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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 infrastructures in general) and provides general modelling guidelines. Further extension and population of the core facility ontology lead to the full-blown model of the specific facility infrastructure of interest. Due to their energy consumption magnitude (comparable to small cities), airports were chosen as a sufficiently challenging test-bed platform. For the purpose of the ontology development and population, Malpensa (MXP) airport located in Milan and Fiumicino (FCO) airport located in Rome (serving as pilots within the CASCADE project) were used owing to the variety of their technical systems and associated sensor and actuator devices installed at each site. Therefore, specific airport ontology instances were developed to store and provide all the static data regarding the infrastructure of MXP and FCO airports with particular emphasis on their energy profiles. In addition, the corresponding relationships among the modelled devices, as well as the signals going to/from them, were defined. Apart from the facility data model, the proposed metadata layer also includes an adequate ontology application programme interface (API) aimed at facilitating extraction of the stored data. The ontology APIs were developed for seamless integration of the ontology-based facility data model within the EMS.

The remainder of this paper is organized as follows. Section 2 analyses the overall methodology for improving the energy efficiency of complex infrastructures and proposes the architecture of the ontology-based EMS. Section 3 defines the ontology as an integrative metadata concept and explains in detail the main aspects of the facility ontology underpinning the EMS architecture. In addition, this section describes the chosen modelling approach and provides a brief description of the main entities of the core facility ontology. Section 4 explains how the facility ontology was utilized to increase the interoperability among EMS components. Furthermore, in order to integrate the ontology model as part of the metadata layer of the overall EMS framework, the ontology APIs were developed and thoroughly elaborated in this section. Section 5 describes in detail two specific ontology instances which were populated in order to represent the full-blown models of the MXP and FCO airports chosen as a test-bed platform. Section 6 provides the final conclusions of this paper.

2. Methodology for energy efficient complex infrastructures

This section describes the methodology applied in developing the proposed facility/energy management solution. It also gives the necessary context for a better understanding of the ontology-based facility data model within the broader socio-technical system. The method proposed addresses the need for systematic procedures that align with ISO 50001 energy management standards [26] or more recent Maturity Models for Energy Management [31,32]. These conceptual tools provide high-level guidelines that need to be further developed into low-level applicable activities and technologies [31]. The activities involved in its practical implementation rely on the appropriate management of a breadth of unstructured and diverse data sources. Therefore, advancements on data management, such as ontology-based data repositories/models, provide a better support for energy efficiency decisions and will play an important role in achieving full maturity and widespread adoption of standardized energy management practices. Furthermore, in some cases, the data and information management capabilities of contemporary energy management and diagnostics software packages emphasize data and framework interoperability as solely justifying a cost effective investment [33].

The development of such data intensive system can be defined as driven by three types of technical and organizational issues that are characterized as follows.

2.1. Drivers for an structured approach

Requirements gathered during the initial stage of this research established a need for a technology solution with high scalability and replicability potential [34]. A structured approach that supports modularity and flexibility is required to optimize deployment times through a diversity of facilities differing in size, location, energy systems, or governed by different organizational structures. Three main drivers have been identified as challenges to the proposed methodology. These drivers can also be seen as derived from the commonly known barriers to ICT renovation of inherent complexity, unforeseeable requirements and perpetual change [35]. These three main drivers are as follows.

2.1.1. Growing complexity of data interfaces

Organizations hold, operate and maintain a diversity of ICT assets generating disparate and unconnected data sets. Within the building sector, a variety of protocols such as BACnet, CAN, KNX/EIB and MODBUS impose a lock-in barrier to developing a comprehensive data integration solution. This problem was addressed in CASCADE by adopting a multi-paradigm service oriented architecture (SOA) framework where loosely coupled systems interact committing to a set of business rules and data transformation rules (BR/DTR) using flexible file formats such as XML and JSON. In addition, an ontology metadata layer was chosen to support the integration and interoperability of the mentioned fragmented data structure.

2.1.2. Energy management readiness of legacy systems

Data generated by existing BMS are often insufficient or incomplete to serve effective energy efficiency analysis. These technologies are designed to monitor real time variables at several system points and facilitate remote operational control of settings such as schedules or set points. Implementing energy management software that uses FDD algorithms requires careful consideration regarding existing data storage capacity, quality of data, BMS protocol compatibility and sensor reliability, among others [36].

2.1.3. Considering interaction of human and physical systems

Complex infrastructures are operated according to demanding standards driven by legislative obligations or strategic sustainability programmes. Systems operation is influenced by organizational style and subjected to existing contractual arrangements affecting operations and maintenance (O&M) day to day practices. Moreover, know-how of energy efficiency in practice is often buried in arcane knowledge and sometimes locked by facility management companies. Introducing new standards such as the ISO 50001 [26] represents an opportunity to build a common pool of engineering expertise within an organization, and to minimize interpretation of ISO 50001 principles [37].

