example. To that effect, doors connecting multiple environments should be considered alongside the effects of a single thermostat that controls multiple environments or sub-environments, which is common in modern office spaces. This added complexity would also motivate expanding our ontology to support some form of feedback system in which the success of certain actions in improving IEQ would be evaluated, and the system could update itself to more suggest actions more accurately in future usage.

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, then a query on the ontology could place 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 that focus on room components, indoor/outdoor environments, and air quality. Finally, we developed the ontology and verified its functionality by answering the competency questions using SPARQL queries. Formal reasoning with semantic technologies enables the filtering out of undesirable action suggestions, such as suggestions that would otherwise cause a worsening of indoor air quality. In the future, we plan to implement PMV-centered suggestions by considering the interrelation between air temperature, relative humidity, and air speed. This ontology could serve as the foundation on top of which to develop an industrial-scale IEQ management system by integrating 3D geometric models and thermodynamic simulation modules.

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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

$$PMW = [0.303 \cdot exp(-0.036 \cdot M) + 0.028] \cdot$$

$$\left\{(M - W) - 3.05 \cdot 10^{-3} \cdot [5733 - 6.99 \cdot (M - W) - P_a] - 0.42 \cdot [(M - W) - 58.15]\right\}$$

$$\left\{-1.7 \cdot 10^{-5} \cdot M \cdot (5867 - P_a) - 0.0014 \cdot M \cdot (34 - t_a)\right\}$$

$$\left\{-3.96 \cdot 10^{-8} \cdot f_{cl} \cdot [(t_{cl} + 273)^4 - (\underline{t_r} + 273)^4] + f_{cl} \cdot h_c \cdot (t_{cl} - t_a)\right\} \quad (1)$$

$$t_{cl} = 35.7 - 0.028 \cdot (M - W)$$

$$-I_{cl} \cdot \left\{3.96 \cdot 10^{-8} \cdot f_{cl} \cdot \left[(t_{cl} + 273)^4 - (\underline{t_r} + 273)^4\right] + f_{cl} \cdot h_c \cdot (t_{cl} - t_a)\right\} \quad (2)$$

$$h_c = \left\{2.38 \cdot \left|t_{cl} - t_a\right|^{0.25} for\ 2.38 \cdot \left|t_{cl} - t_a\right|^{0.25} > 12.1 \cdot \sqrt{v_{ar}}\right\}$$

$$or \left\{12.1 \cdot \sqrt{v_{ar}}\ for\ 2.38 \cdot \left|t_{cl} - t_a\right|^{0.25} < 12.1 \cdot \sqrt{v_{ar}}\right\} \quad (3)$$

$$f_{cl} = \left\{1.00 + 1.290 \cdot I_{cl}\ for\ I_{cl} \leq 0.078 m^2 \cdot K/W\right\}$$

$$or \left\{1.05 + 0.645 \cdot I_{cl}\ for\ I_{cl} > 0.078 m^2 \cdot K/W\right\} \quad (4)$$

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]

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

(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