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Ontology-based facility data model for energy management

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ABSTRACT

Context: Definition of a comprehensive facility data model is a prerequisite for providing more advanced energy management systems capable of tackling the underlying heterogeneity of complex infrastructures, thus providing more flexible data interpretation and event management, advanced communication and control system capabilities. *Objective:* This paper proposes one of the possible implementations of a facility data model utilizing the concept of ontology as part of the contemporary Semantic Web paradigm. *Method:* The proposed facility ontology model was defined and developed to model all the static knowledge (such as technical vendor data, proprietary data types, and communication protocols) related to the significant energy consumers of the target infrastructure. Furthermore, this paper describes the overall methodology and how the common semantics offered by the ontology were utilized to improve the interoperability and energy management of complex infrastructures. Initially, a core facility ontology, which represents the generic facility model providing the general concepts behind the modelling, was defined. *Results:* In order to develop a full-blown model of the specific facility infrastructure, Malpensa and Fiumicino airports in Italy were taken as a test-bed platform in order to develop the airport ontology owing to the variety of the technical systems installed at the site. For the development of the airport ontology, the core facility ontology was first extended and then populated to reflect the actual state of the target airport facility. *Conclusion:* The developed ontology was tested in the environment of the two pilots, and the proposed solution proved to be a valuable link between separate ICT systems involving equipment from various vendors, both on syntax and semantic level, thus offering the facility managers the ability to retrieve high-level information regarding the performance of significant energy consumers.

1. Introduction

Currently, facility management systems, and energy management systems (EMSs) in particular, are characterized by high complexity in order to integrate heterogeneous devices which often come from a variety of vendors using different communication protocols. To provide more intelligent, holistic facility management systems capable of tackling their underlying heterogeneity, classification and description of different information within the target infrastructure are needed. The aim of such facility and energy management systems is to provide more flexible data interpretation and event management, advanced communication and control system capabilities, in case of regular/operational phase as well as in the exceptional/alarm situations when efficient fault detection and diagnosis (FDD) is crucial [1–3]. FDD has the potential to provide beyond the state of the art energy management by detecting the problems in early phase system design, equipment efficiency and operational settings. However, to support harmonization of this diversity and interoperability between different proprietary systems, which will at the same time facilitate the FDD algorithms, definition of standardized and comprehensive facility data model is necessary.

Application of emerging advanced Semantic Web technologies represents the next step in evolution of facility management systems, which considers increased usage of open-source and/or standardized concepts for data classification and interpretation [4]. The advantage of such technologies can be seen as improving the interoperability and reducing the heterogeneity of the system, but also in better downward and upward compatibility of technical systems and accompanying software. By applying the Semantic Web technologies, it is possible to define a comprehensive facility data model as a metadata layer which classifies and describes relevant data within the domain of interest, i.e. the target facility. One way of providing such a facility data model is based on the concept of ontology modelling [5]. The ontology-based modelling approach

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is the most widely adopted Semantic Web paradigm and can be used for formal representation of knowledge through the definition of set of concepts within a domain of interest by describing their corresponding relationships [6].

Additionally, by providing reasoning and inference capabilities, ontologies can be used to cope with the "big data" paradigm [7] and to facilitate rapid exploitation of information. As "big data" represent large and complex collection of data sets that are difficult to process by using conventional database management tools, advanced technologies for efficient representation and handling of large quantities of data are still needed. Ontologies can make data become easier to retrieve, correlate and integrate, by transforming the information into knowledge, by attaching the meaning to data and by providing inter-relationships between modelled entities. As one of the pillars of the Semantic Web, ontology can be defined as a formal way of knowledge representation [6]. Apart from the classification and modelling of data and entities of interest, ontology can be used to reason upon the modelled domain as well. More precisely, ontology is used to define entities, properties, relations, actors and basic concepts, building a common vocabulary for all the members of the domain in which it is defined. As such, ontology has a broad perspective of possible applications, such as sharing a common understanding among people and/or software applications, providing reusability of domain knowledge and making domain assumptions explicit [8].