2.2. Methodology backbone

The overall ISO 50001 intent is leveraged upon the construction of a measurement-based energy action plan underpinned by FDD techniques and tailored to a specific infrastructure. To materialize this intent, participation of different partners providing diverse expertise and functionalities was involved, namely: (1) data acquisition technology and centralized database, (2) additional sensors and data loggers, (3) facility ontology model and API, (4) fault and detection and diagnosis data processing and (5) ISO 50001 EMS front end software.

The implementation procedure itself requires a set of processes to be performed before the software is fully installed. An energy audit should be conducted at the target facility providing an insight into the energy systems in place, the ICT systems and the organizational structure. This audit leads to the identification of the significant energy users, the establishment of the energy baseline, the CO_2 emissions boundaries, and the construction of key performance indicators (KPIs). The organizational structure and O&M policies have to be analysed in order to deliver a customized software implementation targeted at different stakeholders. Furthermore, the results of the energy audit and acquired information are also utilized for the development of the facility ontology model.

A description of how the system works can be better understood by analysing a CASCADE system workflow which is shown in Fig. 1. Firstly, data are acquired by means of existing BMS or additionally installed sensors/data loggers and are stored in a centralized data server. Different FDD algorithms and data processing are performed remotely. The FDD tool detects a fault in a system that is translated into a message and enriched with additional semantics from the ontology. For instance, this semantic enrichment considered extraction of various information from the ontology related to the faulty device and its context such as its technical specification, in relation to other designated (sub)systems, its topological perspective or any other related data available. The data stream finishes at the ISO 50001 user oriented EMS (shown in Fig. 1). In other words, semantically enriched faults are sent forward to the EMS which incorporated them as energy conservation opportunities following the ISO 50001 philosophy of plan-do-check-act principle [26]. Eventually, the energy manager can assign actions to O&M personnel, and track the effectiveness of these actions.

In reference to the literature, the proposed CASCADE approach introduces the ontology based middleware by which the data from multiple sources within the airport are semantically enriched to provide systematic decision support to a distributed energy management team in airports of varying size and complexity. The use of the ontology model to enrich and reason upon the data passing through different applications affects the decision-making at the user level as aggregated and enriched information supports more precise fault diagnostics and eliminates the need for data guessing and data interpretation tasks.

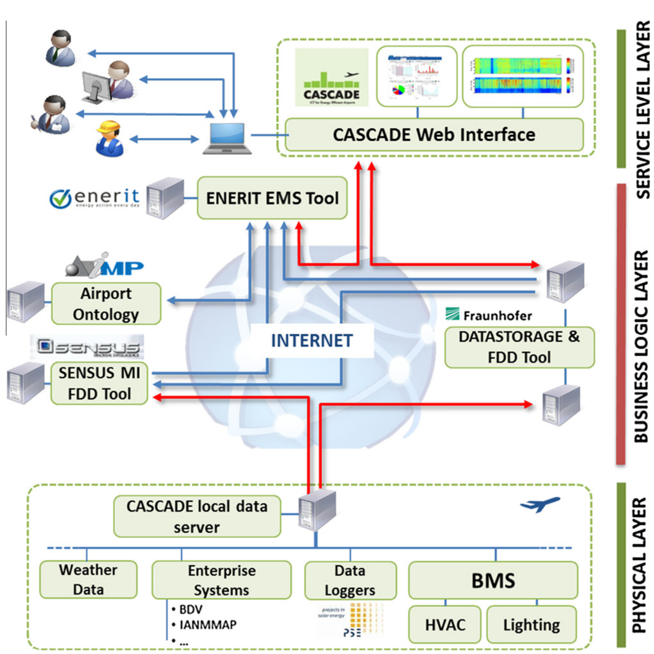

Fig. 1. CASCADE EMS approach.

2.3. Proposed system architecture

Data integration within the proposed ontology-based EMS framework is orchestrated deploying a three-tier service oriented architecture as shown in Fig. 2. This approach builds upon typical BMS three-tier structure of: (1) field, (2) automation, and (3) management levels by introducing a business logic layer and establishing interfacing rules in XML/JSON syntax. The main advantage of using a middle tier is that it relieves client side applications from data transformation tasks that require high information exchange rate, thus imposing a performance burden to the whole system. The application layer uses lean clients such as web browsers that only handle data presentation logic. These three layers are described as follows.

In the **Physical layer**, data acquisition occurs. This is achieved using the existing infrastructure or by adding sensors and data loggers when necessary, to provide a minimal data set required for FDD and energy management processing tasks. Data transfer is performed using the existing LAN enterprise bus or wireless technologies deploying secure channels and firewalls. A database/data warehouse stores all of this low-level data acquired from the infrastructure. For the purpose of filtering, reasoning and aggregating the acquired data, the facility ontology will be used acting as a semantic interpreter at the middle layer. This facility data model institutes a stable-in-time metadata knowledge structure, independent from both applications and data type that may change in the future, use different communications protocols or be configured following different rules.

