Advanced Engineering Informatics 27 (2013) 496–505

Contents lists available at SciVerse ScienceDirect

Advanced Engineering Informatics

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

Extending the information delivery manual approach to identify information requirements for performance analysis of HVAC systems

Xuesong Liu [a,*], Burcu Akinci [b], Mario Bergés [b], James H. Garrett Jr. [b]

[a] Carnegie Mellon University, Pittsburgh, PA 15213, United States
[b] Dept. of Civil and Environmental Engineering, Carnegie Mellon University, Pittsburgh, PA 15213, United States

ARTICLE INFO

Article history:
Received 16 August 2012
Received in revised form 6 May 2013
Accepted 20 May 2013
Available online 29 June 2013

Keywords:
Information requirement
Information delivery manual
HVAC systems
Performance analysis algorithms

ABSTRACT

Heating, Ventilation and Air-Conditioning (HVAC) systems account for more than 15% of the total energy consumption in the US. In order to improve the energy efficiency of HVAC systems, researchers have developed hundreds of algorithms to automatically analyze their performance. However, the complex information, such as configurations of HVAC systems, layouts and materials of building elements and dynamic data from the control systems, required by these algorithms inhibits the process of deploying them in real-world facilities. To address this challenge, we envision a framework that automatically integrates the required information items and provides them to the performance analysis algorithms for HVAC systems. This paper presents an approach to identify and document the information requirements from the publications that describe these algorithms. We extend the Information Delivery Manual (IDM) approach so that the identified information requirements can be mapped to multiple information sources that use various formats and schemas. This paper presents the extensions to the IDM approach and the results of using it to identify information requirements for performance analysis algorithms of HVAC systems.

1. Introduction

Heating, Ventilation and Air-Conditioning (HVAC) systems account for more than 15% of the total energy consumption in the US [1,2]. However, research studies show that about 10–40% of the energy used by HVAC systems is wasted due to degradation faults, such as biased or drifting sensors, malfunctioning controllers, stuck dampers and fouled coils [3–6]. Actively detecting faults requires continuously monitoring and analyzing the status of hardware and software components that are part of HVAC systems. However, due to the increasing complexity of HVAC systems, manually monitoring thousands of components in these systems is very challenging and impractical [7–10]. Hence, researchers have developed computer algorithms in the past 20 years to automatically analyze and improve the energy performance of HVAC systems. Examples of these algorithms include computer-aided fault detection and diagnosis (FDD), automated commissioning and optimized operating schedules [11–13].

Laboratory experiments have been conducted to validate the energy saving capability of these performance analysis algorithms [14–16]. However, very few of real-world facilities have deployed them. One primary reason identified by several researchers is that it is very difficult for system operators to manually collect the information required by these algorithms. For example, Jagpal [7] discussed seven barriers to automated fault detection for HVAC systems, of which four are related to the difficulties associated with collection of the needed information: (1) detailed design data are seldom available; (2) measured data are unavailable; (3) some variables cannot be measured directly; and (4) design intent is poorly specified [7]. Similarly, Luskay et al. [8] emphasized the importance and difficulties of collecting needed information for automated and continuous commissioning tools [8]. In a previous study, the authors have analyzed these performance analysis algorithms and found that they require a variety of information, such as the dynamic sensing measurements and control signals, the configuration and specification of the HVAC subsystems and components, and the property of the building elements [17]. These information items are created by engineers from different disciplines including architecture, mechanical engineering and structural engineering, and managed using a variety of dispersed documents and software tools such as design drawings, spreadsheets, diagrams and manuals [18]. Hence, it is very challenging for system operators to manually collect and integrate all the information required by performance analysis algorithms.

To address the challenge of deploying performance analysis algorithms in different buildings and HVAC systems, the authors

* Corresponding author. Tel.: +1 (412) 953 2517.
E-mail addresses: pine@cmu.edu (X. Liu), bakinci@cmu.edu (B. Akinci), marioberges@cmu.edu (M. Bergés), garrett@cmu.edu (J.H. Garrett Jr.).

1474-0346/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.aei.2013.05.003

previously proposed a self-managing framework that integrates heterogeneous sources of information about the building and HVAC systems and automatically provides the required information to different algorithms [17]. In order to automatically provide the required information, this self-managing framework first needs an information repository that contains all information required by different algorithms. These algorithms are described by researchers in academic and scientific publications, such as journal articles, conference papers, theses and research reports [9–16]. Hence, these publications need to be explored and analyzed such that information requirements contained in each publication can be identified and documented. The objective of the study described in this paper is to investigate a formal approach to identify and collect a general set of information requirements of performance analysis algorithms for HVAC systems.

