Automation in Construction 84 (2017) 154–165

Contents lists available at ScienceDirect

Automation in Construction

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

Usability evaluation of a web-based tool for supporting holistic building energy management

Kris McGlinn[a], Baris Yuce[b,e,*], Hendro Wicaksono[c,d], Shaun Howell[e], Yacine Rezgui[e]

[a] ADAPT Centre, The Knowledge and Data Engineering Group, School of Computer Science and Statistics, Trinity College Dublin, Dublin, Ireland
[b] College of Engineering, Mathematics and Physical Sciences, Streatham Campus, University of Exeter, EX4 4QJ Exeter, UK
[c] Institute for Information Management in Engineering, Karlsruhe Institute of Technology, Karlsruhe, Germany
[d] Department of Management, Airlangga University, Surabaya, Indonesia
[e] BRE Institute of Sustainable Engineering, School of Engineering, Cardiff University, Queen's Buildings, The Parade, Cardiff CF24 3AA, UK

ARTICLE INFO

Keywords:
Ontology
BEMS
Genetic algorithm
Artificial neural network
Fuzzy logic
Information visualisation
IFC

ABSTRACT

This paper presents the evaluation of the level of usability of an intelligent monitoring and control interface for energy efficient management of public buildings, called BuildVis, which forms part of a Building Energy Management System (BEMS.) The BEMS 'intelligence' is derived from an intelligent algorithm component which brings together ANN-GA rule generation, a fuzzy rule selection engine, and a semantic knowledge base. The knowledge base makes use of linked data and an integrated ontology to uplift heterogeneous data sources relevant to building energy consumption. The developed ontology is based upon the Industry Foundation Classes (IFC), which is a Building Information Modelling (BIM) standard and consists of two different types of rule model to control and manage the buildings adaptively. The populated rules are a mix of an intelligent rule generation approach using Artificial Neural Network (ANN) and Genetic Algorithms (GA), and also data mining rules using Decision Tree techniques on historical data. The resulting rules are triggered by the intelligent controller, which processes available sensor measurements in the building. This generates 'suggestions' which are presented to the Facility Manager (FM) on the BuildVis web-based interface. BuildVis uses HTML5 innovations to visualise a 3D interactive model of the building that is accessible over a wide range of desktop and mobile platforms. The suggestions are presented on a zone by zone basis, alerting them to potential energy saving actions. As the usability of the system is seen as a key determinate to success, the paper evaluates the level of usability for both a set of technical users and also the FMs for five European buildings, providing analysis and lessons learned from the approach taken.

1. Introduction

Taking into account the whole Building Lifecycle (BLC), which includes the life stages of a building from design, through construction, operation, and on to eventual demolition/recycling [1,2], buildings are responsible for about 50% of total energy consumption in the EU [3]. The EU has established the Energy Performance of Buildings Directive (EPBD) [4], which by 2019 requires public buildings to consume zero energy. New strategies to reduce energy consumption during the operational phase of the BLC are a necessary step to achieving this goal. Energy use during operation is strongly influenced by the operation and utilisation of the different spaces [5] and the behaviours of occupants [6]. A large number of variables introduced through these interactions makes the task of reducing energy consumption challenging. Tools which monitor and analyse the different factors that contribute towards building energy consumption, so that actions may be taken (or enable to be taken) to improve energy efficiency, whilst also maintaining or improving user comfort, are required.

Within the commercial domain, tools already exist which provide methods for analysing energy consumption of devices and areas in a building [7–9]. These tools provide various platforms to visualise actuators status, historical data and device health status based on different time stamps and ranges. However, there are limitations to these traditional building energy management systems (BEMS). Firstly, there is a lack of flexible and user-friendly interfaces which provide integrated knowledge about the entire built environment in a manner which is accessible to the user, e.g. Facility Managers (FM). There is also a lack of intelligent control systems which go beyond the

* Corresponding author at: College of Engineering, Mathematics and Physical Sciences, Streatham Campus, University of Exeter, EX4 4QJ Exeter, UK.
E-mail addresses: Kris.McGlinn@scss.tcd.ie (K. McGlinn), B.Yuce@exeter.ac.uk (B. Yuce), Hendro.Wicaksono@kit.edu (H. Wicaksono), HowellSK5@cardiff.ac.uk (S. Howell), RezguiY@cardiff.ac.uk (Y. Rezgui).

http://dx.doi.org/10.1016/j.autcon.2017.08.033
Received 3 November 2016; Received in revised form 20 August 2017; Accepted 30 August 2017
Available online 09 September 2017
0926-5805/

traditional approach of relying on the user's expert knowledge of the building, to enact energy saving changes to building configuration. To overcome the above weaknesses, a holistic and intelligent solution for FMs is required. This should be capable of running autonomously and provide knowledge about the entire built environment in near real time for enhanced decision support.

Within the research community, various systems and methodologies have been suggested to provide this kind of intelligent control to support energy management [10]. These systems bring together buildings sensory and actuation infrastructure, to measure and enact change in the environment, and the building control and automation systems [11]. For automated intelligent control, the sensitive nature of user comfort remains. This means, it is not always possible to adapt heating, cooling, and ventilation without consent from the responsible party (e.g. the FM), as the consequences of changing set points could be contrary to their responsibilities of providing adequate user comfort. The holistic knowledge-based intelligent system must, therefore, work with the FM, informing them about energy saving strategies, but also leaving them with final control over implementation of new configurations.