The **Business logic layer** represents the orchestration of different service providers within the proposed solution. Data sharing and exchange use internet secure channels and adhere to shared BR/DTR using common XML/JSON syntax. Different applications perform tasks remotely such as FDD algorithms, energy management software requesting and providing services and data to/from other applications, including the facility ontology model or communicating with the user interface. The facility ontology metadata layer structures and describes the target infrastructure related data providing all accessing applications with a common shared taxonomy of the domain of interest. The ontology is accompanied by corresponding APIs for extraction of the needed information by querying the ontology. Additional aspects of the ontology such as its class hierarchy, querying types, API development and its main role in energy management are described in detail in the following sections.

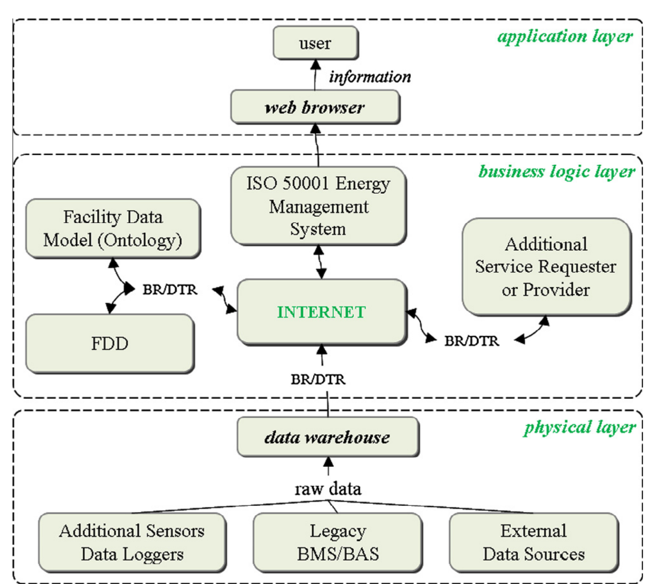

Fig. 2. Proposed ontology-based EMS architecture.

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The **Application layer** deploys and displays the novel EMS as the final graphical user interface (GUI). This GUI will also convey meaningful information about the results of the FDD algorithm, ultimately allowing access to FDD visualization tools. The ontology is used in this front layer to enrich the information about the detected faults or malfunctioning device/(sub)system which is visualized to the end-user. This creates a high impact on the interface of the client-oriented EMS responsible for graphical visualization, since it will enrich the information coming from the low-level devices or FDDs by including static information such as spatial layout, device specifications and its interconnections, and dynamic variables such as temperatures, pressure levels, air/water flows or other features, in a consistent manner.

The described CASCADE methodology, as reflected in the architectural definition influences the ontology modelling approach. More precisely, the facility ontology model reflects the need to accommodate data provided by static data sources (physical layer) and generated by services such as the FDD tool (business logic layer). Concepts pertaining to the organizational aspects (application layer) are also reflected in the ontology development. Furthermore, the facility ontology emerges as crucial in managing the diverse data streams generated by the proposed methodology and becomes particularly powerful by providing hierarchical, semantic and topological features to conventionally generated data. In the next section, the particularities of the proposed facility ontology model are described, and two practical examples of its use case implementations are shown.

3. Ontology model aspects

Ontology represents one of the building blocks of the Semantic Web and can be defined as a formal, explicit specification of a shared conceptualization [38]. In other words, it is a formal way of representing the knowledge as a set of concepts and their relationships within a domain of interest. In this paper an ontology-based facility data model, generic at first, was developed with the aim to improve the energy efficiency of the target infrastructure/building. The main aspects provided by the proposed ontology within the integrative EMS (shown in Fig. 1) would be the following:

(1) modelling the domain of interest (the target infrastructure/building) by classifying installed systems and field devices/signals,
(2) technical characterization and semantic interpretation of low-level signals (to which field device signal belongs, what its characteristics are, relation to other signals, etc.), and
(3) providing the topological profile of the target infrastructure (geographical location of the field devices and belonging signals).

By utilizing the ontology concept the aim was to model the semantics, i.e. to structure the technical characteristics of the systems relevant from the energy management perspective. Furthermore, the ontology modelling concept has been selected as the core IT technology to build the transversal middleware which could provide a homogeneous and common integration platform for diverse field devices supervised by the EMS. This approach provides consistent, yet flexible means for classification and description of each device/signal being addressed by the EMS. In that way, the ontology was used to provide semantic enrichment of signals coming either directly from the field devices or as an output of performed FDD algorithms thus delivering precise information about detected fault (such as pressure drop and hydraulic imbalance) to the end-user. Apart from the enrichment of their output, technical parameters of the monitored field devices stored within the ontology were seen as valuable for performing the FDDs in addition.

