An Ontology for Proactive Indoor Environmental Quality Monitoring and Control

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ABSTRACT

Proactive monitoring and control of indoor air quality in homes where there are pregnant mothers and infants is essential for healthy development and well-being of children. This is especially true in low income households where cooking practices and exposure to harmful pollutants produced by nearby industries can negatively impact on a healthy home environment. Interdisciplinary expert knowledge is required to make sense of dynamic and complex environmental phenomena from multivariate low level sensor observations and high level human activities to detect health risks and enact decisions about control. We have developed an ontology for indoor environmental quality monitoring and control based on an ongoing real world case study in Durban, South Africa. We implemented an Indoor Air Quality Index and a thermal comfort index which can be automatically determined by reasoning on the ontology. We evaluated the ontology by populating it with test sensor data and showing how it can be queried to analyze health risk situations and determine control actions. Our evaluation shows that the ontology can be used for real world indoor monitoring and control applications in resource constrained settings.

Categories and Subject Descriptors

• Computing methodologies~Ontology engineering **• *Human-centered computing~Ambient intelligence***

Keywords

Indoor Environmental Quality; Air Quality Index; Pollutants; Pollution; Ontology.

1. INTRODUCTION

Pervasive sensing and monitoring of our natural and built environment forms a crucial element in maintaining and advancing human life and activity. Sensor applications include: prevention of natural disasters, avoiding life threatening situations, enhancing productivity, promoting business, and improving health and well-being.

Advances in sensor technology has resulted in widely available low cost sensors. In a typical sensor application real world occurrences are measured and captured as observations by sensors, formatted and transmitted through a communication network to a processing device that analyses and makes sense of the observations to determine if any responsive actions are required [5,9]. Proactive computing aims to bridge the gap between the virtual and the physical world by making computing devices understand the environment, anticipate user actions and in some cases automatically act on his/her behalf [27,28]. Making sense of unbounded data with multivariate observations from heterogeneous sources, taking and enacting decisions about control actions requires a complex interplay of expert knowledge including the sensor, application, context, domain perspectives. For example, the indoor environment is a dynamic and complex system of various environmental phenomena, building features and human activities. Exposure to poor indoor environmental quality is a growing and serious health concern that varies from allergic reactions of sensitive individuals to indoor pollutants, to life threatening illnesses [14,15]. It has been estimated that people spend 90% [1] of their time in indoor environments, which further makes poor indoor environments a serious health concern.

This is especially true in poorer residential communities in certain parts of South Africa where nearby light and heavy industry emit harmful pollutants, cooking practices and lifestyle impact on indoor air quality. In such settings a continuous monitoring system can be implemented with low cost sensor platforms. However, detecting hazardous indoor environment situations and determining control actions to mitigate these requires a wide range of multidisciplinary domain knowledge including sensor data processing, air and environmental quality, and occupational health. Ontologies have been well investigated to be useful in capturing background and expert knowledge from different perspectives, integrating data from heterogeneous sources, building knowledge bases, knowledge acquisition (reasoning), analyze data streams and manage knowledge and system dynamisms [6,17,19,20,22]. The observations recorded from the sensors can be combined with the knowledge of human activity and building characteristics captured in the ontology for analysis.

In this work, we designed, implemented and evaluated an ontology for indoor air quality monitoring and control based on a real world case study. We implemented an Indoor Air Quality Index which can be generated using the ontology. We evaluated

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[1]http://cfpub.epa.gov/eroe/index.cfm?fuseaction=list.listBySubTopic&ch=46&s=343

the ontology by populating it with test data and querying it to analyze indoor environment situations relevant to our targeted scenarios. The ontology is aimed to drive a proactive framework for Indoor Environmental Quality analysis and control. The contributions of this work are: (i) an indoor environmental quality ontology that provides support for representation and reasoning on both low level sensor observations and high level indoor activities for environmental quality analysis. (ii) A semantic Indoor Environment Quality Index.

The rest of this paper is organized as follows. The next Section presents our case study scenario, in Section 3 we discuss related works, in Section 4 we discuss the semantic indoor environmental quality system and the proposed ontology. Sections 5 and 6 presents evaluation and discussion respectively and we conclude and highlight future works in Section 7.

2. CASE STUDY

This work is based on an ongoing study in communities in the highly industrialized south Durban area in South Africa [14,15,21] in which occupational health experts investigate the various effects of exposure to indoor air pollution on pregnant mothers and children.

This area is generally inhabited by low income households. Occupants of houses in such setting are at high risk of indoor pollution. Houses in these areas have the following characteristics in common:

- Mechanical heating ventilation and air conditioning (HVAC) systems are usually not available, therefore ventilation is mainly by natural air infiltration through openings such as windows, doors and vents.
- Indoor activities that aggravates high levels of pollutant concentration include smoking, burning fossil fuel for heating and cooking and burning of incense.
- Nearby light and heavy industry also produce harmful emissions that contaminate indoor air.

The goal of the occupational health care expert is to maintain good ventilation, thermal comfort and harmful indoor air pollutants at acceptable levels. In this setting, occupational health researchers monitor exposure level of sensitive or vulnerable occupants of such buildings by placing expensive and cumbersome pollutant monitors in the indoor environment of the building for a day or two which are then removed and taken to the laboratory for analysis. During the procedure, occupants are also asked to complete activity diaries to collect indoor activity data for analysis. These are then used to understand patterns of air pollution.

There are several limitations and challenges with the current process. It is cumbersome and capital intensive and dependent on manual processing. An occupational health officer needs to physically travel to each house to observe the equipment daily during the monitoring period. The analysis of the result also take several days, therefore it is inadequate to help occupants abate present situations as the result of analysis will only be available some days after the monitoring is completed. Furthermore, the current process has low temporal resolution, as some of the pollutant monitors need several hours usually more than 8 hours to collect enough mass [29, 31].

