Ontology Development towards Expressive and Reasoning-enabled Building Information Model for an Intelligent Energy Management System

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Abstract: In recent years, energy consumption in buildings has been rising and is currently representing a significant percentage of the whole energy consumption on earth. The EU has responded this trend by requiring zero energy consumption by 2020 and by supporting innovative research approaches for improving energy efficiency in buildings without decreasing inhabitants comfort. This paper describes the approach to develop an intelligent system for building specific energy management that allows occupants and facility managers to monitor and control the energy consumption and also detects their wasting points. An ontology based information model for building energy management offering expressive representation and reasoning capability is also introduced in this paper. We highlight an approach to develop the ontology as the knowledge base providing the intelligence of the system. Furthermore we demonstrate how the energy performance analysis is improved using the ontology based approach.

1 INTRODUCTION

A study observing building energy consumption held in 2007 showed that the public and residential buildings represent more than 40% of the whole energy consumption in European Union, of which residential use represents 63% of total energy consumption in buildings sector (Balaras et al., 2007). The energy price has been rising due to high building operational costs, and shortage of fossil energetic resources. These reasons force companies and private persons to organize their behaviour in more energy-efficient way and to look for intelligent and long term solutions.

There are several technical possibilities and products on the market aiming to improve energy usage efficiency designed for business and public buildings. European Union has issued the Directive 2002/91/EC about overall energy efficiency of buildings. The directive aims to improve energy efficiency by taking into account outdoor climatic and local conditions, as well as indoor climate requirements and cost-effectiveness. The building energy management systems are acknowledged as a significant source for energy costs reduction up to 30% (Smithson, 2013).

Furthermore, in the future, energy savings in buildings can be increased by intelligence improvement of building automation systems. This kind of method is considered in the literature important as the conventional thermal insulation of walls or insulating glazing to improve energy efficiency in buildings (Lonmark, 2008; Spelsberg, 2006). Recently low cost and low energy consuming building automation technologies have already been developed. Recent technologies offer energy measurement and sensors by using small chips that consume less than 10 mW (Watteco, 2009). These chips can be easily installed in building without modifications.

By using these devices, extra energy consumption can be avoided. However, the energy efficiency could be effectively improved, if they are supported by an intelligent software system. In this paper we propose an intelligent system for energy management in buildings by connecting building automation systems and using intelligent information model. The existing Building Information Model (BIM) standards only defines

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definitions, dictionary and information structure. In this paper, we extend the BIM standard to have more expressiveness and reasoning capabilities. We incorporate rules and axioms to achieve these.

The information model is used in the knowledge base that allows intelligent analysis on the relations between energy consumption, behaviour model (activities and events in the building), building related information (geometry, boundary conditions, etc.) and surrounding factors, such as temperature, weather condition, occupant habits and behaviour. The knowledge base is represented using ontologies. We also introduce the ontology modelling method that is aligned with existing building information modelling standard called Industry Foundation Class (IFC).

This paper is organized as follows. In section 2 we discuss the state of the art and related work. Next, we introduce the developed system of intelligent energy management in section 3. Section 4 describes our approach in generation of ontology as the centre point of our intelligent system. In section 5 we give overview how the energy analysis is performed using ontological query. Finally we make our conclusion in section 6.

2 RELATED WORK

In 2009 Electric Power Research Institute USA conducted research of electricity consumption feedbacks in household. They categorized feedback mechanism based on the information availability into standard billing, enhanced billing, real-time feedback, real-time plus feedback, etc. (Neenan et al., 2009) The research showed that real-time plus feedback leads to the best improvement of energy conservation comparing to the other feedback mechanism, despite the higher cost of implementation. Real-time feedback allows users to monitor their energy consumption and/or control appliances in their home through building automation system (BAS) and home area network (HAN).