This paper presents a holistic, flexible knowledge-based intelligent system, the evaluation of its level of usability and lessons learned from applying the approach taken. The proposed solution consists of a user-friendly web-interface (BuildVis) which interacts with the holistic intelligent decision support system, and enabling the FM to configure building environment optimisation. As it is the FM who must use the proposed solution (framework), the level of usability of the interface is a key indicator of success. The proposed framework presents suggestions, through the interface, which are designed to be simple to understand and execute. The suggestions are generated through analysis of building data using data mining techniques and theoretical rule generation based upon energy simulations. This hybrid approach of real and simulated rule generation is required due to the varying number of sensors available and the need to keep costs down by not introducing extra sensor installations into the building.

From this analysis, a rule base is developed which is triggered according to the changing values of the available building sensors and set points in near-real time. These are presented to the FM, who may then enact the changes. To support the integration of multiple data sources and improve interoperability, the solution makes use of building information modelling (BIM) principles and semantic web technologies in the form of a holistic knowledge base, into which the rules are integrated. The paper is structured as follows: the following section discusses relevant existing work. Next, the requirements and implementation of the tool are presented. Finally, the BEMS GUI interface is discussed before its evaluation and a discussion of the results are given.

2. Background

This section presents the background and related studies for the existing building energy management systems (BEMS) and their subsystems. It is divided into six parts; an overview for the BEMs, sensing and activation infrastructure in the built environment, simulation to supplement sensor data, data modelling and data management, data monitoring and control and finally social and behavioural considerations in energy efficient buildings.

2.1. Building energy managements systems

'Building Energy Management System' (BEMS) is a term used to encapsulate a number of systems developed to improve the energy efficiency of operational buildings. BEMS collect data about the current state of the building, analyses this data and then, either a/provides analysis and feedback to an appropriate stakeholder, who must enact some change or reconfiguration of the building's systems, or b/an automated control system acts upon the available data to reconfigure the building automatically. Conceptually, a BEMS architecture can be categorized into different layers, for example; the sensor layer, computational layer, and application layer. Collectively, these monitor environment states, perform statistical and algorithmic analysis, and provide feedback and control mechanism to users [12].

As an alternative architecture in the smart home domain, BEMS can be divided into four components; the sensor and actuation infrastructure, middleware, processing engine, and user interaction interface [10]. In this architecture, the sensor and actuation infrastructure handles all interaction between the digital infrastructure and the physical environment. The middleware integrates the infrastructure through a common interface. The processing engine conducts some 'processing' on the collected data to learn about the environment and building user activities so as to improve the buildings energy consumption. Data on the environment includes measurements relating to temperature, CO2, humidity etc. (see Section 2.2). User activities include scheduled activities (office work, meeting, lunch, etc.) and interrupt activities (toilet break, drink, exercise) [49]. The user interaction interface then supports interaction with end users; sending them notifications to stimulate behaviour, gather feedback and commands from them. Other architectural configurations for buildings and smart homes can be found in [13,14] which define the similarities and differences in the sensing, data management and reasoning and human interaction layers. These separations of concern form the basis of the framework defined in this paper.

2.2. BEMS sensing and actuation infrastructures

To monitor the built environment, BEMS require a sensing infrastructure to measure phenomena such as temperature, humidity, lux levels, CO2, and occupancy. This is achieved through the use of sensing technologies like PIR (passive infrared), thermostats, CO2, ultrasound, cameras, and/or tag based system, like RFID, Bluetooth and Ultra-Wide Band [15,16]. Based on these measured data, BEMS can adapt device behaviour to reduce energy consumption whilst also maintaining comfort levels, for example, by adjusting HVAC to a desired temperature. A common issue for commercial BEMS is the limitation of the sensing infrastructure. For example, occupancy detection is central to many BEMS systems [6,15,17], but existing sensor installations like PIR can only detect movement, and so, calculating numbers of occupants is difficult [6]. Reasoning and sensor fusion can be used to make inferences about more complex behaviours, but, these systems are not commercially available yet [16].

2.3. Energy simulation and surrogate models

There is a general lack of sensing infrastructure in existing buildings. Further, the investment cost of a comprehensive sensing network is often prohibitive due to a long return on investment period. This leads to the role of simulation being pivotal in predicting building behaviour [18–19] for retrofit BEMS installations. Physical building simulation tools such as EnergyPlus [20] are able to supplement the directly sensed observations with comprehensive predicted knowledge about the building's response to potential control scenarios. In order to mitigate the time per simulation, for use in optimisation algorithms, surrogate models can be used [21]. This use of simulated data to train machine learning software, which can then approximate the simulation outcome within a narrower decision space, in far less time. However, integrating data within a BEMS from such software, simulation tools, physical sensors, and occupants, requires a comprehensive and robust approach to interoperability across these heterogeneous resources.

2.4. Data management in BEMS and linked data

BEMS data integration requires consideration of the underlying data