Our ontology driven indoor environmental quality system attempts to deal with these limitations by proposing a continuous monitoring approach that provides for control feedback in the form of alerts to the occupants in order to take proactive actions to abate unhealthy situation indoors.

2.1 Key Terms

2.1.1 Indoor environmental quality (IEQ)

This is a broad term that describes "*a building's environment in relation to the health and wellbeing of those who occupy space within it.*[2]" In this work our usage scenario is focused on two main aspects of IEQ, Indoor Air Quality and Indoor Thermal Comfort [13].

2.1.2 Indoor Air Quality (IAQ)

We use Indoor Air Quality as a qualitative measure of how good or bad the air in the indoor environment is with respect to pollution or contamination by pollutants.

2.1.3 Air Quality Index (AQI)

We use Air Quality Index as a quantitative measure of the current level of pollution in the air based on the concentration levels of pollutants monitored [14]. An index is a range of values that corresponds to different scales of concentration level and possible health effects of each index. In this work we adopted the structure presented in the Technical Assistance Document for the Reporting of Daily Air Quality - the Air Quality Index by United States Environmental Protection Agency (EPA) [26].

2.1.4 Thermal Comfort Index

Thermal comfort refers to the level of satisfaction that people feel from the mind with respect to heat level of the environment. For the case study in this work we adopted ISO 7730:2005 [3] standard that defined thermal comfort with varying levels of temperature and humidity for summer and winter.

3. RELATED WORKS

Our work has drawn from different research areas especially in the areas of wireless sensor networks (WSN) for air quality monitoring and ontology engineering. The use of pervasive sensing devices and sensor networks to monitor both the indoor and outdoor environmental phenomena for different applications is currently an active research area. Various techniques and architectures exist that have been proposed, these vary from personal sensors such as wearable devices on individuals, fixed devices in the indoor environment to participatory sensing whereby sensors are attached to vehicles for monitoring environmental pollution and air quality using WSN [3,4,11,30].

Jiang et al. [2] proposed a personalized mobile sensing for IAQ monitoring whereby individuals carry portable sensing devices called M-pod that senses the air quality and transmit to the nearest mobile phone through Bluetooth. This collaborative sensing technique is focused on measuring the user's personal exposure to air using a zone based proximity method. [17]. While this system saves energy and allows data sharing among users, it does not include indoor activity in the analysis and also does not offer control of unhealthy indoor air quality.

Bhattacharya et al. [4] proposed a WSN technique that introduced demand control of the HVAC system into IAQ monitoring. The system is based on an ontology driven context aware middleware. The architecture monitors various gases, Particulate Matter (PM_{10}

[2] http://www.cdc.gov/niosh/topics/indoorenv

[3] http://www.iso.org/iso/catalogue_detail.htm?csnumber=39155

and $PM_{2.5}$), temperature and humidity. The framework is able to provide some controls on the HVAC system, however, it does not include occupant's activity in the processing, and the approach will be very impracticable to use in resource constraint settings where mechanical ventilation systems are not affordable.

Saad et al. [24] implemented an indoor air quality index on a wireless sensor network for indoor air quality. The index was implemented as a web service for the occupants to observe and know the status of the house environment. This is related to our work, however, the work did not capture the indoor activities of the houses monitored. Even though the index provides some pointers to pollution status of the indoor environment, the system does not provide any form of control feedback to the occupants, and it does not offer any form of reasoning service as it was not based on ontology.

Ferdoush and Li [11] proposed a Wireless Sensor Network (WSN) using the Raspberry Pi and Arduino prototyping platforms for Environmental Monitoring Applications. The experimental WSN demonstrates the use of low cost, low resource platforms for environmental monitoring. This is suitable for resource constraint settings that our work is focused on, however, the study is only focused on the hardware architecture and networks and did not offer control mechanisms.

In [10] and [16] citizen participatory methods were studied for air pollution monitoring. Wireless sensor nodes are carried by people or installed in automobiles and transmit data via a mobile phone to a central data processing location to monitor urban air pollution. These methods support massive data collection in a simple and cost-effective manner especially in urban areas. However, the approach is focused only on the outdoor environment.

The works in [18] and [23] have attempted ontology approaches to study Air pollution though with different purposes. From the urban planning point of view the work in [18] employed ontology in integrating air quality models and 3D city models. In this approach, the ontology of air quality models was created based on air pollutant dispersion, transport and transformation models and was integrated with CityGML an open information model used for representation and exchange of virtual 3D City Models [18]. This was to help in urban planning process by helping planners deal with air pollution issues. This approach is not specific about indoor air pollution and does not include analysis of indoor activity of occupants and their effect on indoor air pollution.

In [23], an ontology for air pollution analysis and control was proposed and applied in both an expert system and a multi-agent system, an approach focused on urban pollution especially from the industries [23]. While this approach is closer to our work in that it proposes an ontological approach to analyze and control air pollution, it is not focused on the indoor environment, and does not include activities in the indoor environment for analysis and control of air quality.

4. THE SEMANTIC INDOOR ENVIRONMENTAL QUALITY SYSTEM

In the scenario described in Section 2, low cost sensors can be installed in multiple dwellings to observe pollutant levels and transmit observations to a central server which analyses the observations in near real-time by querying the ontology and sends alerts to occupants especially if there is need to take action to abate poor indoor air quality.

Figure 1 shows the key components of our proposed framework. These includes low cost sensors, installed in the monitored houses transmitting sensor data at preconfigured intervals to our proposed framework through a GPRS mobile network. For our initial pilot system we deployed temperature, humidity, Particulate Matter (PM_{10} and $PM_{2.5}$) and Carbon Monoxide sensors on a Raspberry PI and Arduino platform. The server analyses the data using the ontology and sends feedback via an SMS (short message service) to the occupant's pre –registered cellphone when necessary.