Each building automation technology may offer different functionalities, and has its own strength and weakness. For example, the technology digitalSTROM offers good functionality in energy metering, but it does not support occupancy metering. In order to achieve comprehensive energy management by taking into account as much as related conditions and factors, an integration of different building automation systems is required.

Ontology can be used as generic model to facilitate the integration (Reinisch et al., 2008). The ontology is not only used to describe functionalities of building automation systems, but also to represent states of building, and relations with behaviour model and surrounding factors. In this paper, we introduce also method to generate ontology components semi-automatically based on user events and building specific information.

An ontology based approach was introduced in EU funded project ISES based on description logic ontology containing rules and constraints. The ontology is represented with OWL-DL combined with SWRL and is used as the information model for integrated lifecycle energy management in building. The approach addressed not only interoperability issues with other systems, but also allowed quality control by end user using knowledge-based management methods (Scherer et al., 2012).

The EU funded project HESMOS developed an ontology-equipped framework to address the integration of distributed and heterogeneous data from ICT building energy systems. The framework comprises IFC-BIM as a central integration part and a link model to bind the distributed data together. The core link model is represented with OWL, which includes the capabilities of model management and decision support (Guruz et al., 2012).

Both EU projects do not strongly consider the alignment of existing standards, for instance IFC, with the developed information model. They do not include the modelling of occupant behaviour as one of the factors that affects the energy consumption in the building. This paper introduces an approach that addresses these points.

3 OVERVIEW OF THE CONCEPT

In this paper, we propose an intelligent system, which considers different aspects of a building. The system allows the users to have an integrated view of energy consumption in their apartment, office, as well as in entire building. With the help of building automation system and other metering systems installed on the site the energy consumption can be evaluated in different detail levels and quality, for instance, energy consumption per appliance, per group of appliances, per zone in the building, or per user event (Wicaksono et al., 2010). Figure 1 depicts the designed approach of the energy management system developed in our recent research project.

