Automation in Construction 86 (2018) 210–225

Contents lists available at ScienceDirect

Automation in Construction

journal homepage: www.elsevier.com/locate/autcon

Ontology-driven development of web services to support district energy applications

J.-L. Hippolyte*, Y. Rezgui, H. Li, B. Jayan, S. Howell

BRE Trust Centre for Sustainable Engineering, Cardiff School of Engineering, Queen's Buildings, The Parade, Cardiff CF24 3AA, United Kingdom

ARTICLE INFO

Keywords:
Ontology design
Domain engineering
Software development
Intelligent web services
Semantic web

ABSTRACT

Current urban and district energy management systems lack a common semantic referential for effectively interrelating intelligent sensing, data models and energy models with visualization, analysis and decision support tools. This paper describes the structure, as well as the rationale that led to this structure, of an ontology that captures the real-world concepts of a district energy system, such as a district heating and cooling system. This ontology (called ee-district ontology) is intended to support knowledge provision that can play the role of an intermediate layer between high-level energy management software applications and local monitoring and control software components. In order to achieve that goal, the authors propose to encapsulate queries to the ontology in a scalable web service, which will facilitate the development of interfaces for third-party applications. Considering the size of the ee-district ontology once populated with data from a specific district case study, this could prove to be a repetitive and time-consuming task for the software developer. This paper therefore assesses the feasibility of ontology-driven automation of web service development that is to be a core element in the deployment of heterogeneous district-wide energy management software.

1. Introduction

Heterogeneity of data representation models and communication protocols is one of the numerous challenges faced by novel urban energy systems, such as microgrids and district heating and cooling networks [1–4]. The holistic and ICT (Information and communications technology) driven management of these energy systems alongside other social, technical, economic and political systems is critical for the sustainable development of cities through the smart city paradigm [5–8]. Further, the optimal coordination of the distributed energy resources is a complex problem that requires intelligent software control [4,5,9]. The components of such intelligent software energy management frameworks need to be able to retrieve dynamic local data from a wide range of devices and systems, including sensors, smart meters, actuators, BMS (building management systems), EMS (energy managements systems), that do not necessarily share common data models or communication protocols, as is the case in the context of an urban district. This paper addresses this gap through an ontology-based software to support the semantic integration of local energy management systems with district-wide intelligent coordination software. The application of ontologies as a common vocabulary among agents will be presented within the context of European project RESILIENT. This project aims to couple renewable energy sources and energy storage within low carbon urban environments [10], through the application of a novel ICT framework. Specifically, RESILIENT couples real-time sensor data and weather forecasts with a simulation engine and a semi-automated optimization engine to provide decision support to all energy management stakeholders from both an environmental and a market-driven perspective. Further, RESILIENT aims to answer the following overarching question: can these heterogeneous physical and virtual components be effectively integrated through a District Information Model (DIM); a semantically formalized description of the socio-technical state of the network? In order to support the objectives of the RESILIENT ICT framework, the final product of this research will play the role of a “mediator”, i.e. an intermediate layer between the clients (the software frameworks that automate decision-making on the district energy system) and the local servers (the BMS/EMS that control and monitor the various components of the district energy system) [11]. A common vocabulary is required to overcome the diversity of metadata in both the intelligent energy management frameworks and the local BMS and EMS. A domain specific ontology is used to capture the underlying real-world concepts that are represented by these metadata (the domain here is district scale energy management) [12]. The development process of the mediation component depends on the machine-interpretable knowledge expressed by this domain ontology. Such an ontology, once deployed in the right operational environment, can

* Corresponding author.
E-mail address: hippolytej@cardiff.ac.uk (J.-L. Hippolyte).

http://dx.doi.org/10.1016/j.autcon.2017.10.004
Received 20 April 2016; Received in revised form 18 September 2017; Accepted 3 October 2017

support real time knowledge querying by the underlying multi-agent framework [13]. The research presented in this paper produced a two-fold solution to the issue of deploying district-wide energy management software. Firstly, in order to provide a semantically accurate representation of the district physical components and stakeholders, a socio-technical ontology of district energy, named ee-district has been developed. The name ee-district stands for "energy efficient district", as its final application is intended to be the optimal coordination of the district energy resources. Secondly, a preliminary way of consuming the ee-district ontology has been implemented. The development of a semi-automated web service generator should facilitate the integration in district-scale energy systems of:

- software components intended to monitor or control energy resources and infrastructures in the district (whether they are accessible directly or through a BMS);
- and software components intended to map the presented data model of these resources and infrastructures with the ee-district semantic model.