3.1. Core facility ontology

The core facility ontology was developed to provide a generic facility model representing the complex infrastructure in general. It is comprised of the common concepts identified as relevant from the perspective of the facility modelling usually present in any type of complex infrastructure (Fig. 3). To identify the common concepts, various types of facilities were analysed such as airports, exhibition centres, and sport arenas. The purpose of the core facility ontology is to provide the modelling guidelines for the description of the technical characteristics of systems installed at the site, and for definition of their topological profile (considering, for instance, the location of the modelled entities). Initially, it was necessary to define the modelling approach which will be undertaken and the general concepts behind the modelling. Those issues highly influenced the decision regarding granularity, abstraction and classification of different real world objects at different levels of the ontology hierarchy.

OWL is one of the most applied ontology modelling languages built upon RDF(S), and was used for the development of the core ontology model [39]. This included definition of the ontology classes, arrangement of the class hierarchy and definition of the properties and their possible values. The concepts, i.e. the ontology entities identified as part of the core facility ontology model are shown in Figs. 6 and 7 (indicated with the red[1] colour) and described in the following subsections. In total, core facility ontology consists of 33 classes (or entities) and 41 properties 14 of which are object and 24 that are data-type properties. Starting from this generic model, the following steps included further extension and instantiation, i.e. population of the core facility ontology in order to model a specific target infrastructure (as shown in Fig. 3). After the ontology model is populated, the end-user will not have to understand and deal with the ontology as a modelling paradigm. Furthermore, all the static knowledge stored within the ontology is meant to be presented to the end-user in an easily understandable manner through the corresponding graphical user-interface.

3.2. Compliance with modelling standards

Harmonization of the facility ontology model was performed by linking to other existing ontologies and information models. The reuse and extension of existing models should be taken as one of the general objectives to avoid potentially large overhead in ontology engineering (by modelling already existing concepts) and to support the interoperability with existing approaches [30]. As part of the efforts undertaken to establish the semantic correlation with other existing ontologies, Suggested Upper Merged Ontology (SUMO) [27], which is the largest high-level ontology today, was taken as a starting point for the development of the facility ontology model. More precisely, the proposed ontology was leveraged upon the basic SUMO concepts as will be indicated in the following subsection. Considering it is an upper level, domain-independent ontology which provides a framework by which disparate systems can utilize common knowledge and from which other domain-specific ontologies can be derived, it facilitates metadata interoperability and knowledge sharing among SUMO compliant ontologies. In this way, by means of upper ontologies, the developed model was made generic in nature.

[1] For interpretation of color in Figs. 6 and 7, the reader is referred to the web version of this article.

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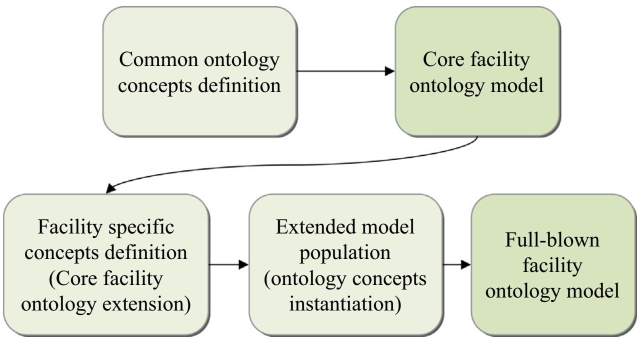

Fig. 3. Facility ontology model development.

Common Information Model (CIM) [28] was taken into account as one of the leading standards in the energy management domain. The basic CIM data model, derived from IEC 61970 series of standards [40], was partly used for development and alignment of the facility ontology. Furthermore, Industry Foundation Classes (IFC) [29] data model was also taken as a standardized specification for BIM. These standards affected the definition of the basic domain entities such as the data types, devices, and (sub)systems. In addition, based on the development activities of the facility ontology proposed in this paper, contribution to the current building data model standardization efforts was made through the EU Energy Efficiency Semantics collaboration platform [41].

3.3. Facility modelling approach

Contrary to the existing models, which usually elaborate only specific facility aspects, the proposed modelling approach was aimed to offer a comprehensive facility model encompassing both characterization of the facility infrastructure entities and facility management activities. To provide the insight into the chosen modelling approach, this subsection presents some of the main entities of the core facility ontology class hierarchy in a top-down approach including their interdependencies. The highest entities of the ontology class hierarchy which were inherited from the SUMO standard [27] and their relevant decomposed (sub)entities are as follows:

(a) **"abstract"** – for modelling of the abstract entities such as data types, communication protocols, maintenance procedures and operation cycles of devices:
  (a.1) **"dataExchange" –** for definition of the data types and communication protocols used for data exchange among device and components of the integrated system;
  (a.2) **"policy" –** for modelling of the device management procedures from the perspective of system operation and maintenance.
(b) **"physical" –** for modelling of the real world objects such as entire systems with associated devices and signals:
  (b.1) **"plant" –** for modelling of concrete (sub)systems installed at the site (such as HVAC, lighting system, and thermal energy/power supply) starting with signals, through components and devices (water pumps, air handling units (AHUs), electrical switchboards, lighting devices, etc.) to overall (sub)systems;
  (b.2) **"topology" –** as the base for definition of the topological model of the target infrastructure and its facilities by using "area", "zone" and "sector" subclasses.