As seen in Figure 1, the generic ontology is

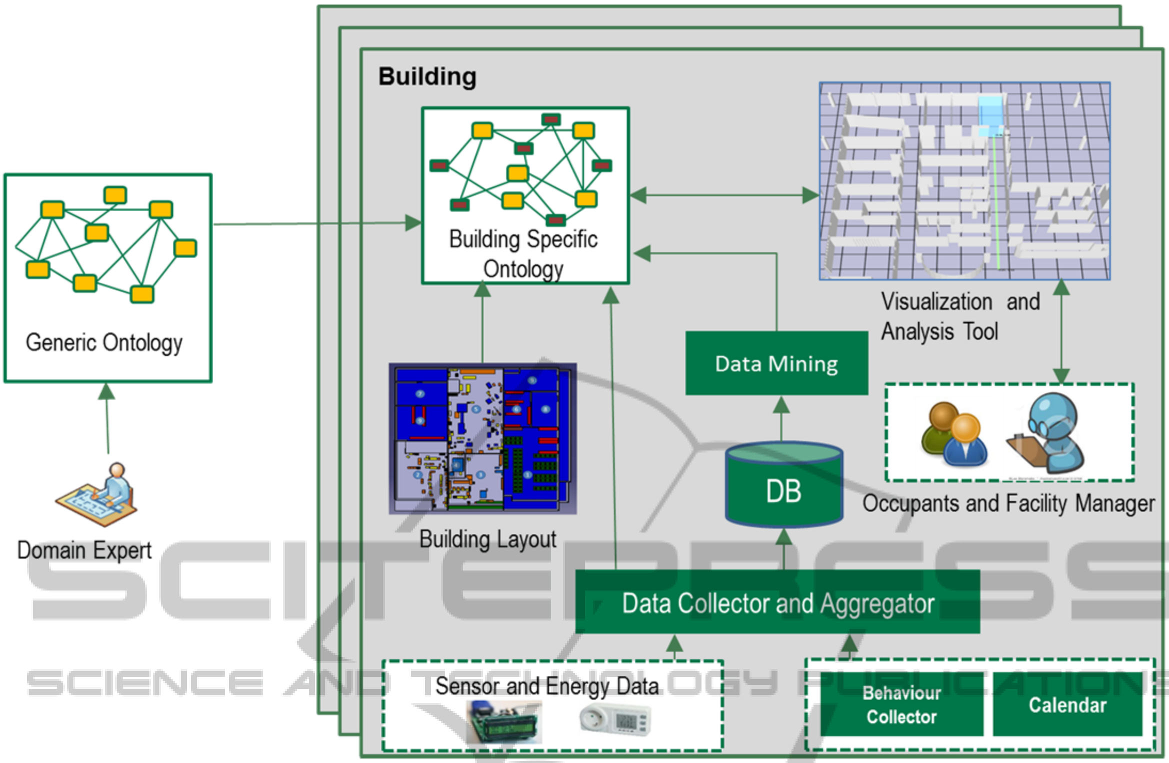

Figure 1: Overview of the developed energy management framework.

created by a building information modelling expert. The generic ontology represents domain knowledge for building holistic energy management. It contains definitions, terminologies (T-box), and taxonomies that are aligned with IFC. The information model contained in the generic ontology is applicable in any building. The generic ontology is then instantiated and enriched with building specific information resulting building specific ontologies. The development of ontology will be explained further in section 4.

The data collector and aggregator module is developed for collecting energy data and sensor data from different building automation systems installed in the building. It contains an interface to communicate with different building automation logic control units or gateways via web services. The module is also responsible to collect occupant activities or behaviours in the building. For this, a web-based interface to model occupant activities is developed. Furthermore, an interface to the calendar reflecting the schedules and activities of the occupants is being developed.

The collected data are aggregated and stored in a database. In order to allow visual representation of energy consumption data, we perform necessary data pre-processing such as removing erroneous values, data transformation, data selection and data conversion. The data are prepared to enable an energy consumption analysis in different criteria based on relation between rooms, appliances, time, and user events. Therefore it allows a data-driven analysis that is conducted directly on the collected data by performing SQL-query, simple calculation, or visualization, for instance, energy consumption per time unit and each appliance. The data is provided in such a form to enable the execution of data mining algorithm for finding the energy usage pattern.

The data mining module evaluates energy consumption data that are collected and aggregated and extracts the knowledge in forms of patterns and relationships from the data. Through this module, energy consumptions can be related to device levels, room, and time, which in addition to that, can be combined with relation to occupant behaviours and surrounding conditions. As seen in Figure 1 the extracted knowledge is incorporated in the building energy management knowledge base represented by building specific ontology. The relationships between data are modelled as rules and represented as SWRL.

A building plan is usually drawn in 2D using CAD software applications, such as AutoCAD.

Unfortunately, 2D-drawings only contains geometrical information, for instance, lines, points, curves, circles, etc. the CAD layouts cannot describe any semantics of building components contained in the drawing. We can still understand semantic of the drawing because we already know the symbols representing certain building components or appliances, such as doors, walls, fridge, etc. (Wicaksono et al., 2010). However different AutoCAD versions provide different representations of the geometrical and object-related information which makes difficult an automated extraction of data. In the frame of the FP7 KnoHolEM project a method to interpret the semantic from 2D-drawings and populate the ontology has been developed. The final aim is to allow a semi-automated extraction of semantic information

The developed tool combines user input with pattern matching methods. The user interprets the CAD layout and the tool maps the CAD layouts to ontology classes and facilitates the creation of ontology individual on the corresponding classes. Thus the ontology will be populated with building specific information coming from CAD layouts.

The resulted ontology allows a knowledge-driven analysis. It means the analysis is not conducted directly on the data, but by utilizing ontology that represents the knowledge.