The development of the ontology revolved around three core requirements: (i) Adequate representation of sensor measurements pertaining to indoor environmental quality (ii) Representation and reasoning services for analyzing environmental quality situations based on these measurements and for detecting harmful situations; (iii) determining possible control actions to mitigate harmful situations.

4.1 Conceptual Framework

The Indoor environmental quality is influenced by complex interactions of several different phenomena, including natural sources e.g. weather, indoor activities of occupants e.g. cooking, burning fossil fuel, candle or incense indoor, nearby

Figure 1. Semantic indoor environmental quality system.

anthropogenic activities, e.g. nearness to industries, burning bushes or fossil fuel, and also from features and or structures of the building itself such as type of ceiling, number of windows and so on.

After analysis of the case study and several iterations of conceptual modeling we settled on the conceptual framework shown in Figure 2. The framework supports the three design goals of the ontology: The *monitoring* layer captures measurement and observation data. It provides representation support for building environment description, sensor observations and the occupant's activities in the indoor environment. While the environment description provides such data as features in the building, their type and quantity (e.g. number of windows, type of ceiling etc.), sensor observations provide values of sensor measurements of certain properties (e.g. temperature, humidity, pollutants concentrations, etc.) of the environment. The Activity component provides a list of activities that impact positively or negatively on the air quality or thermal comfort of the environment.

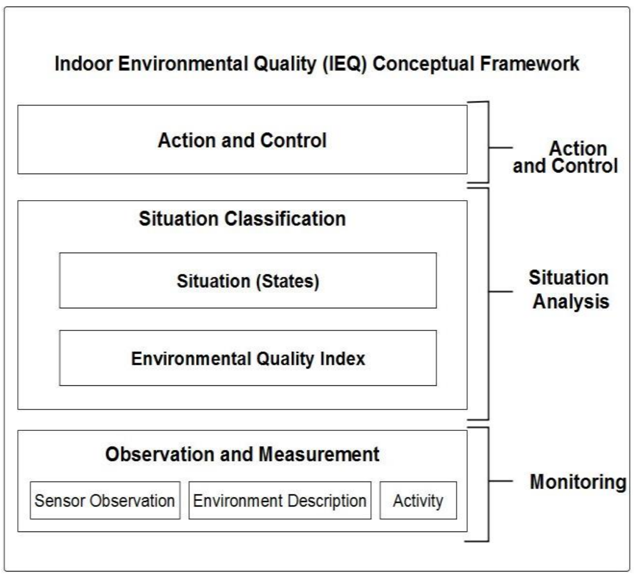

Figure 2. Conceptual framework for indoor environmental quality

The *Situation analysis* layer provides representation and reasoning support for situation detection and classification. The Environmental Quality Index which is a sub-layer of the situation layer is a level of abstraction over observation and measurements that provide support for classifying quantitative observation values to qualitative states (situations) of the environment. The *action and control* layer describes concepts and relationships to determine if any control action is necessary to abate a possible harmful situation.

While our approach is not geared towards activity recognition, by capturing known activities relevant to the indoor environments in the target communities provides crucial knowledge for control feedback that can be exploited to abate poor indoor environmental situation. Some activities are known to induce pollutants, e.g. cooking with paraffin stove in the house is known to increase indoor particulate matter concentration. This approach is especially useful, in low resource settings where complex sensors and activities recognition systems are not available. This makes it possible to control detected poor indoor air quality situations by giving control feedback to the occupants to avoid or perform certain activities in order to mitigate excessive exposure to poor air quality. Known activities in the target households and their expected effect on the indoor environmental qualities are manually captured and stored in the ontology from expert knowledge.

4.2 IEQ Ontology Implementation.

4.2.1 Ontology Principles and design goals

The principles and design goals for our IEQ Ontology are as follows:

- To follow the conceptual frameworks as discussed in Section 4.1 and as shown in Figure 2 and to satisfy the 3 core requirements outlined in Section 4.
- To create an air quality index and thermal comfort index as well as corresponding qualitative states with the ontology based on the case study.
- To reuse relevant existing ontologies.

4.2.2 Ontology Engineering Methodology

We chose to adopt the well-known Methonthology [12] ontology engineering method as it provides sufficient details, support prototyping, and allows reuse of existing ontologies. Methontology proposes seven activity phases for use in building ontology such as specification, knowledge acquisition, conceptualization, integration, implementation, evaluation and documentation. We followed the phases of this method as described below.

- *Specification:* During this phase we defined the core requirements of IEQ ontology as mentioned in Section 4. That is to provide support for (i) Adequate representation of sensor measurements pertaining to indoor environmental quality (ii) Representation and reasoning services for analyzing environmental quality situations based on these measurements and for detecting harmful situations; (iii) determining possible control actions to mitigate harmful situations.
- *Knowledge acquisition*: In this phase we acquire knowledge from domain experts in the field of occupational health and participated in field works in order to acquire domain knowledge.
- *Conceptualization:* In this phase we defined the structure of our ontology starting with glossary of terms from domain vocabulary and built the conceptual model (Section 4.1) by describing the problems and its solutions in terms of domain vocabulary.
- *Integration:* we reused three different ontologies, i.e. the W3 Semantic Sensor Network (SSN) ontology [7], CSIRO's new Time-new ontology [8], and the Activity pattern ontology[4] [1].
- *Implementation:* In this phase we developed the IEQ ontology in the Protégé[5] ontology editor.