Facility modelling considered the definition of the entire facility infrastructure from high-level (sub)systems to low-level signals. Therefore, the base class "plant" (inherited from IEC 61970-Part 301 (CIM base) standard [40]) was modelled through its main subclasses "system", "device", "component" and "signal" thus reflecting the top-down infrastructure of a particular system. As a top-level entity of the "plant" class hierarchy, class "system" should model entire integrated (sub)systems such as HVAC, power supply, and water supply. The following subclass of the "plant" entity is class "device" which represents a standalone piece of equipment installed at the site constituting the designated technical system. The "device" class (inherited from IFC [29]) is further decomposed to "actuator" (actuating devices such as ventilation fans or circulation pumps), "sensor" (metering equipment such as flow meters and sensors) and "functional" entity (devices which provide some service to the environment such as heat exchangers, storages or filtering compartments). Class "component" is modelled also as a subclass of "plant" entity and it may represent specific parts of more complex devices, but which could be considered at the same time as standalone entities (such as control valve of cooling/heating coil).

Finally, the lowest-level entity of the "plant" class hierarchy is class "signal" which should model particular signals going to/from the controllable (actuators) and readable devices (sensors). Furthermore, it may be modelled as a "setValue" type of control signals used for setting the actuator's operation state or target value, or as an "alarm", "measurement" and "state" type of reading signals used to indicate the operation state of corresponding device or certain measured value.

In order to define the relations among defined entities, properties were used to indicate which components compose a specific device or system (property "partOf" and inverse one "aggregatedOf"). On the other hand, property "connectedTo" was used to indicate the logical aggregation of device instances (not necessarily physically connected). Operational cycles (working hours) of the field elements were defined through the property "schedule" (modelled as part of the "policy" entity of "abstract" class). Furthermore, relations among actual equipment and signal entities were defined indicating which signal belongs to which device or component (property "belongsTo" and inverse one "belonging_signal"). Signals are further defined with properties indicating their unique identifier, data type (modelled within "dataExchange" entity of "abstract" class), their description and source (such as BMS and specific device).

The aim of modelling the topological aspect of the target facility was to provide the information about the specific functional area or location of field devices which could enable the interpretation of the incoming signals in terms of their source location. As shown in Figs. 6 and 7, the main entity of the "topology" class hierarchy is class "area" representing any topological unit of the facility. The lowest-level entity of class "area" is class "room" which should represent the premises, offices, halls, etc. Moreover, specific entities were defined in order to model more abstract topological units as compared to actual premises. For example, floors (class "level") were defined as aggregation of all "area" instances located at the same level. Also, specific topological entities (classes "sector" and "zone") were modelled in order to represent certain logical aggregation of several premises. For instance, the class "sector" was used to model the high-level topological units such as, in the case of the airport, buildings, hangars, runways. On the other hand, class "zone" was used to model smaller areas as compared to class "sector" such as terminals or gates, which can be still seen as physical and/or functional aggregation of actual premises. Specific properties were defined to indicate the relation between aggregated and single area instances (property "partOf_area" and the inverse one "aggregatedOf_area").

For topological mapping of the field-level devices, property "contains" (with its complement, "locatedAt") was defined to indicate which devices are installed in a certain area. All area instances were modelled with properties describing their topological relation to other neighbouring areas ("connectedTo_area" and "adjacentTo_area") which could be found useful in spatial correlation of the received data. Moreover, "area" instances were defined with additional attributes indicating their unique identifier, surface area and volume.

4. Ontology as integration platform

Following an extensive overview of the main ontology aspects, this section is primarily focused on further elaborating the potential benefits of the proposed EMS solution having an ontology-based metadata layer as a common integration and interoperability platform for diverse, heterogeneous ICT systems. Namely, the proposed metadata layer, leveraging upon the ontology-based data model, is aimed at providing the semantic enrichment to the signals coming from the BMS, additional sub-metering and data loggers, or applied FDD algorithms, thus offering high-level information to the operator/end-user for further analysis. Considering the ontology features previously presented, it is important to highlight that all stakeholders and the EMS components (as shown in Fig. 2), will be able to share the knowledge about the system and moreover to understand each other when referring to the same devices. For instance, the BMS may use one, usually proprietary, data naming format for the representation of the sensor readings, whereas, on the other hand, the FDD component (which is often used as an external module, transparent for the system) may use its own data naming format. In this way, the ISO 50001 EMS module responsible for communicating acquired data and FDD results could visualize, instead of the non-intuitive device identifiers (ID), complete device names, their properties and locations in a human understandable manner. All this heterogeneity in different systems and data formats introduces serious interoperability issues and requires tedious translation procedures in communication between system components. The proposed metadata layer aims to solve this problem by leveraging its implementation on the utilization of a holistic ontology-based facility data model. Thus, the three fundamental features will be enabled: (1) the knowledge about the system will be centralized and stored within the ontology-based facility data model, providing critical semantic relations within the domain of interest; (2) by establishing a common vocabulary of the system entities, the facility data model will enable all system components to "understand" each other when referring to a particular entity, in a seamless and transparent way; (3) having a centralized knowledge repository, all relevant information will be up to date, synchronized and accurate.