The visualization and analysis tool facilitates the visual interaction between the user and the system. The building geometry is visualized in 3D. The visualization and analysis tool is an instrument for the end users to query the ontology. By using the tool the facility manager is able to identify energy wasting and anomalies, to examine the building states, e.g. which windows or doors are currently open, etc. The tool also allows the building occupants to have better understanding of the energy performance in their building and it also empower their engagement in balancing comfort and energy efficiency. The occupant can have an overview of the energy efficiency of the zones, where he is responsible for, thus it increases his awareness to avoid energy wasting and achieve more energy efficiency.

4 ONTOLOGY DEVELOPMENT

The knowledge base as the centre point of the developed energy management system is represented in OWL (Web Ontology Language), a W3C specified knowledge representation language (Smith et al., 2004). Basically there are two types of ontologies that we develop. We develop a generic ontology representing a common information model for building energy management, and then it is populated and extended with building specific information resulting more building specific ontologies corresponding to the specific buildings. It is illustrated in Figure 2.

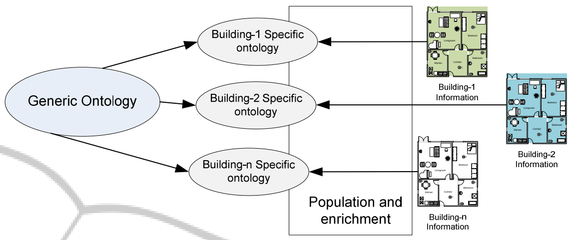

Figure 2: Generic ontology and building specific ontology.

In our work, there are six main steps to develop the ontology resulting a building specific ontology. The steps are illustrated in Figure 3. The following subsections explain each step to develop the ontology.

4.1 Definition of Ontology Main Resources

The ontological classes as well as their attributes and relations representing the resources needed for the energy management in buildings are created manually by experts. It is depicted as step 1 in Figure 3. The ontology containing these hand-crafted elements is called generic ontology. It only contains the ontological classes or Tbox components that describe the knowledge structure, definitions and terminology. It does not contain any ontological individuals or Abox components and contains no building specific information. Figure 4 depicts the ontology main classes representing the different resources needed for the energy management in building.

The class `BuildingElement` models the building structures that are observed, examined and analyzed in energy management activities. The building elements are passive entities which have state, but do not have capabilities to measure or to observe their own states. The class `BuildingElement` and its sub classes represent the fundamental of Building Information Model (BIM). It is aligned with the domain layer in IFC2x4.

The class `BuildingControl` indicates the entities related to building automation system elements in the building. It represents the sensors,

