Knowledge-based Analysis of Residential Air Quality

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Abstract: This paper proposes an approach for residential air quality investigations (IAQ), building on a knowledge-based theory of building science for systems integration. We present a case study related to the diagnosis of an air quality problem in a residential building, and we suggest that a logic-based formalization can help direct investigators towards solutions. This is a problem of significant practical importance, which has not been specifically addressed in the AI research community. It is envisioned that a formal methodology could improve storage and retrieval of archival information, and it could be used as a reasoning engine for diagnosis.

1 INTRODUCTION

Building Science is the integrated study of building performance. This is an evolving discipline concerned with a wide range of issues, including indoor air quality (IAQ), heating systems, and construction materials (Mora et al. 2011). In this paper, we suggest that a knowledge-based formalization of building performance could lead to the development of automated reasoning tools to support practical investigations.

We focus on IAQ investigations. We suggest that there are at least two ways in which formal methods can inform IAQ investigations. First, a formal ontology representing the domain can clarify exactly how different components of the system interact. Second, given such an ontology, we can automatically diagnose problems through formal reasoning. However, the reasoning required is non-monotonic because conclusions need to be retracted as new information is obtained. This means that a full treatment of the problem may require a precise model of ontology evolution. We propose a solution based on formal models of belief change.

This is a preliminary position paper, outlining the advantages and challenges related to formal reasoning for IAQ investigations. The goal is to outline possible solutions, to be explored in future work in collaboration with building scientists.

2 MOTIVATION

2.1 Building Science Integrated Systems

Air quality impacts human health as well as climate change, due to issues of power consumption. However, the factors influencing air quality can be complex and difficult to measure. Building Science Integrated Systems (BSYS) is the knowledge-based study of building systems, with the goal of developing practical systems to assist in reasoning about problems with building performance.

BSYS research is case driven, using case studies to discover the knowledge used by professionals to diagnose and solve building problems. IAQ investigations are carried out by experts that use working hypotheses to limit the solution space, and also use case-based reasoning associating systems to potential causes (de Mast 2011). IAQ problems are usually identified by occupants' complaints related to odors or breathing problems. An investigation then consists of *screening* for possible sources of the problem, and then *testing* air quality.

Figure 1 illustrates the high-level structure of reasoning involved in IAQ investigations. We remark that, from a formal perspective, the process involves *abductive reasoning, deductive reasoning* and *diagnosis.*

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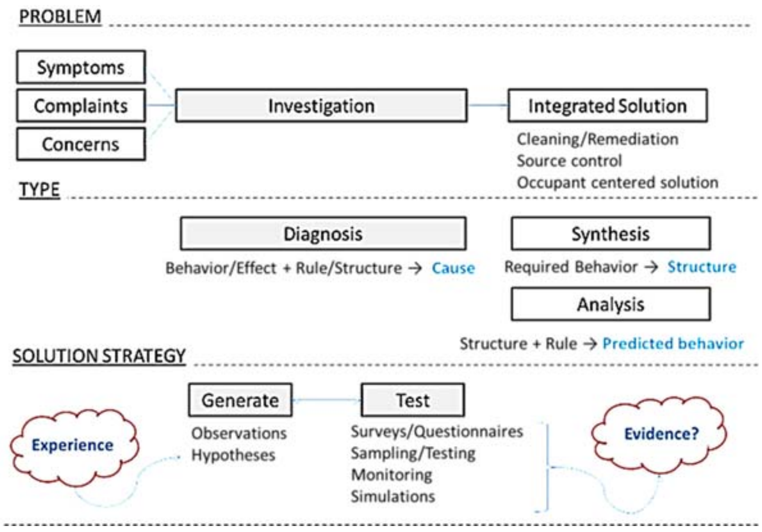

Figure 1: Reasoning about Air Quality.

2.1 Case Study

In this section, we present a case study that will be used to motivate and guide the development of our formal approach. The case study is a microbial investigation of a house with a child with asthma like symptoms. This case study is an informal description of an actual investigation carried out in British Columbia, Canada. The investigation is concerned with asthma symptoms brought on by indoor air quality, as discussed in (Morgan 2004).

The climate around the house is characterized by mild winters with long periods of rain with little sun, and mild summers. The envelope cladding is cedar which is strapped to a wood-frame structural wall. The house has a ventilated attic and an unvented crawl space, which are outside of the conditioned envelope. Electric baseboards are used for heating and ventilation is uncontrolled, through the envelope cracks. The house is occupied by a mother and her child. We present the results of the two preliminary steps of an IAQ investigation for this case study.

Screening:
The goal of screening is to gather quick evidence to test the hypothesis developed as part of the inspection. In this case the initial hypothesis is that the house has "normal and typical" types and amounts of airborne mold spores. This hypothesis could be disproved by observing visible mold.

Sampling/Testing and Monitoring:
From the screening, no mold colonies are observed in the house. Air samples can be taken to verify that the dynamic indoor conditions are within healthy limits, not excessively damp or dry. Laboratory testing can be done to check for spore counts in various parts of the house, such as the attic or basement. In this particular case, suppose that we find a higher concentration of sports in an unventilated crawl space. Based on this, it can be confirmed that there is a high risk of mold spores, that will migrate into the house.