[4] http://descartes-core.org/ontologies/activities/1.0/ActivityPattern.owl

[5] http://protege.stanford.edu

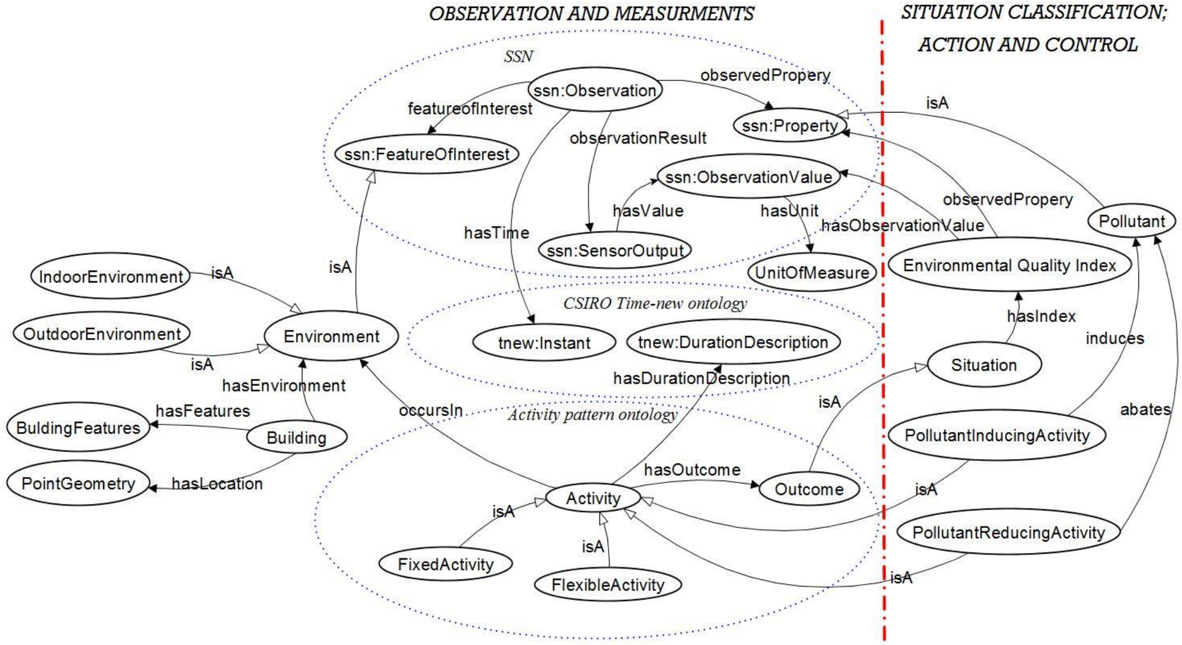

Figure 3. Fragment of indoor environmental quality ontology showing the main concepts

- *Evaluation:* Methontology defines evaluation as carrying out technical judgement on the ontology. As shown in Section 5, we evaluated our ontology by populating it with test data and querying for field scenarios to show that the ontology can achieve the goals of building it.
- Finally, in the *documentation* phase, we documented the process, approaches, implementation and usage of the ontology which led to this paper.

4.2.3 Ontology Implementation

The ontology was developed using the Protégé ontology editor 4.3. Figure 3 shows the key modules and concepts of our indoor environmental quality ontology. The ontology imports the Semantic Sensor Network (SSN) ontology [7], CSIRO's Time-new ontology [8] and the activity pattern ontology [1]. Figure 3 shows the main concepts and relations of the observation and measurement layer of the conceptual framework, described in Section 4.1 and shown in Figure 2.

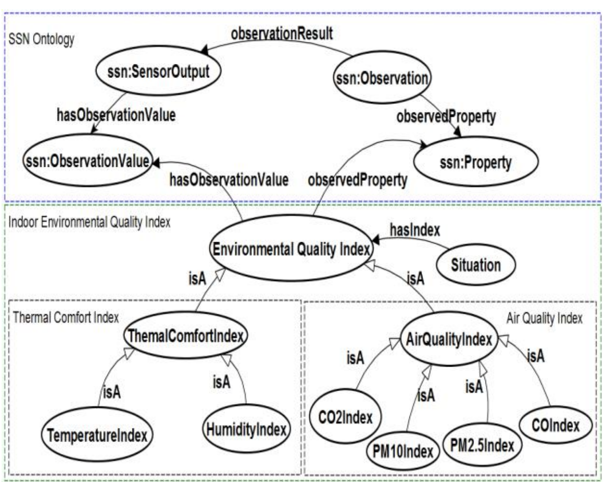

Figure 4. Fragment of IEQ ontology for the situation classification layer

Figure 4 shows the fragment of the ontology for the Situation classification layer of our conceptual model. This includes the Air Quality Index and Thermal Comfort index. While the Air Quality Index aggregates values of indices for each of the pollutants, Thermal Comfort index aggregates both temperature and humidity observation values. The control layer of our conceptual model provides support for representing activities and situations. Figure 5 shows concepts and relationships in the ontology that represent the Action and control layer of the conceptual model. This part of the ontology is used to generate control feedback alerts to building occupants to identify unhealthy situations and recommend activities which can lower pollutant levels.

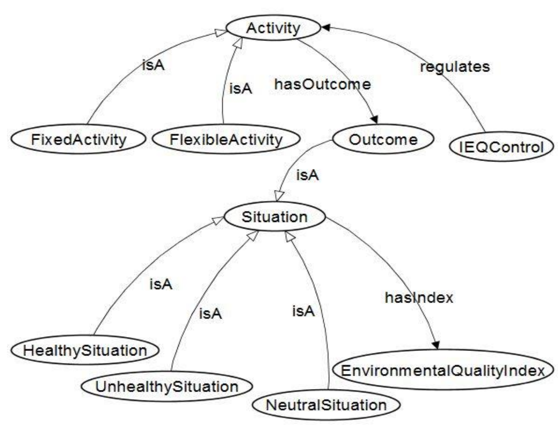

Figure 5. Fragment of the IEQ ontology for the control-action layer

Table 1. Indoor air quality index for Particulate Matter (PM_{10}) adapted from [2, 26]