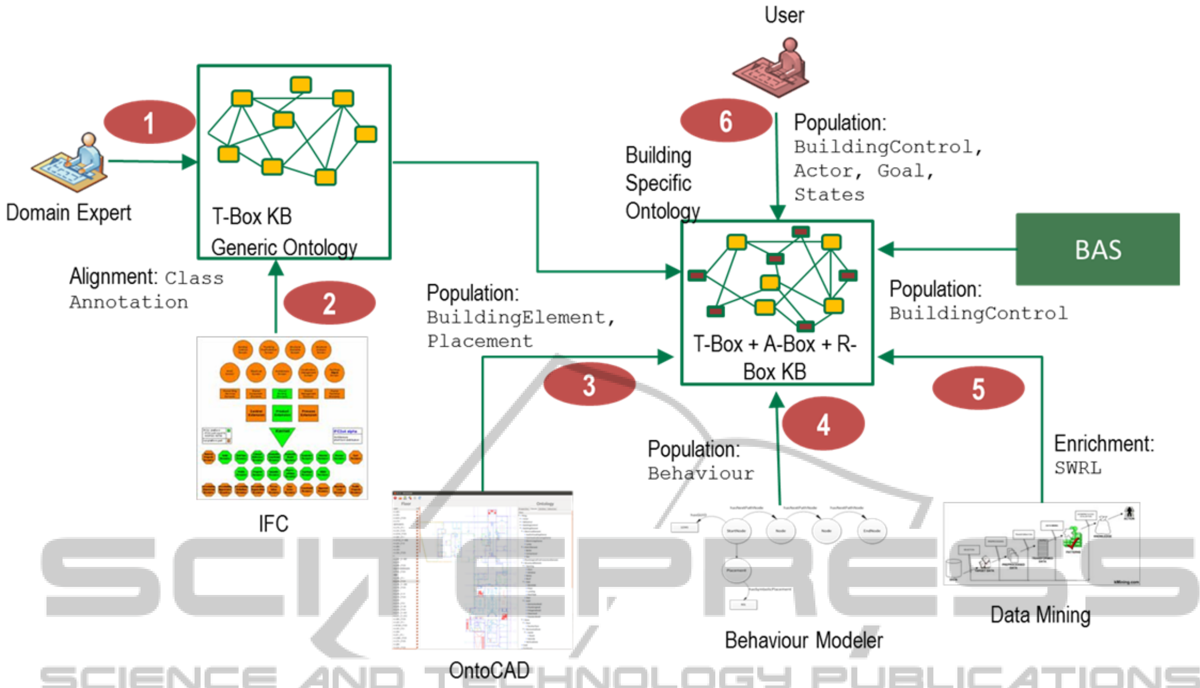

Figure 3: Ontology development process.

actuators, controller, alarm, etc., which are elements of a building automation system. It has capabilities to measure, to observe, and to control the state of `BuildingElement`. It aligns with entities in the IFC2x4 domain *IfcBuildingControlsDomain*.

The class `Actor` represents the human actors having bahaviour that can affect the states of BuildingElement. The `Actor` can be organizations or persons, who have name, postal address, telecom address, etc. It is aligned with the *IfcActorResource* in IFC2x4.

The class `Behaviour` represents behavior performed by `Actor`. The `Behaviour` can affect the state of `BuildingElement`. There are two methods to model the behavior in the building, i.e. bottom up and top down. This will be described further in section 4.4.

The class `State` represents the state of `BuildingElements`. It can be divided as `ComplexState` and `SimpleState`. Examples of `ComplexState` are `ComfortState` and `EnergyEfficiencyState`, whereas examples of `SimpleState` are `WindowState`, `DoorState`, etc.

4.2 Explicit IFC-OWL Mapping

The modern building drawing already contains semantic information represented using IFC entities. To support the ontology population from IFC drawing containing semantic information, we develop a method to map the IFC entity to OWL class explicitly. We use class annotation to perform the mapping. As seen in Figure 5, the class annotation `correspondToIfcEntrity` maps the IFC entity, for instance *IfcWall* to OWL class Wall, and the class annotation `correspondToIfcEnumerationElement` maps the IFC enumeration value *STANDARD* to OWL class `StandardWall`.

The explicit IFC-OWL class mapping accelerates the ontology population process from IFC drawing containing semantic information. If we have an entity in our IFC drawing, by querying the ontology using SPARQL, we can find the corresponding OWL class. For example, the following SPARQL statement finds the OWL class `Wall`, if we have the IFC entity *IfcWall*.

```
SELECT ?class ?ifc
WHERE {
 ?class
knoholem:correspondToIFcEntity ?ifc
.
 ?class
knoholem:correspondToIFcEntity
"IfcWall"
}
```