The objective of this research is to assess the feasibility of ontology-driven automation of web service development that is to be a core element in the deployment of heterogeneous district-wide energy management software. Following this introduction, Section 2 establishes the grounds for the development of the ee-district ontology by means of a real-world use case. Then, Section 3 gives a short literature review in the related fields of semantic modelling applied to energy applications, ontology engineering methodologies and metaprogramming. In light of this theoretical background, Section 4 presents the methodology followed by the authors to develop the ontology and the web service generator. Section 4.3 details the architecture of the ee-district ontology. Sections 5 and 6 discuss the effectiveness of the designs presented in the previous section by means of their implementations. Section 7 discusses notable related works and the potential benefits of the ontology-driven generation of web services to the field of urban energy management before the conclusion gives an overview of the work achieved as well as directions for future work.

2. Motivating use case

The RESILIENT project should cater to a wide range of socio-technical energy management problems faced by facility managers or owners. These problems are getting more complex due to the increasing amount of factors that needs to be taken into account, to deliver a holistic (i.e. systems engineering) solution. One such case study was identified in the Ebbw Vale pilot site. The district information model aims to cater to such problems. The Ebbw Vale pilot site, a district named "The Works", is situated in South Wales, United Kingdom covering a total area of 750,000 m^2. It has newly constructed, as well as retrofitted, buildings, operating in various sectors — educational, commercial and leisure. As shown in Fig. 1, the site consists of a learning centre, schools, offices, a multi-storey car park, a leisure centre and an energy centre. The energy centre is the source of heating to buildings and also provides low voltage electricity directly to the learning centre and the car park. The energy centre consists of a 342 kW gas-fueled CHP (Combined Heat and Power), a 1.6 MW biomass boiler, and additional supplementary gas boilers. It is also the main source of heating energy for the buildings on site. The CHP produces electricity, which is used mainly by the learning centre. Electricity is also being supplied by an 8 MW HV ring main supply. One of the use cases identified in this pilot site involves optimizing the multi-energy generation mix of the energy centre. Currently the heat exchangers of the energy hub, which provide district heating, work at fixed setpoints. Optimization of setpoints according to varying demand and environmental conditions could bring about significant energy savings and greenhouse gas emission reduction. The ee-district ontology helps capture semantic knowledge in a district, like Ebbw Vale, and makes this information machine understandable. The information collected consequently helps decision making software to optimize the day to day operations in the district. The optimization aims to reduce green house gas emissions while taking into account the various constraints — technical, environmental, and economical. The proposed ee-district ontology will play a key role in supporting the delivery of semantic optimization and decision making capabilities as elaborated in the paper.

3. Theoretical background

This section summarizes the relevant literature with a focus on: ontologies for energy management, ontology engineering methodologies, and metaprogramming and web services.

3.1. Ontologies for energy applications

Semantic modelling in energy applications has the potential to support (a) automatic control of the grid operation, (b) computer-aided decision making for human intervention, (c) data sharing among numerous components and tools, and (d) integration of the grid functionality [14]. Rohjans et al. (2010) combined domain ontologies based on the "Common Information Model" (CIM) with "Object Linking and Embedding for Process Control Unified Architecture" (OPC UA) and web services in order to design service oriented architectures for smart grid utilities [15]. In short, the proposed semantic model allowed to identify "which service provides which function under which conditions". Conversely, Uslar et al. (2010) pointed out limitations in the CIM, in terms of (a) scalability (integration of new objects and relations corresponding to new grid technologies), (b) multi-utility support, and (c) integration of the IEC 61850 standard for the design of electrical substation automation (information technology layer and control layer) [15]. Zhou et al. (2012) developed a smart grid information model relying on ontologies for: electrical equipments, organisations, and infrastructures; factoring in weather and spatio-temporal information. Andrén et al. (2013) addressed the problem of adaptability in smart grids [16]. These authors proposed a holistic approach that harmonises modelling, design and validation. Their approach relies on semantic models that extend existing standards. The lack of a self-contained ontology dedicated to district energy management lead the authors to develop their own ontology, which captures the knowledge of this specific domain while relying on a selection of fundamental reused ontologies.

3.2. Ontology engineering methodologies

Many ontology development methodologies have been brought since the dawn of formal ontology languages, including: Ushold and King's methodology [17–19], METHONTOLOGY [20], On-to-knowledge methodology [21], NeOn [22], and UPON [23]. In the middle of the nineties, Ushold, King and Grüninger have popularised some of the now commonly used terminology in the field of ontology development, starting from Tom Gruber's definition of ontology as the "specification of a conceptualisation" [24], which is now widely accepted in the Artificial Intelligence community and more generally in the field of computer and information science. Their methodology brings together formal and informal ontology design approaches. It first helps to categorise ontology usages according to the required level of formality, the targeted purpose and the reusability potential in various contexts. Then it provides guidelines on how to conceptualise a domain of study by collating the involved elements of the considered "real world system" and by identifying the requirements through usage scenarios and competency questions. METHONTOLOGY also provides guidelines on the main subtasks to develop new ontologies. METHONTOLOGY distinguishes between the actual phases of ontology engineering (planification, specification, formalization, integration, implementation and