Air quality /Health risk state	Ontology instance (class) PM_{10}Index	Index Values	PM_{10}	
			Concentration Values (µg/m3)	Description and control action
Good	PM10IndexGood	up to 50	0 - 54	Good Air Quality **Control Advice:** Nil
Moderate	PM10IndexModerate	51 - 100	55 - 154	Moderate Air Quality **Control Advice:** Nil
Unhealthy for Sensitive Groups	PM10IndexUnhealthyforSensitiveGroup	101 - 150	155 - 254	Unhealthy Coarse Particle Level For Sensitive People **Control Advice:** Limit ***{activities that induces fine particles}***
Unhealthy	PM10IndexUnhealthy	151 - 200	254 - 354	Unhealthy Coarse Particle Level for all **Control Advice:** Reduce ***{activities that induces fine particles}***
Very unhealthy	PM10IndexVeryUnhealthy	201 - 300	355 - 424	Very Unhealthy Coarse Particle Level **Control Advice:** Stop all ***{activities that induces fine particles}*** and Do all ***{activities that removes fine particles}***
Hazardous	PM10IndexHazardous	301 - 500	425 - 604	Hazardous Coarse Particle Level **Control Advice:** Consider evacuating the house temporarily and consult IAQ expert

4.2.4 The Air Quality Index

The IEQ ontology allows for representation and automatic calculation of the Air Quality Index from current sensor observations. The Air Quality Index was adapted from the Air Quality Index by the United States Environmental Protection Agency [2, 26]. Table 1 shows the range of values and states represented by the Air Quality Index. It describes six states of health concern, i.e. good, moderate, unhealthy for sensitive groups, unhealthy, very Unhealthy and hazardous. Each state corresponds to a range of index values and the six different ranges altogether comprises index values from 0 to 500. Each pollutant has a range of concentration values that correspond to each state of the AQI. For example (as shown in Table 1), PM_{10} concentrations between 0 and 54ug/m3 correspond to the Good state. A corresponding instance of PM_{10} Index PM10GoodIndex, denotes this state in the ontology. Similarly other states are also represented in the ontology. The unhealthy range of values has control feedback alert messages, which describes what the occupants could do when necessary to abate unhealthy situation detected by the system. The adapted air quality index for PM_{10} is shown in Table 1 as an example. The same was done for all the monitored pollutants.

We used the HermiT 1.3.8.3 reasoner packaged with the Protégé ontology editor to reason over the IEQ ontology, after starting the reasoner, a DL query is evaluated to analyze and determine the air quality state to which the current concentration value corresponds. Table 2 shows the DL query for the PM10IndexGood, the index that correspond to Good air quality state. A similar query is evaluated for each of the indices of the AQI represented by the ontology. In a similar way, the reasoner analyses the current sensor measurements for the different pollutants and determines the health risk state for the pollutant. Besides DL queries, the IEQ ontology also provides support for SPARQL queries using the Jena framework[6].

Table 2. Air quality index for PM_{10} using DL queries

PM_{10} Index	DL Query
PM10IndexGood	Equivalent To (observedProperty value ParticulateMatter10) and (hasValue some double[>= "0.0"^^double , <= "54.0"^^double])

4.2.5 The Thermal Comfort Index

We represented thermal comfort in the monitored houses using temperature and humidity values recorded by sensors. Table 3 shows range of values that are considered thermally comfortable in an indoor environment. Based on the values in this table, Figure 6 shows an example SPARQL query and results in Protégé to determine which houses are too cold.

Table 3. Temperature and relative humidity scale for thermal comfort

	Temperature	Relative humidity
Winter	20^0C - 24^0C	30% - 70%
Summer	23^0C - 26^0C	30% - 70%

[6] http://jena.apache.org/

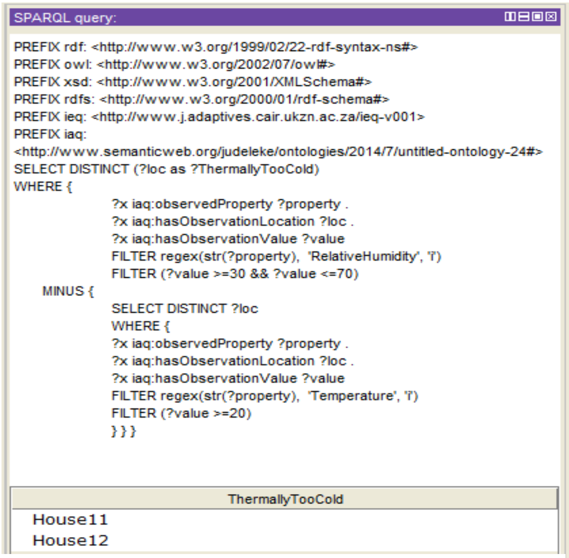

Figure 6. A SPARQL query to find houses that are too cold using our thermal index scale

5. EVALUATION

We evaluated our ontology by demonstrating that it can achieve the purposes and goals of the proposed framework. Our goals are to: (i) Adequately represent sensor measurements pertaining to indoor environmental quality (ii) Provide representation and reasoning services to analyze environmental quality situations based on these measurements and detect harmful situations; (iii) determine control actions to mitigate harmful situations. In order to evaluate our IEQ ontology fulfilled these goals, we populated the ontology with test sensor data and queried it for situations relevant to each of our target scenarios.

5.1 Representation of Sensor Observations

In Figure 7, we show a sample query listing evaluated on the ontology to list the houses and sensor values of locations with unhealthy levels of Particulate Matter (PM10).