Considering that the proposed metadata layer is based on the ontology, its integration into the overall EMS solution is provided by the corresponding ontology interface. Consequently, the main responsibility of the ontology interface is to enable knowledge extraction, as well as delivery of the requested information, such as technical characteristics of the field-level devices, their topological information, energy management regulations and procedures related data, in a transparent way. In other words, in order to integrate the ontology, a custom designed API was developed, which ensured all knowledge stored within the ontology could be easily extracted, acquired and reasoned upon by any stakeholder.

In relation to this, a detailed ontology-supported information flow is shown in Fig. 4. As previously elaborated, relevant information for the EMS may come either from a BMS system, operating at the facility, or from one or more FDD engines sitting either locally within a BMS or on a remote server offering diagnostics as a service. Furthermore, information coming from a BMS may be enriched with additional measurements (such as from smart-meters), providing more detailed diagnostics of the most critical energy consuming devices. In either way, the relevant information is first wrapped into a custom XML/JSON format, which offers a definition of proprietary data naming convention, and then forwarded towards the application server where the EMS is deployed. Collected data, carried out within the XML/JSON messages, may contain device status, indicating some faults in the regular operation, such as a wide range of performance monitoring parameters including electricity consumption, the amount of hot/cold water entering the HVAC system, water temperature and pressure. XML messages are then gathered within the EMS which is responsible for reasoning upon these data. However, considering that XML messages are compiled after a specific data naming convention (depending on the source component such as the BMS, FDD, smart-meters), the EMS would have to be aware of each of applied naming schemes in order to properly interpret the information of interest. This issue is bridged with the introduction of a common metadata layer, hosting the facility data model and accompanying API. Each XML message is first parsed in order to acquire the source device ID (for instance, device which triggered an alarm) and corresponding measurement/status value. The extracted device ID is then used to query the ontology in order to obtain additional relevant information, such as full specification of the device, which system/sub-system it belongs to, what the neighbouring devices are, where it is located within the facility itself. Querying is performed through the ontology API, which has several functionalities ranging from generation of SPARQL [42] queries, to communication with the ontology data store and offering the gathered information in appropriate format to the rest of the system. The facility ontology can reside without any restrictions either locally, within the EMS, or on a remote server, serving as a remote knowledge store (e.g. Virtuoso Universal Server as implemented in the CASCADE solution), as shown in Fig. 4. Regardless of the implementation, the overall communication chain is completely transparent for the stakeholders owing to the developed API. The information retrieved from the ontology, is first used for consolidating the high-level energy conservation measures in accordance with the ISO 50001 standard, which are then delivered to the facility energy manager via appropriate user interface, thus closing the information flow. In this way, the facility ontology model can provide critical semantic enrichment of the signals coming from devices/systems, thus enabling the delivery of the high-level, immediately applicable, energy conservation measures to the EMS end-user.

4.1. Ontology API functionalities

In order to extract and deliver the required information stored within the ontology, an appropriate interface between the ontology and the rest of the system components had to be defined. Therefore, the ontology API (as shown in Fig. 4) was developed so as to entail a range of critical functional requirements, providing a transparent interface for integration of the facility ontology model and other software components within the EMS.

The following are several examples illustrating employment of the relevant ontology API functionalities:

(1) *Technical characterization and semantic interpretation of signals* – enables field-level device characterization based on the unique device ID embedded within the signals coming from sensors, offering additional device characteristics (extracted via SPARQL queries), to which system it belongs, to which device/component it is connected, where it is located, etc.

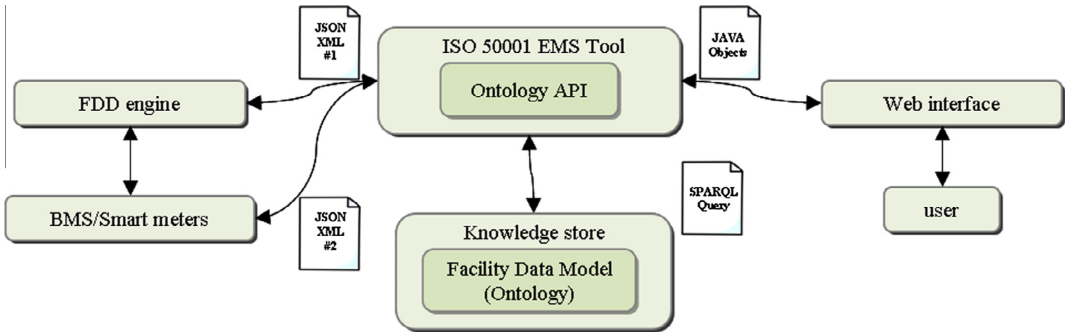

Fig. 4. Ontology supported information flow.