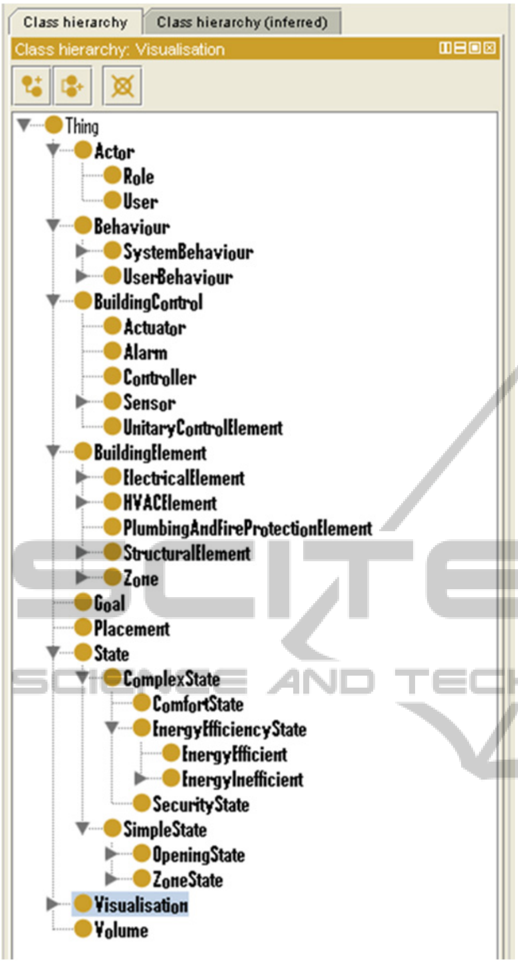

Figure 4: Ontology main classes.

4.3 Population of BuildingElement using Developed Tool OntoCAD

A layout of a building is commonly created as a two dimensional drawing or sketch using CAD software applications, such as AutoCAD. Further AutoCAD-based software tools are used to plan and model many domains of a building, such as ventilation, heating, access controls and photovoltaic (Krahtov et al., 2009). The number of elements in a sketch and its complexity may vary (Donath, 2008). CAD is one of the easiest and oldest technologies used in the industry. At the same time CAD is the least effective technology when it comes to accomplishing building information modeling because it demands a great amount of effort. Recent research shows evidence that it does not ensure high quality, reliable, and coordinated information that the higher level of BIM produces (Vanlande et al., 2008).

We develop a tool to extract the semantic information from CAD drawing and populate the ontology using the extracted semantic information. The tool is called OntoCAD. First, A CAD drawing is exported to DXF. Then we import the primitives in our tool OntoCAD from the exported construction layout files. The primitives are extracted and clustered in layers like they were in AutoCAD. This vector based data representation is the basis for the viewer and the pattern matching algorithms. An important user input at the beginning is the mapping of the ontology specific data and object properties with the OntoCAD functions, for instance the computation of the object position. The implemented pattern matching and classification algorithms recognize building elements based on user defined templates. The user selects an object that can directly be populated in the ontology or he can choose to search for similar objects and then populate all of them at once. He has the possibility to directly validate the result and if necessary apply some corrections to the results. The results are continuously and automatically saved to the ontology.

Figure 5: IFC-OWL explicit mapping.

4.4 Behaviour Modelling

The next step to develop the ontology is the behaviour modeling as seen in step 4 of Figure 3. In our work, we develop two approaches to model the behaviour. The first approach is bottom up. In bottom up approach, behaviours are modeled based on building states. In other words, it is based on the relationships between sensor output values. A simplified example of a bottom up behaviour is as follow:

$$CoffeeMachine \sqcap KitchenOccupied \sqsubseteq CoffeeBreak \quad (1)$$

The system can infer that the activity `CoffeeBreak` currently occurs, if the occupancy sensor in the kitchen shows that the kitchen is occupied, and the coffee machine there is turned on.

The drawback of this approach is that we need a lot of different sensors to be able to give statement about the activities. To model this kind of behaviour is an extensive task. A machine learning method can be helpful to extract the relations representing behaviour from different sensor data.

The second method is the top down approach. The behaviours are modelled using common modelling approaches, such as UML or BPMN diagram. Behaviours are defined as sequences of different sub activities. The drawback of the approach is the impossibility to identify the occurring activities automatically. The system cannot know what kinds of activities are currently occurring in the building. Therefore it needs a manual activity instantiation from the occupants. This kind of manual activity logging causes extensive work to the occupants.