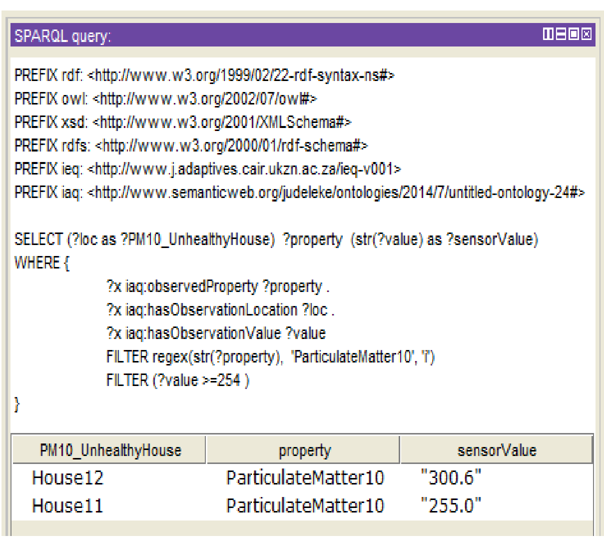

Figure 7. SPARQL query showing houses with unhealthy level of PM$_{10}$

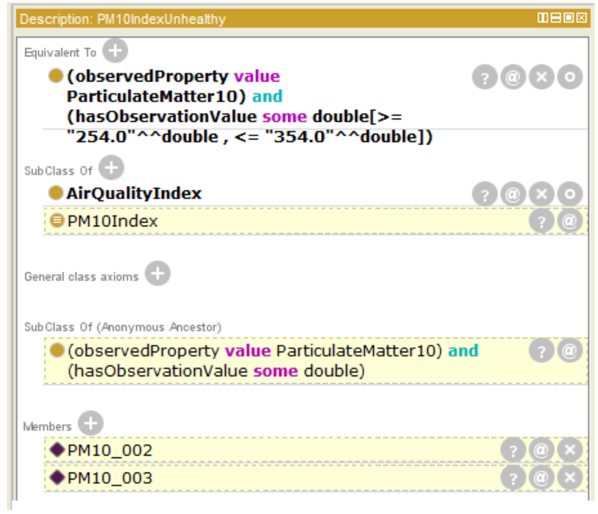

Figure 8. PM$_{10}$ observations automatically classified as unhealthy based on observation value

5.2 Indoor Situation Classification

Indoor situation detection and classification is based on the Indoor Environmental Quality Index (EQI) that is composed of the Air Quality Index and Thermal Comfort index. In Section 4.2.4 and Table 2 we show how the EQI is implemented with DL queries. Figure 8 shows a query for PM10 sensor observation measurements that are classified as unhealthy using the Air Quality Index.

5.3 Control Actions

We designed control actions as alerts that the system sends via SMS to the house occupants when it is necessary to take actions. To evaluate this, we query the ontology for appropriate actions for each situation detected in the indoor environment. Figures 9 and 10 show query listings and results on activities to engage and to avoid respectively in order to abate unhealthy PM$_{10}$ levels.

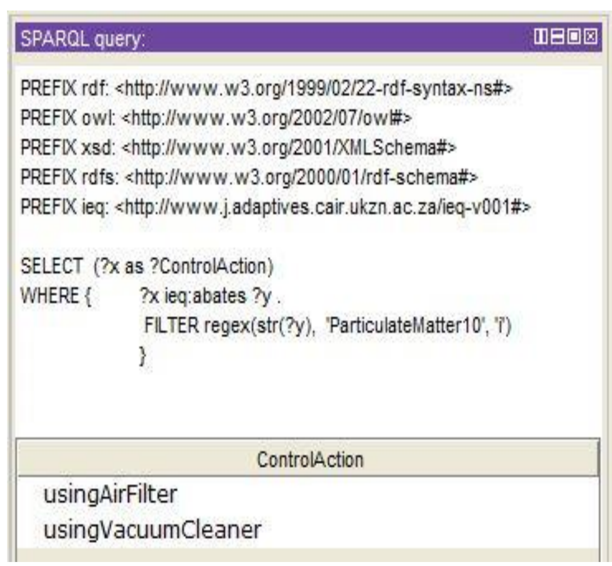

Figure 9. SPARQL query showing actions to abate unhealthy PM$_{10}$ level

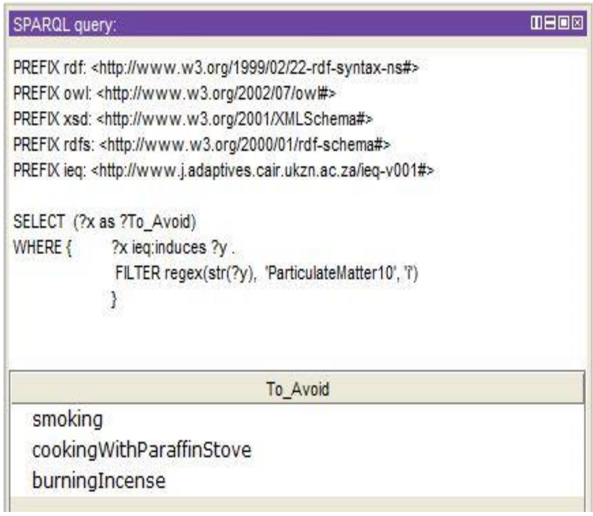

Figure 10. SPARQL query showing activities to avoid to abate unhealthy PM_{10} level

6. DISCUSSION

We provided an ontological framework for indoor environmental situation analysis and classification using an indoor air quality index and indoor thermal comfort index. We defined quantitative and qualitative states (descriptions) for ambient pollutants, which enables us to define the indoor air quality index by querying the ontology for the values on the scales. Our current index is based on scales found in the literature, but since the values and corresponding states are modelled in the ontology, they can easily be modified and tailored towards different target usage scenarios.