(2) *Updating the facility ontology model* – enables updating of specific class instances and their properties based on the received information/data from sensors (using SPARQL Update commands). Update arguments are considered to be both unique device identifier and desired property value.
(3) *Applying a generic inference engine* – in order to maintain consistency of the data stored in the ontology, a set of rules (defined in SWRL [43]) can be defined within the inference engine which is responsible for reasoning upon the class instances. For instance, corresponding relations among class instances could be automatically established as a result of reasoning, such as in the case of transitive relations (e.g. if there is a device belonging to a specific system, then the components of this device belong to the same system as well).

Furthermore, the ontology API features both local and remote access to the ontology, thus enabling high flexibility in the overall system architecture. The following subsection describes interfacing with the ontology in more detail, entailing both scenarios.

4.2. Interfacing with ontology

In the case when the ontology is used to store only static data, which will rarely or almost never change, there is no need to store the ontology at a remote server since it will create an unnecessary communication burden and decrease the reliability due to the potential communication failures, thus resulting in a less robust system. Instead, the same ontology instance should be deployed "locally" at the side of each end-user. From the technical perspective, the ontology API development was based on Apache Jena [44] which is an open source, Java framework for building Semantic Web and Linked Data applications offering a wide range of functionalities when it comes to the operation with the other ontologies and/or RDF stores. Once developed, the custom designed ontology API is distributed in the form of a library which has all the aforementioned functionalities implemented within.

However, if the use case suggests frequent changes in the facility ontology, encompassing both changes in the overall class hierarchy as well as class instances, it is of vital importance that all stakeholders share the same view of the system infrastructure, which can only be achieved if they access the same ontology instance. Therefore, in such a case it is recommended that the ontology is deployed on a "remote" server, where it will provide easy access to all stakeholders. For the implementation of the CASCADE solution, the Virtuoso Universal Server [45,46] was utilized for this purpose, i.e. as a remote knowledge store, having in mind its core functionalities in terms of querying the ontology. The advantage of the built-in SPARQL end point within Virtuoso Server was taken to provide transparent and data effective communication with the server using only the HTTP protocol. For the purpose of firing queries, parsing the query results, and, more importantly, initiating a communication with the Virtuoso server, the Jena framework [44] was utilized as in the previous case.

5. Airport use case

The flexibility of the proposed facility modelling approach reflects the possibility to instantiate any complex infrastructure starting from the core facility ontology. This procedure includes first extension and then population of the core facility ontology according to the actual state of the target facility. For the purpose of modelling the test-bed platform, airport infrastructures were chosen. Airports serving as the critical transportation infrastructure nodes are significant energy consumers and emission producers. Owing to their rather complex infrastructure, technical characteristics and different aspects of the existing devices and modules installed at the site, two major European air-traffic hubs, MXP airport in Milan (with total electricity consumption of 140GWh for 2009) and FCO airport in Rome (with total electricity consumption of 176GWh for 2009) were analysed (shown in Fig. 5). Therefore, two airport ontology instances were developed representing the facility models of MXP and FXO airports. Various data sources such as technical sheets, equipment manuals, audits, questionnaires and interviews were utilized to acquire the input data which were then transferred to the ontology [47]. More precisely, based on the gathered data, the core facility ontology model was first extended and then further populated into two separate ontology instances. These two ontology instances, built upon the core facility ontology, represent two full-blown airport ontology models tailored to reflect the actual state of the chosen airports. Extended class hierarchies of these two full-blown models are shown in Figs. 6 and 7 (where additionally defined entities are marked with yellow). Serving as the central data repository of the overall EMS solution (shown in Fig. 1), the airport ontology was used to store all the static data regarding the target systems and significant energy users (such as nominal air supply flow, fan drive power, and air flow frequency of AHUs) which could be exploited further for FDDs or to calculate potential energy waste due to detected faults.

5.1. Airport ontology population

For the purpose of the ontology population, detailed facility technical characterization was performed. Gathered data were transferred into the airport ontology by instantiating the ontology entities with associated property values and relations. In order to provide the means for semantic interpretation of signals coming from the field devices, all signals extracted from the data-point list of the main BMS (more precisely, the DESIGO system which