Integrated Solution:
In this case study, the following solution may be proposed:

1. *Contaminant Removal* - clean out existing mold from the attic and crawlspace.
2. *Dispersion Control* – fix air tightness of attic and crawlspace.
3. *Clean Fresh Air Provision* – provide controlled ventilation.

This simple case study serves to illustrate the process that an investigator may follow in an IAQ investigation. Note that the investigation requires screening and testing various possible explanations for a symptom; these tests may be expensive. Note also that the proposed solution is occupant centered. As such, it considers all the house systems that can possibly play a role in affecting the occupant exposure to microbial contaminants in the air. The solution involves three measures to mitigate the exposure of any microbial source by a receptor inside the house.

The fundamental point for our purposes is that the investigator follows a relatively predictable reasoning process. Given the symptoms, we look to verify find possible causes. However, given the cost of the relevant tests and the importance of the solution to the occupants, any AI intervention to guide the process could be potentially valuable.

3 PRELIMINARIES

3.1 Ontologies

An ontology is a formal specification of an application domain, that makes explicit the individuals in the domain as well as the relationships between the individuals. Ontology languages provide a uniform, structured vocabulary for representing and reasoning about objects in a wide range of applications. One of the most popular ontology languages is the Web Ontology Language (OWL) (Motik et. al 2012), which was originally developed for the Semantic Web but has found application in a wide range of applications.

OWL is built on top of the Resource Description Framework (RDF). The syntax of RDF is based on the idea of an RDF triple, which consists of a property that is applied to two individual objects. Hence, RDF is able to express statements of the form

MotherOf (Mary, John)

to indicate that the individual Mary is the mother of the individual John.

OWL extends RDF with additional vocabulary for describing relationships between *concepts*, *properties* and *individuals*. The portion of the ontology that defines roles and concepts is called the *T-Box*; the portion of the ontology that defines individuals is called the *A-Box*. It is significant to note that ontology languages (such as OWL) are first-order logics. ropositional logic is not expressive enough to explicitly capture the distinction between statements about concepts and statements about individuals.

3.2 Answer Set Programming

Answer Set Programming (ASP) is a logical framework for Knowledge Representation based on the notion of finding non-circular solution to sets of constraints (Baral 2003). The constraints are written in the form

$$B \leftarrow A$$

where A and B are propositional variables. This rule is read as an implication, that B is true whenever A is true. An *answer set* for a set of rules is a minimal set of propositional variables that satisfies the rules in a non-circular manner.

Answer set programming has proven to be one of the most effective declarative models for non-monotonic reasoning, and a number of powerful solvers for answer set programming have been developed.

3.3 Belief Revision

Belief revision refers to the process in which an agent must incorporate some new information together with some pre-existing beliefs. One of the most influential approaches to belief revision is the AGM approach (Alchourron 1985). In the AGM approach, the state of the world is represented by an interpretation of a propositional signature. The beliefs of an agent are represented by a set of interpretations K, intuitive the set of states that an agent considers possible. An AGM revision operator is defined syntactically through a set of postulates, and it has been shown that every AGM revision operator $*$ works as follows.1 Given a belief state K and a formula φ for revision, $*$ maps K to a total-preorder $\prec$ over states in which the minimal elements are precisely the elements of K. We think of $\prec$ as a "plausibility ordering" that indicates the most plausible alternatives to the agent's initial beliefs. The revised belief state $K * \varphi$ is the set of $\prec$-minimal states that are consistent with φ.

4 KNOWLEDGE REPRESENTATION FOR BUILDING SCIENCE

4.1 An Ontology for Building Science Investigations

Looking at the case study, it is apparent that IAQ investigations require a great deal of background knowledge and expertise. It is also apparent that, given the required background knowledge, solving the problem involves enumerating all possible states of the world that give rise the reported conditions. One sensible solution, therefore, is to start with a background *knowledge base* that consists of a large set of constraints and dependencies between residential conditions and health outcomes.

The first step towards the development of practical tools to support this process may therefore be the development of a formal ontology. This essentially involves listing all of the relevant components of a building, along with relationships between them.

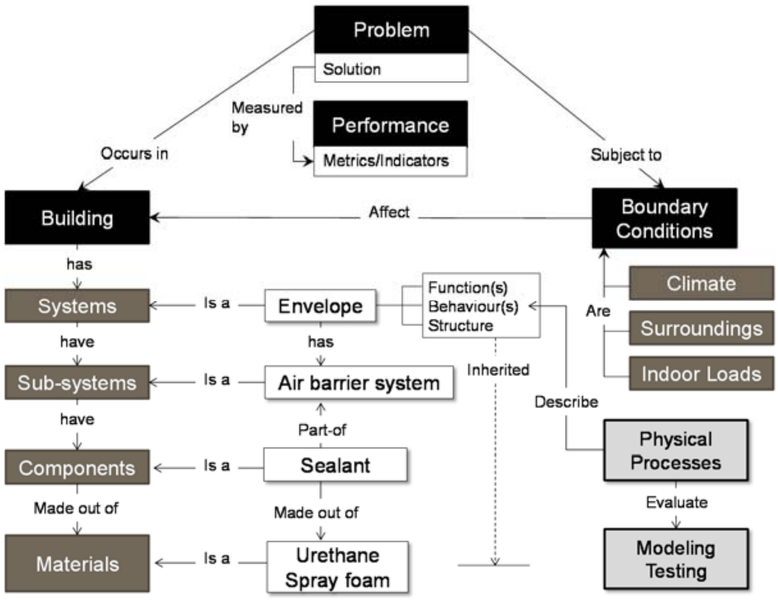

Figure 2: Building Science Ontology.