Ontology modelling can be seen as one possible paradigm for providing and implementing a Building Information Model (BIM) of target facility. However, it is important to emphasize that opting for the ontology modelling approach, apart from the plain modelling of the domain of interest, a variety of advantages are provided such as reusability and automated reasoning upon the modelled entities. For instance, there exists a plethora of technologies that offer conceptual modelling (concerned with describing the domain of interest), but only ontologies combine this feature with Web compliance, formality and reasoning capabilities [9]. So far, a number of facility ontology models were proposed in the literature to improve home [10–14] and building EMS's [15–24]. For instance, the ThinkHome ontology, proposed in [10], is part of an energy efficient smart home system including concepts related to thermal comfort, building information and external weather. In [11,12] ontologies were proposed as a reasoning backbone of home energy management which models the information about the home appliances, their energy efficiency and energy management strategies for the reduction of the energy consumption. One of the efforts to develop a smart building ontology is the SESAME ontology [15] which aims to describe an energy aware building and relationships between the objects and actors included within the energy conservation scenario. In [16,17] authors aimed to optimize building energy consumption by developing an ontology which provides the decision support model for assessing the energy saving measures based on the measured data. Furthermore, in [18] an ontology-based EMS for buildings was designed to ease the implementation of new services and the integration of existing control systems. Finally, in [19] infrastructure components and energy metrics were modelled using an ontology that provides context-based information retrieval support to make energy aware decisions regarding scheduling and resource allocation.

In this paper, an ontology-based metadata layer was proposed which was developed as part of the FP7 project CASCADE (Grant Agreement No. 284920) [25], specifically to underpin an EMS incorporating the ISO 50001 plan-do-check-act principle [26] and to provide integration and interoperability of the underlying systems of target complex infrastructures such as airports. More precisely, the aim of the CASCADE project was to develop a framework and methodology in order to increase the overall energy efficiency and reduce gas emissions of the airports underpinned by the FDD algorithms. As part of the CASCADE solution, the ontology-based approach was used as one of the possible paradigms for the definition of a comprehensive facility data model. The proposed facility ontology model was particularly defined to model all the static knowledge related to the relevant energy consumers installed within the target infrastructure (such as vendor data regarding the equipment characteristics of HVAC, and lighting system). Furthermore, the role of the ontology was to provide a common vocabulary in order to increase the interoperability and to enable transparent data transfer between different system components. Compared to existing facility data models, the advantages of the proposed ontology lie in information harmonization, semantic data enrichment (spatial tagging, topological relationship identification, signal/device dependency detection, etc.), reusability, interoperability, extensibility, but most of all, in the facilitation of automated reasoning upon stored entities. More precisely, it facilitates reasoning (logical inference) upon its entities, providing intelligent services, delivering more refined and useful knowledge (i.e. complex interpretation, abstraction, signal/device dependency detection, spatial positioning, data pre-processing, validation, correlation, etc.) in comparison with raw data provided by legacy building management systems (BMSs). A huge benefit of this unified ontology-based data model lies in the fact that it also represents a one-stop shop for all of the involved heterogeneous subsystems, i.e. a central point of access, configuration, extension, maintenance, etc., thus ensuring consistency and coherence which are difficult to maintain in distributed data models.

The novelty of the proposed facility ontology model resides in encompassing both characterization of the facility infrastructure entities and facility management activities. Contrary to the existing models which are usually focused solely on specific facility aspects, the proposed ontology offers comprehensive facility infrastructure model starting from the field-level devices and signals, to the communication means, to the high-level systems from technical, functional and topological perspective. Furthermore, it addresses the needs of multiple data sources and tools to communicate in providing systematic ISO 50001 energy management in complex infrastructures. Since comprehensive facility data models are lacking in the literature, particularly in the energy domain, this paper aims to present the general concepts behind the facility ontology modelling approach and its role within EMSs. The task of ontology modelling was to structure and classify the semantics, i.e. the technical characteristics of the systems operating at the site. The ontology was modelled in such a way to facilitate the interpretation and semantic enrichment of signals coming from the field-level devices or from the applied FDDs, thus enabling the high-level information for the end-user (such as the energy manager). At the same time, the ontology enables the FDD to use a knowledge-driven analysis (instead of a data driven analysis) to find energy wasting conditions due to the faulty devices and to detect energy usage anomalies in the targeted infrastructure. In this way, by introducing the advanced FDD algorithms which are capable of detecting the faulty devices on time, it is possible to identify the potential energy conservation opportunities and perform corresponding corrective actions, thus resulting in significant savings from the energy efficiency perspective.

To provide the reusability of domain knowledge and support to the concept of Linked Data, the proposed ontology model was linked to other existing ontologies and information models such as Suggested Upper Merged Ontology (SUMO) [27], Common Information Model (CIM) [28] and Industry Foundation Classes (IFC) [29]. In this way, by referencing and making the semantic relations to already existing concepts, the interoperability of the proposed ontology model with existing approaches was supported [30]. Initially, the core facility ontology was defined to represent the generic facility model (integrating common concepts of complex