A key aspect of the conceptual framework and ontology is that it allows for analyzing quantitative low level sensor observations to produce abstract qualitative situations. It also introduced the notion of indoor activity as a key part of IEQ monitoring and control. The ontology distinguishes between pollutant inducing and pollutant reducing activities. Occupants can be alerted via SMS to minimize or avoid some pollutant inducing activities when the pollutant's concentration is at a level that can negatively impact on their health.

Our approach is not geared towards activity recognition. Rather, the prior knowledge of common activities in each of the houses captured in the ontology is used to provide control feedback to abate poor indoor environmental situation. Our ontology approach to indoor air quality analysis and control supports integrating both occupants' activities indoor with sensor observations to analyze indoor environmental quality, it allows for controlling indoor air quality based on controlling occupants activity. It has been recognized that source control is the most effective way of controlling indoor air pollution.[7] Therefore, our approach allows for exploiting control of some activities that induces pollutants as a measure of abating indoor air pollutants that aggravates undesirable indoor air quality. This makes it useful even in resource constraint settings where HVAC systems are not affordable. However, our IEQ ontology also allows for integration with an activity recognition system or framework when it is available.

Although our ontology is primarily targeted for monitoring the indoor environment to provide feedback control for the occupants in resource constraint settings, the approach can also be applied to several other applications related to indoor environmental quality such as controlling HVAC systems.

[7]http://www.epa.gov/iaq/is-imprv.html#Source_Control

7. CONCLUSION AND FUTURE WORKS

7.1 Conclusion

We have presented an ontology for a proactive indoor environmental quality monitoring and control. The ontology is aimed at driving a proactive system for analysis of indoor air pollution and proactively guide the occupants by sending alerts to the occupants to be able to avoid excessive exposure to indoor pollutants. We have presented our target use case scenario, we reviewed related literature and presented the conceptual framework of the proposed system. Our ontology is evaluated by reasoning and querying the ontology after populating with test data for situation related to the targeted scenario.

7.2 Future Works

We have started to deploy the Indoor Environmental Quality ontology in a real world pilot where it will be integrated with our sensor platform already developed with low cost sensors and prototyping platforms (Raspberry Pi and Arduino). As a step further we have planned to integrate prediction algorithms into the system to enable it to anticipate future pollutant levels in the indoor environment and take proactive adaptive control actions such as providing warnings or triggers to other systems.

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9. REFERENCES

[1] Abdalla, A., Hu, Y., Carral, D., Li, N. and Janowicz, K. 2014. An ontology design pattern for activity reasoning. In *Proceedings of the 5th Workshop on Ontology and Semantic Web Patterns* (WOP2014) co-located with the 13th International Semantic Web Conference (ISWC 2014) CEUR-WS.org, 2014, 1302, 78-81.

[2] Air Quality Index, a Guide to Air Quality and Your Health. *U.S. Environmental Protection Agency Office of Air Quality Planning and Standards Outreach and Information Division Research Triangle Park, NC*. February 2014. EPA-456/F-14-002.

[3] Al-Haija Q. A., Al-Qadeeb H. and Al-Lwaimi A. 2013. Case study: Monitoring of air quality in king Faisal University using a microcontroller and WSN. *Procedia Computer Science,* Volume 21, 2013, Pages 517-521, ISSN 1877-0509, DOI=http://dx.doi.org/10.1016/j.procs.2013.09.072.

[4] Bhattacharya, S., Sridevi, S. and Pitchiah, R. 2012. Indoor air quality monitoring using wireless sensor network. In *Sensing Technology (ICST), 2012 Sixth International Conference on*. vol., no., pp.422,427, 18-21 Dec. 2012 doi: 10.1109/ICSensT.2012.6461713 URL:http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6461713&isnumber=6461638.

[5] Buchmann, A. and Boris K. 2009. Complex event processing. *it-Information Technology Methoden und innovative Anwendungen der Informatik und Informationstechnik* 51.5 (2009): 241-242.

[6] Calbimonte, J. P., Corcho, O. and Gray, A. J. 2010. Enabling ontology-based access to streaming data sources. In *The Semantic Web–ISWC 2010* (pp. 96-111). Springer Berlin Heidelberg. DOI= http://dx.doi.org/10.1007/978-3-642-17746-0_7.

[7] Compton, M., Barnaghi, P., Bermudez, L., GarcÃ-a-Castro, R., Corcho, O., Cox, S., Graybeal, J., Hauswirth, M., Henson, C., Herzog, A., Huang, V., Janowicz, K., Kelsey, W. D., Phuoc, D. L., Lefort, L., Leggieri, M., Neuhaus, H., Nikolov, A., Page, K., Passant, A., Sheth, A. and Taylor, K. , 2012. The SSN Ontology of the W3C Semantic Sensor network incubator group. *Web Semantics: Science, Services and Agents on the World Wide Web*, 2012, Vol. 17(0), pp. 25 – 32. DOI=http://dx.doi.org/10.1016/j.websem.2012.05.003.

[8] Cox, Simon J. D. Time Ontology Extended for Non-Gregorian Calendar Applications. *markers* 4, no. 5: 8. http://www.semantic-web-journal.net/system/files/swj1006.pdf.

[9] David C. L. 2001. The Power of Events: *An Introduction to Complex Event Processing in Distributed Enterprise Systems.* Addison-Wesley Longman Publishing Co., Inc., Boston, MA, USA.

[10] Devarakonda, S., Sevusu, P., Liu, H., Liu, R., Iftode, L. and Nath, B. 2013. Real-time air quality monitoring through mobile sensing in metropolitan areas. In *Proceedings of the 2nd ACM SIGKDD International Workshop on Urban Computing* (p. 15). ACM.

[11] Ferdoush S. and Li X. 2014. Wireless sensor network system design using raspberry pi and Arduino for environmental monitoring applications. *Procedia Computer Science,* Volume 34, 2014, Pages 103-110, ISSN 1877-0509, DOI=http://dx.doi.org/10.1016/j.procs.2014.07.059.

