Towards an Indoor Environmental Quality Management Ontology*

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Abstract
Buildings consume one-third of the world's energy and are some of the major energy consumers on the planet. Occupants use this energy for enhancing indoor environmental quality (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 as each building is under different environmental conditions, and every occupant has different clothing insulation and a different metabolic rate. In this work, we propose an ontology that, based on real-time data from Internet of Things (IoT), can be used to suggest 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. We demonstrated that the ontology with an application can recommend suitable actions to improve IEQ. In future work, this ontology could serve as the foundation on top of which to develop an occupant-centric building automation system for enhancing IEQ and energy efficiency, based on 3D geometric models and thermodynamic simulation modules.

Keywords
Ontology, Indoor Environment Quality, Occupant Profile

1. 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, acoustic comfort, visual comfort, and control systems [3].

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In a given room, thermal comfort 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; however, the electric heater does not affect humidity, unlike the space heater.

In this work, we approach this problem from a Semantic standpoint by proposing an ontology that can be used to find a viable solution to improve IEQ for occupants while minimizing energy use in a room. The ontology combines several sets of knowledge: 1) indoor environmental conditions including air temperature, relative humidity, air speed, sound pressure, and luminosity, 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.

We assessed the ontology through a set of simulated scenarios where user profiles can be used to quantify the IEQ requirements and evaluate the IEQ management system with competency questions. Users can inform quantitative factors for thermal comfort, acoustic comfort, visual 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 IoT sensor data as well as other information that the user provides, including occupant profile descriptions. We found that the ontology was able to be used to infer how to change indoor environmental parameters to meet the comfort requirements of multiple occupants and suggest viable actions to reach the desirable indoor environmental condition.

2. Building occupancy 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 from IoT sensors or users. To evaluate thermal comfort, 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, particulate matters, carbon monoxide, sulfur dioxide, and nitrogen dioxide [9]. The scope of this use case is limited to a small room that one to three people can use. The target population of the application is individuals who regularly occupy the room. This use case is designed for building occupants 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 or decrease IEQ parameters. If non-power-consuming components are available, they are prioritized over power-consuming components to minimize energy consumption. As an initial phase of the research project, 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. Therefore, applications that reflect large spaces where comfort factors differ in different points 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.

3. The Indoor Environmental Quality Ontology

To suggest an action for increasing the occupants' overall comfort, our ontology-enabled system 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 IoT sensors.

3.1. Ontology Overview

The figure below shows the relationships between the most important high-level resources in our ontology. Central to our project is a *Room*, which has *Room Component*—objects in the room that have some effect on the room's environment—and one or more *Occupant*s, which have various characteristics from which we may calculate a comfort range. *Room Component*—objects are either power-consuming or non-power-consuming, with priority given to actions that use *Non-Power Consuming Component*—objects during action recommendations. Each *Room Component* has multiple possible *Component State*s and *Component Action*s; each action produces a new *Component State*, as well as a different *Environment* consisting of IEQ parameters measured by *saref:Sensor* from SAREF ontology[10]. Additionally, each *Room* has one or more associated environments, including *Indoor Environment*s, which refer to the *Current Indoor Environment* and some set of possible indoor environments, and *Delta-Defined Environment*s, which are Environments defined by their difference from some other Environments such as *Current Indoor Environment* or *Outdoor Environment*. While the *Current Indoor Environment* is defined in absolutes, *Resultant Indoor Environment*s are defined in relatives and are also *Delta-Defined Environment*s because they are defined by difference from *Current Indoor Environment*. 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. More detailed descriptions and conceptual diagrams about

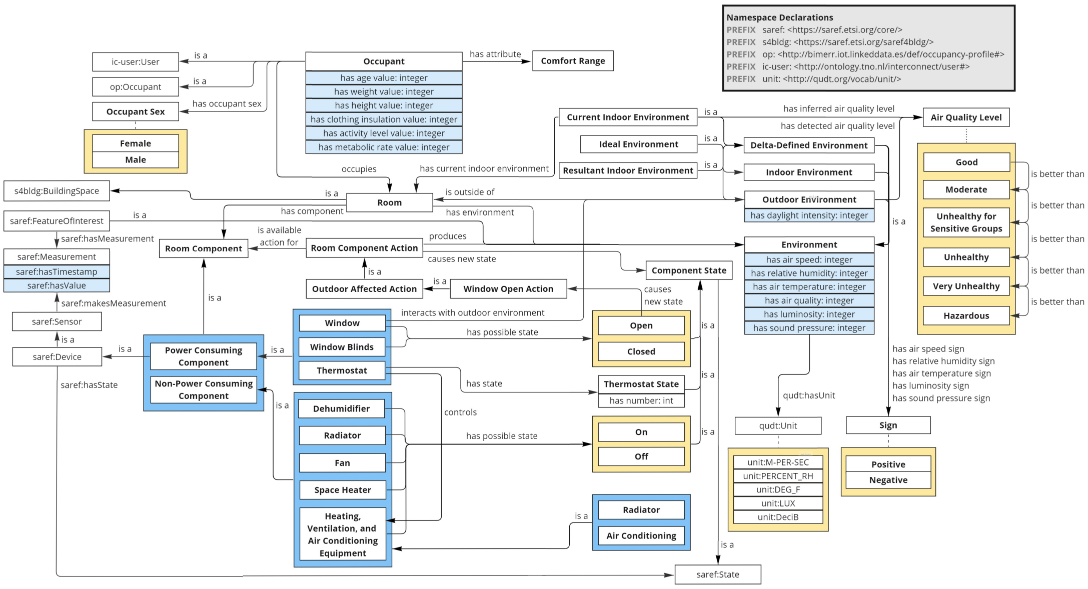

Figure 1: Ontology Overview Diagram

Room Component—objects, *Environment*, *Outdoor Air Quality*, and *Occupant*s can be found on our website.