This can be done through a knowledge acquisition process with Building Science experts. One informal ontology, originally presented in (Mora et al. 2011), is depicted in Figure 2. Of course, this is not a formal ontology; it is simply a partial diagram of key building components. However, it would certainly be straightforward to extend this ontology and translate it into some variant of OWL for reasoning.

4.2 Reasoning about Static Building Performance

Given the required background knowledge, IAQ problem solving involves enumerating all possible states of the world that give rise the reported conditions. If we have a particular symptom, we can then identify all of the minimal world models that support the symptom in a non-circular manner while respecting all background conditions. The natural model for this kind of reasoning is *answer set programming*.

The general approach being proposed here is to develop a set of logic programs that encode expert knowledge of building systems, where the answer sets represent *explanations* of air quality problems. At a very high-level, there may be simple propositional rules, such as:

$$MoldInHouse \leftarrow MoldInRoof$$

While other rules may state conditions on symptoms:

$$AggravatedBreathing \leftarrow MoldInHouse, Asthma.$$

Significantly, these rules must span all relevant background knowledge. For example, in the case study described, every cause of aggravated breathing must be encoded.

4.3 Reasoning with a Dynamic Building Ontology

Ontology evolution occurs when a domain is described by a formal ontology, and we acquire new information about the domain that is not consistent with the current specification. This occurs frequently in Building Science. Suppose we start with an assumption that there is mold in the roof. This will have an impact on air quality, and cascading effects on people living in the house. But two things could change the way this impacts of knowledge:

1. We may look in the roof and discover there is no mold after all.
2. We may remove the mold from the roof.

In both cases, changing our view on the mold in the roof will impact our views on the building performance. Formally, we have to change the ontology representing our building.

Superficially, this is problem is similar belief revision; many authors have proposed that the methods developed in belief revision theory can be applied to ontology evolution problems. However, as noted previously, the most widely known approaches to belief revision are propositional whereas ontology languages such as OWL are variants of first-order logic. As such, it is difficult in the general case to use belief revision operators to capture ontology evolution. However, in the concrete case of Building Science, we suggest that this may not be a problem.

Our suggestion is the following. If the building is being modelled by an OWL-RDF ontology, we can divide the ontology into two components. The A-Box can be translated directly into a propositional theory, in which each statement about an individual is translated into a propositional atom. The T-Box is not translated into a set of logical statements; instead, the T-Box is used to define a total pre-order over interpretations for revision. Intuitively, the plausibility of an interpretation is determined by how many of the T-Box axioms are violated. This approach is motivated by the fact that, in Building Science applications, we actually do not want to change the definitions of properties and concepts. The theoretical advantage of this approach is that we do not have to address any first-order issues in the revision. The practical advantage is that it takes an OWL-RDF input, and it can produce an OWL-RDF output that differs minimally while respecting as many conceptual axioms as possible. As a result, we suggest that it would be possible to implement this approach as a plug-in for the ontology reasoning tool Protégé-OWL.

5 CONCLUSIONS

In this position paper, we have proposed formal logical methods may be useful for reasoning about building performance. At this point, it may appear that the proposed solution is simply some form of advanced expert system. There is a sense in which this similarity is genuine: creating an ontology for building science involves a large knowledge acquisition effort in collaboration with domain experts. This kind of interdisciplinary, practical ontology development has already been effectively carried out in other domains, such as medicine and molecular biology. However, this practical effort is not all that is required; the proposed solution actually requires fundamental theoretical advances in Knowledge Representation and Reasoning.

The main problem that must be addressed here is the issue of *ontology evolution*. In many domains, including building science, the basic ontology used to represent the domain changes periodically as new information is obtained. When the new information conflicts with something in the ontology, some form of conflict resolution must be employed to propagate the new information throughout the ontology without inconsistencies. Many solutions have been proposed for this problem, based on existing work in other areas of Computer Science such as Database Theory or Belief Change. To date, however, there is not a generally accepted approach to ontology evolution. Our belief is that the concrete study of BSYS using ontologies, answer sets, and belief revision operators could provide a step in that direction.

It is also worth noting that using answer set programming to reason with ontologies is an idea that has previously been explored (Magka 2013). As these formalisms have been developed in parallel in different AI communities, it has historically been difficult to combine the two in a practical problem-solving domain. Again, we suggest that this application provides an appropriate domain for reconciling these formalisms, while solving an important practical problem.

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