4.5 SWRL Generation using Data Mining

In our work, data mining algorithms are used to identify energy consumption patterns and their dependencies. Data mining is defined as the entire method-based computer application process with the purpose to extract hidden knowledge from data (Kantardzic, 2003). In our work, we use different data mining procedures to generate knowledge for recognition of energy usage anomalies, energy wasting and also to predict the energy consumption.

In this work, we relate the energy consumption with the behavioural occupant's pattern in the building.

We aim to recognize energy consumptions that do not occur normally in the building. To perform this task, we have to know how energies are consumed normally regarding occupant events and surroundings. For example, normally when an occupant is currently working and the outside temperature is comfortable, let us say greater than 20 degrees Celsius, total energy consumption in the building is low, for instance lower than 10 kWh. If in the same pre condition total energy consumption in building is more than 10 kWh, then it is considered as a usage anomaly.

It is difficult for users if they always have to log their activities. In our work we use simple sensors to recognize user activities automatically. Simple sensor can provide important hint about user activity. For instance, an occupancy sensor in a kitchen can strongly give a clue whether somebody is currently cooking. Of course it should be combined with information of appliance states in the kitchen.

The rules representing normal energy consumptions are obtained through data mining classification rules algorithm. The algorithm is based on a divide-and-conquer approach. The created rule (2) shows the probability of 67% about how often it could happen if the activity is working while outside temperature is greater than 20 degree with total energy consumption is lower than 10. This value is called confidence. The rules described in (2) represent a condition that normally occurs. The rule is transformed to (3), in order to represent an anomaly condition, by negating the consequent part of the rule (Wicaksono et al., 2012).

Event="Working" ∧ OutsideTemperature_ ≥20→TotalEnergyConsumption<10 (conf:0.67) (2)

Event="Working" ∧ OutsideTemperature_ ≥20→TotalEnergyConsumption≥10 (3)

The rules created by data mining algorithm are stored in ontology as SWRL. SWRL rule (4) represents the transformed rule (3), which is stored in ontology. The class `UsageAnomaly` is a sub class of `ComplexState`.

UserBehaviour(?e)∧
hasName(?e,"Working")∧
OutsideThermometer (?ot)∧
hasValue(?ot,?otv)∧
swrlb:greaterThanOrEqual(?otv,20)∧
SmartMeter(?sm)∧ hasValue(?sm,?smv)∧
swrlb:greaterThanOrEqual(?smv,10) →
UsageAnomaly(?e) (4)

The rules resulted from data mining algorithm do not always have 100% confidence. Therefore we represent the rules as SWRL in order to enable verification by using SWRL editor such as Protégé. The editor enables users to add, modify and delete the resulted rules.

4.6 Modeling States

In our work we divide the state to `SimpleState` and `ComplexState`. To model both kinds of states, we formulate a set of competency questions. Table 1 gives examples of competency questions in order to model a complex state `EnergyInefficient`

Table 1: Competency questions to model states.

Question-ID	Competency questions	Example of answers
Q1	Which heaters are currently in **energy inefficient** state in the building?	Heater2, Heater3
Q1.1	Which heaters are currently **switched on**?	Heater1, Heater2, Heater3
Q1.2	Which openings are currently **open**?	Window2, Door3, Window4
Q1.3	Which heaters and openings are currently **located in a same closed zone**?	Heater1 and Door1, Heater2 and Window2, Heater3 and Door3, Heater4 and Window4

The SWRL illustrated in (5) implies a complex state of energy inefficiency, if a window is opened, a heater is turned on, and they both are located in a closed zone. The necessary classes are created based on the formulated competency questions. For example, as seen in (5), the classes `HeaterSwitchOn` and `OpeningOpen` are created based on competency questions Q1.1 and Q1.2.