The Information Delivery Manual (IDM) approach was developed by the buildingSMART alliance to identify the processes that are undertaken within a building project and the information required by each process [19]. Its objective is to support the information specified by the Industry Foundation Classes (IFC) schema [20], which provides a standard way to represent and manage the semantic-rich information of building projects. However, according to our review of performance analysis algorithms for HVAC systems, it was found that IFC schema only covers about 60% of the information required by these algorithms. Hence, in order to increase the coverage of information requirements found in the publications that we studied, this research extends the IDM approach to identify and document the information requirements represented in multiple data models. The following sections will introduce the extended IDM approach and the results of using it in this context.

2. Background research

In the past two decades, hundreds of research studies have been conducted to develop algorithms that save the energy waste due to faults occurring in the HVAC systems. Computerized fault detection and diagnosis (FDD) approaches and automated commissioning approaches assess the performance of the HVAC systems, and detect and diagnose the faults. Katipamula and Brambley surveyed the FDD approaches that are used in the HVAC systems and categorized them into three groups according to how much a priori knowledge is used in the reasoning process [9,10]: (1) quantitative model-based approaches [21–25], which use mathematical models of the underlying physical principles; (2) qualitative model-based approaches [26–30], which use the qualitative relationships derived from knowledge of the physical principles; and (3) data-driven approaches [31–35], which use the historical process data generated from the systems.

In order to develop an approach that can automatically provide information required by these algorithms, the authors investigate approaches that can identify information requirements from these algorithms, and integrate and extend existing data models to support the required information. In the architecture, engineering, construction and facilities management (AEC/FM) industry, many software applications use standard or proprietary data models to manage the design information about buildings and HVAC systems [36,37]. A data model describes the semantics of objects and the relevant relationships and constraints in a domain. For example, Building Information Modeling (BIM) is an approach that provides a standard and semantic-rich data model to represent and manage information throughout the whole lifecycle of buildings [38]. In order to improve the interoperability of data models, organizations such as buildingSMART International and FIATECH, are developing open and formal data models that can be used by software firms and developers. These data models are also promoted by AEC/FM stakeholders. For example, the National Building Information Model Standard is developing a formal process for AEC/FM stakeholders to implement standard data models in various projects [39]. The availability of such data models directly promotes automated information integration and support for a variety of applications, including the performance analysis for HVAC systems. However, since each data model is developed with a unique purpose, they represent different types of information. For instance, the Green Building XML (gbXML) data models represent detailed thermal properties, such as the *U*-value of the glazing and wall [40]. The EnergyPlus data model contains detailed information about the configuration of HVAC components and subsystems [41]. Hence, in order to handle the ever-increasing types of data models and volume of required information, an approach that can automatically integrate various types of data models is needed.

To integrate multiple data models, two steps are generally needed [42,43]: (1) schema-centric integration, which matches the schema elements of different data models; and (2) data-centric integration, which merges data from different data models using the matched schemas. Previous research studies have mainly investigated (semi-)automated approaches for schema matching [44–47]. They use various approaches, including generic matching approaches (e.g., linguistic-based approaches and constraint-based approaches [48]) and domain-knowledge-assisted matching approaches [49,50] to analyze the similarity of classes, properties and relationships in different schemas.

The second step consists of the two processes: (1) data matching, which identifies the data items that represent the same real-world objects; and (2) data fusion, which merges the properties and relationships of data items together. Shahandashti et al. reviewed how several prior research studies have investigated the data fusion approaches for construction engineering [51]. For example, Razavi and Haas developed a data fusion approach that utilized multiple sensor measurements to localize and track material movements on construction sites. They developed a hybrid fusion approach that used a variety of sensors with different levels of accuracy and precision [52]. Pradhan et al. formalized an approach to fusing data from various sources using spatial and temporal properties. These authors developed a taxonomy and a library of procedures that fuse data with different formats and units (e.g., fusing daily data to weekly data) [53].

As a sub-domain of requirements engineering, information requirements elicitation has been studied in several domains, such as data warehouse systems [54], software engineering [55,56], manufacturing [57,58], and architecture, engineering, construction and facilities management (AEC/FM) [59,60]. An information requirement is referred to as the data and information flow that is transmitted or shared among the internal components of a system, and between a system and external actors, including the other systems and users who interact with this system. The information requirement elicitation process includes identifying actors who receive and/or generate information, collecting the information flows amongst these actors, specifying the relevant information items, and defining the location and format for representing the information items [55,59].

The IDM approach provides a formal way to specify the processes in which the information requirements are involved so that it becomes clear when, where and how the information will be needed, as well as by whom and for what purpose. IDM is specially designed as a method to facilitate the identification of information items that are included in the IFC schema [20]. It consists of three components: (1) a set of process maps, (2) a set of exchange requirements (ER), and (3) a set of functional parts (FP). After the functional parts are identified, a Model-View-Definition (MVD) of each functional part is created so that the information items can