[12] Fernández-López, M., Gómez-Pérez, A. and Juristo, N. 1997. *Methontology: from ontological art towards ontological engineering.* AAAI Technical Report SS-97-06. www.aaai.org.

[13] Huizenga, C., Abbaszadeh, S., Zagreus, Leah, Z. and Arens, E. A. 2006. Air quality and thermal comfort in office buildings: Results of a large indoor environmental quality survey. In *Proceeding of Healthy Buildings 2006*, 3, 393 - 397. UC Berkeley: Center for the Built Environment. Retrieved from: http://escholarship.org/uc/item/7897g2f8.

[14] Jafta, N., Batterman, S. A., Gqaleni, N., Naidoo, R. N. and Robins, T. G. 2012. Characterization of allergens and airborne fungi in low and middle-income homes of primary school children in Durban, South Africa. *American journal of industrial medicine* 55, no. 12 (2012): 1110-1121.

[15] Jafta, N., Jeena P. M., Barregard, L. and Naidoo, R. N. 2015. Childhood tuberculosis and exposure to indoor air pollution: a systematic review and meta-analysis. *The International Journal of Tuberculosis and Lung Disease* 19, no. 5 (2015): 596-602.

[16] Jaimes, L. G., Vergara-Laurens, I., and Labrador, M. A. 2012. A location-based incentive mechanism for participatory sensing systems with budget constraints. In *Pervasive Computing and Communications* (PerCom), 2012 IEEE International Conference on (pp. 103-108). IEEE.

[17] Jiang Y., Li K., Tian L., Piedrahita R., Yun X., Mansata O, Qin Lv, Dick R. P., Hannigan M. and Shang L. 2011. MAQS: a personalized mobile sensing system for indoor air quality monitoring. In *Proceedings of the 13th international conference on Ubiquitous computing* (UbiComp '11). ACM, New York, NY, USA, 271-280. DOI=10.1145/2030112.2030150 http://doi.acm.org/10.1145/2030112.2030150.

[18] Metral, C., Falquet, G. and Karatzas, K. 2012. Ontologies for the integration of air quality models and 3D city models. *arXiv preprint arXiv:1201.6511*.

[19] Moodley D., Simonis, I. and Tapamo, J. R. 2012. An architecture for managing knowledge and system dynamism in the worldwide sensor web. *Int. J. Semant. Web Inf. Syst.* 8, 1 (January 2012), 64-88. DOI=http://dx.doi.org/10.4018/jswis.2012010104.

[20] Moodley, D. and Tapamo, J. R. 2011. A semantic infrastructure for a knowledge driven sensor web. *SSN*, pp. 39-54.

[21] Naidoo, R. N., Robins, T. G., Batterman, S., Mentz, G. and Jack, C. 2013. Ambient pollution and respiratory outcomes among schoolchildren in Durban, South Africa. *South African Journal of Child Health*, *7*(4), 127-134.

[22] Nieto, M. A. M. 2003. *An overview of ontologies*. VUB STAR. Lab.[Online]. Available: http://www.starlab.vub.ac. be/teaching/ontologies_overview. pdf (Accessed May 7, 2015).

[23] Opera, M. M. 2009. AIR_POLLUTION_Onto: an ontology for air pollution analysis and control. *Artificial Intelligence Applications and Innovations III*. Springer US, 2009. 135-143. DOI= http://dx.doi.org/10.1007/978-1-4419-0221-4_17.

[24] Saad, S.M., Md Shakaff, A.Y., Saad, A.R.M. and Kamarudin, A.M.Y. 2014. Implementation of index for real-time monitoring indoor air quality system. *Electronic Design (ICED), 2014 2nd International Conference on*, vol., no., pp.53,57, 19-21 Aug. 2014 doi: 10.1109/ICED.2014.7015770 URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=7015770&isnumber=7015759.

[25] Taylor, K. and Lucas L. 2011. Ontology-driven complex event processing in heterogeneous sensor networks. *The Semantic Web: Research and Applications*. Springer Berlin Heidelberg, 2011. 285-299. DOI= http://dx.doi.org/10.1007/978-3-642-21064-8_20.

[26] Technical Assistance Document for the Reporting of Daily Air Quality - the Air Quality Index (AQI) by U.S. Environmental Protection Agency.

[27] Tennenhouse D. 2000. Proactive computing. *Commun. ACM* 43, 5 (May 2000), 43-50. DOI=10.1145/332833.332837 http://doi.acm.org/10.1145/332833.332837

[28] Want, R., Pering, T. and Tennenhouse, D. 2003. Comparing autonomic and proactive computing, *IBM Systems Journal*, vol.42, no.1, pp.129,135, 2003 doi: 10.1147/sj.421.0129 URL:http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5386845&isnumber=5386828.

[29] Yanosky, J.D. and Maclntosh, D. L. 2001. A comparison of four gravimetric fine particle sampling methods. *Journal of the Air and Waste Management Association.* Vol. 51, Iss. 6.

[30] Yu, T. C., Lin, C. C., Chen, C. C., Lee, W. L., Lee, R. G., Tseng, C. H. and Liu, S. P. 2013. Wireless sensor networks for indoor air quality monitoring. *Medical Engineering & Physics*, Volume 35, Issue 2, February 2013, Pages 231-235, ISSN 1350-4533, DOI=http://dx.doi.org/10.1016/j.medengphy.2011.10.011.

[31] Zhu, Y, Smith, T. J, Davis, M. E., Levy, J. I., Herrick, R. and Hongyu, J. H. 2011. Comparing gravimetric and real-time sampling of $PM_{2.5}$ concentrations inside truck cabins. *Journal of Occupational and Environmental Hygiene*, 8:11, 662-672, DOI: 10.1080/15459624.2011.6172.