$$^{Q1.1}\mathit{HeaterSwitchedOn(?h)} \wedge {}^{Q1.2}\mathit{OpeningOpen(?o)} \wedge \mathit{Inside(?z)} \wedge {}^{Q1.3}\mathit{isLocatedIn\ (?o,\ ?z)} \wedge {}^{Q1.3}\mathit{isLocatedIn\ (?h,\ ?z)} \rightarrow {}^{Q1}\mathit{EnergyInefficient(?h)} \quad (5)$$

The simple state class `OpeningOpen` is represented as axiom (6). It implies that if an opening sensor gives the value true, and it is installed on a certain opening, it can be inferred that the opening is currently open.

$$\mathit{Opening\ and\ (hasSensor\ some\ (OpeningSensor\ and\ (hasBinaryValue\ value\ true)))} \sqsubseteq \mathit{OpeningOpen} \quad (6)$$

Analogue to the OpeningOpen the simple state `HeaterSwitchedOn` is represented using the axiom (7).

$$\mathit{Heater\ and\ (hasSensor\ some\ (EnergyMeter)\ and\ (hasBinaryValue\ value\ true))} \sqsubseteq \mathit{HeaterSwitchedOn} \quad (7)$$

5 ENERGY ANALYSIS THROUGH ONTOLOGY QUERY

In knowledge base represented in ontology, all conditions of energy wasting and anomalies are represented as SWRL. Periodically data acquisition module requests real-time data from building automation gateway. These data contain states given by all installed building automation devices. SWRL rules are used to decide whether these incoming data correspond to complex states, e.g. energy inefficiency and anomaly condition. We develop a rule engine based on SWRLJessBridge to support the execution of SWRL rules combined with Protégé API that provides functionality in managing OWL ontology.

First the attribute values of relevant ontological instance are set to values corresponding to incoming data. For example, if opening sensor attached to window gives a state "Open", then the attribute `hasState` of corresponding ontology instance of concept `OpeningSensor` is set to "Open". After that the rule engine executes the SWRL rules and automatically assigns individuals to the ontology classes defined in the rule's consequent. For example for rule (5) the instance of class `Heater` is additionally assigned to `EnergyInefficient` class and for rule (4) the instance "Working" of class `UserBehaviour` to class `UsageAnomaly`.

SPARQL is used to evaluate whether energy inefficient condition or energy usage anomaly occurs. Which appliances cause the energy wasting can be retrieved as well. It is performed by querying all individuals of `EnergyInefficient` or `UsageAnomaly` class. If individuals of these classes are found, the affected individuals are visualized and marked in the visualization and analysis tool. With this mechanism, user can have more awareness in order to avoid more energy wasting. SPARQL is also used to perform further analysis for example to retrieve all windows or doors that are currently open. The SPARQL interface is part of visualization and analysis tool.

6 CONCLUSIONS

In this paper we have presented a system of comprehensive intelligent energy analysis in building. In the developed system, we combined classical data-driven energy analysis with novel knowledge-driven energy analysis that supported by ontology. The analysis is performed on information collected from building automation devices. The ontology supported analysis approach provides intelligent assistance to improve energy efficiency in households or public buildings, by strongly considering individual user behavior and current states in the building. Users do not have to read the whole energy consumption data or energy usage profile curves in order to understand their energy usage pattern. The system will understand the energy usage pattern, and notify user when energy inefficient conditions occur.

We have presented also an approach to develop the ontology as the knowledge base of the intelligent energy management system. There are different methods and steps to generate the ontology. We differentiated between generic ontology as generic information model and building specific ontology containing the building specific information. The generic ontology is aligned with IFC to allow interoperability of our system with existing industry standards. We introduced the main resources of the ontology representing the main elements in energy management in building. We presented briefly a tool called OntoCAD to perform semi-automatic extraction of semantic information and population of building elements in the ontology from CAD drawings. We also introduced our approach to model occupant behaviour and building states that affect the energy performance of the building. In this work, we also integrated SWRL rules that are extracted from different data, i.e. energy consumption, sensor data, and behaviour using data mining algorithms.

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