Based on existing ontologies including SAREF[10], SAREF4BLDG[11], Interconnect[12], Occupancy Profile[13], and QUDT[14], the proposed ontology is structured primarily to support specific types of concepts and secondarily to model the domain in a general manner. The prioritization of supporting specific concepts 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 does not intuitively map to any single relation in the real world, it permits the reasoner to infer properties about the *Resultant Indoor Environment* based on the detected properties of the relevant *Outdoor Environment*.

4. Evaluation

For the scope of this project, we designed six 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, solutions can be different depending on available room components and outdoor environmental parameters as well as the indoor environment. In

```
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 .
}
```

Figure 2: SPARQL Query for Competency Question 1

Table 1
Example result of competency question 1

?airSpeed RoomComponent	?airSpeed NewState	?relativeHumidity RoomComponent	?relativeHumidity NewState
ind:Question4Fan	iem:On	ind:Question4Dehumidifier	iem:On

this paper, we show only two representative competency questions due to the limited number of pages. The full set of the questions can be found on our website.

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 our application uses OWL (DL) reasoning but 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 [7] externally to the ontology.

Additionally, we assume that users manually input their activity level and clothing insulation based on standardized data tables in ANSI/ASHRAE Standard [15]. This standard 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.

4.1. Competency Question 1

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' profiles are a 26-year-old daughter typing something on his laptop, a 59-year-old mother dancing,

```
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 .
}
```

Figure 3: SPARQL Query for Competency Question 2

Table 2
Example result of competency question 2

?airSpeedRoomComponent	?airSpeedNewState
ind:Question5Window	iem:Open

and a 32-year-old son cleaning the house. 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 the other 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.

4.2. Competency Question 2

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 with shorts & a short-sleeve shirt, 44-year-old male Bob is seated and conducting heavy limb movements with typical summer indoor clothing, and 52-year-old female Sarah is walking on a treadmill at 3 mph with a short-sleeve shirt. 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.

5. Related Work

Through comparative analysis for 17 articles, we classified the related works into three categories: energy management, post-occupancy evaluation (POE), and indoor environmental quality (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 [16, 17, 18, 19, 20, 21, 22, 23]. 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 [24, 25]. The five ontologies in the IEQ category contained indoor human comfort concepts but did not concern energy consumption [26, 27, 28, 29, 30]. The final two ontologies included both concepts; however, they don't consider multiple occupant profiles or suggest any action to enhance their indoor comfort [31, 32]. To fully maximize indoor comfort, multiple occupant profile concepts are necessary because occupants typically have different comfort thresholds due to their different metabolic rates and clothing insulations, and finding optimal parameters for the occupants' comfort is a much more complex problem than considering a single occupant's comfort. Moreover, viable actions for improving comfort should be suggested based on their profiles as well as available room components.

To overcome the limitations in the three categories of previous research works, this paper focuses on developing an ontology that provides advice to improve indoor environmental quality and reduce energy consumption based on occupants' profiles and available room components.

6. Discussion

6.1. 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 be used to 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 would not be able to filter out actions that cause unacceptable indoor air quality levels because the necessary information would not be present in the database.

The main benefits of this semantic approach over other techniques, such as machine learning or elaborative scripts, are extensibility and robustness. This approach makes it easier for existing semantic systems to integrate with our ontology, reducing the burden of adoption in smart buildings. Additionally, our approach gracefully degrades with a lack of complete inputs, which is crucial when IoT sensors go offline or occupants fail to provide all requested information.

6.2. Limitations

Firstly, the most significant limitation of our model is that an ideal indoor environment must be declared in terms of a positive or negative delta from the current indoor environment for air temperature, air speed, relative humidity, luminosity, and sound pressure, 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. Secondly, this ontology cannot consider the interrelation between parameters of thermal comfort. For example, an occupant's thermal 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.

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

7. Conclusion

The main contribution of this work is to develop an ontology suggesting viable solutions for enhancing IEQ considering indoor and 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. Additionally, we described competency questions with simulated environmental settings to specify the scope of this work and the essential functionality. We demonstrated the ontology's functionality by answering the competency questions using SPARQL queries. Formal reasoning with semantic technologies enables the filtering out of undesirable action suggestions. Furthermore, unlike the related works, the proposed ontology includes multiple occupant profile concepts to find the optimal IEQ parameters for their different comfort requirements. Finally, existing semantic systems can be easily integrated with our ontology due to the extensibility of the ontological approach.

In the future, our current reasoning system using signs will be expanded to consider more granular changes in parameters by either properly considering precise numeric values computed outside of the ontology rather than positive or negative delta signs. Similarly, window-related logic should be put in place to reason about the effects of other outdoor parameters, such as temperature, on the related indoor space. Furthermore, to be practical in a large room where the available parameters will differ in different points, our ontology must incorporate geometric and thermodynamic reasoning for supporting multiple "sub-environments" and reasoning about what areas of an environment room components can affect. Additionally, such a system should be able to make suggestions considering spatial information and thermodynamic simulation, such as moving a fan to be closer to a certain person with lower temperature preferences.

This ontology could serve as the foundation on top of which to develop an occupant-centric building automation system for improving IEQ and reducing building energy usage, based on 3D geometric models and thermodynamic simulation modules.

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