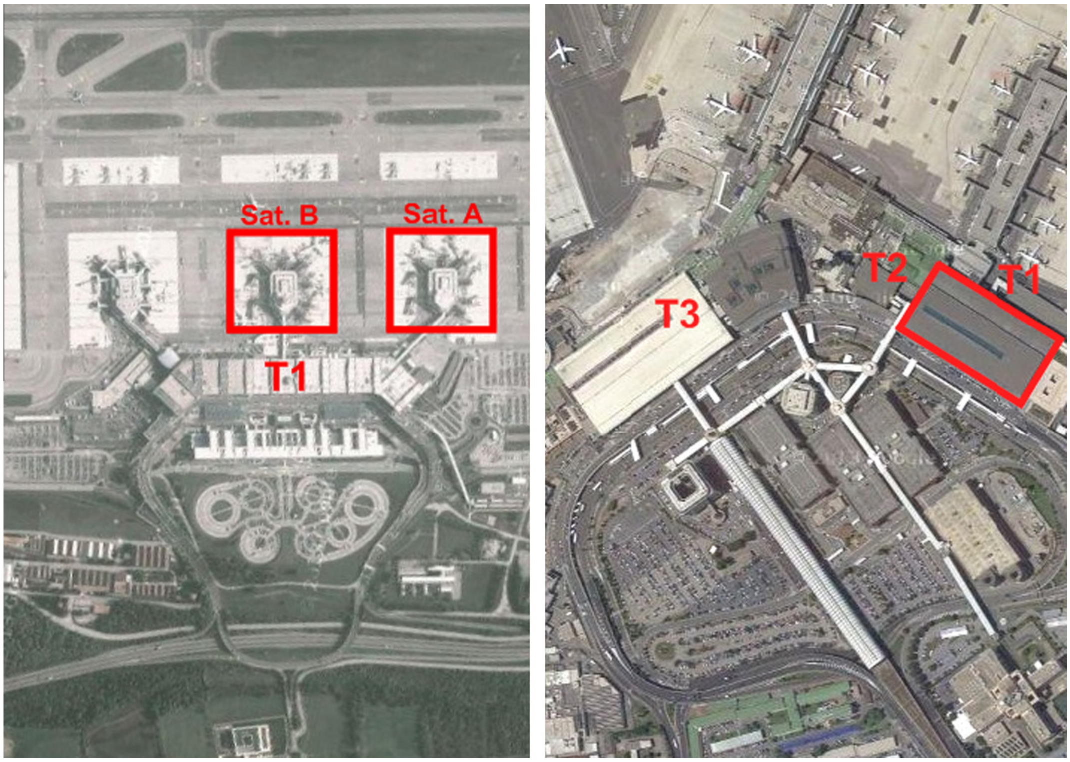

Fig. 5. MXP and FCO airports (target areas).

currently operates at both airports as the main platform for supervision and control [48]) were instantiated as corresponding control or reading signals. Apart from other parameters, every signal instance was defined with a unique identifier from which required additional semantics were extracted, in a fully automated manner, by querying the ontology. Furthermore, for semantic enrichment of low-level signals, different information needed to be instantiated starting from the technical system (such as AHU and water loop system), over the device or functionality which triggers some event or signal (such as cooling/heating coil modelled as actuator or signal instances such as pressure drop and exhaust fan alarm) to corresponding measurement type (such as ambient temperature and humidity defined as reading signals).

For the modelling of the information about the physical placement of devices and associated signals, airport infrastructure and its premises (offices, waiting halls etc.) were mapped and instantiated so they reflected the actual state of the airport. Each topological area was defined with corresponding parameters indicating its interconnection and geographical position with respect to other airport premises. By mapping devices and signals to the associated topological entity, it was possible to extract the information about the location of a specific physical entity.

For the population of airport ontology instances representing MXP and FCO airport facilities specific target airport areas (shown in Fig. 5) were taken into account. In case of the MXP airport, the instantiation of satellites A and B (holding 16% share of total energy consumption) as part of the Terminal 1 (T1) building was performed. Mapping of corresponding target devices (such as double duct AHU group 20 located in Satellite A, water side substations 4 and 5 located in Satellites A and B, respectively) was carried out according to the detailed airport facility 2D plans. T1 of the FCO airport (holding 13% share of total energy consumption) with associated equipment (containing target devices such as AHU groups 1 to 12 and compression chillers 1 to 4) was used for the population of the corresponding ontology instance. Relevant statistics of the populated airport ontology instances, such as number of classes, instances and properties/relations, is shown in Table 1. Once the airport ontology was populated, semantic queries were defined and utilized for the extraction of the data from the ontology as it was described in the previous section.

Both extension and population of the core facility ontology were carried out based on the BMS data point lists carrying the information about every low-level signal that the EMS framework might have to deal with. Since at both airports, signals were complied with the Unified data point naming convention [47], alignment of the airport ontology was carried out accordingly. This included mapping of the data point property value (such as signal identifier, data type, and source) into the airport ontology as the entity instance or property value.

5.2. Ontology API parameters

The airport ontology could be applied by facilitating the manual user input for definition of corrective actions to create the high-level energy saving messages which contain precise information about the critical device. In any case, the extraction of the additional semantics was performed automatically by querying the ontology based on the corresponding input argument, such as, for instance, a signal identifier indicating the critical system or device, and predefined API functions with embedded SPARQL queries. Therefore, as part of the specification of the ontology API, it was necessary first to define parameters/data relevant to be extracted and further exploited within the energy management framework. The excerpt of the full-blown list of parameters (with corresponding source ontology entities) which were determined as relevant and provided through the API of both the MXP and FCO airport ontologies is shown in Table 2. Through the ontology API functions or, more precisely, by using the SPARQL queries embedded within, these data were available on demand and used to assist the creation of the high-level energy saving messages for

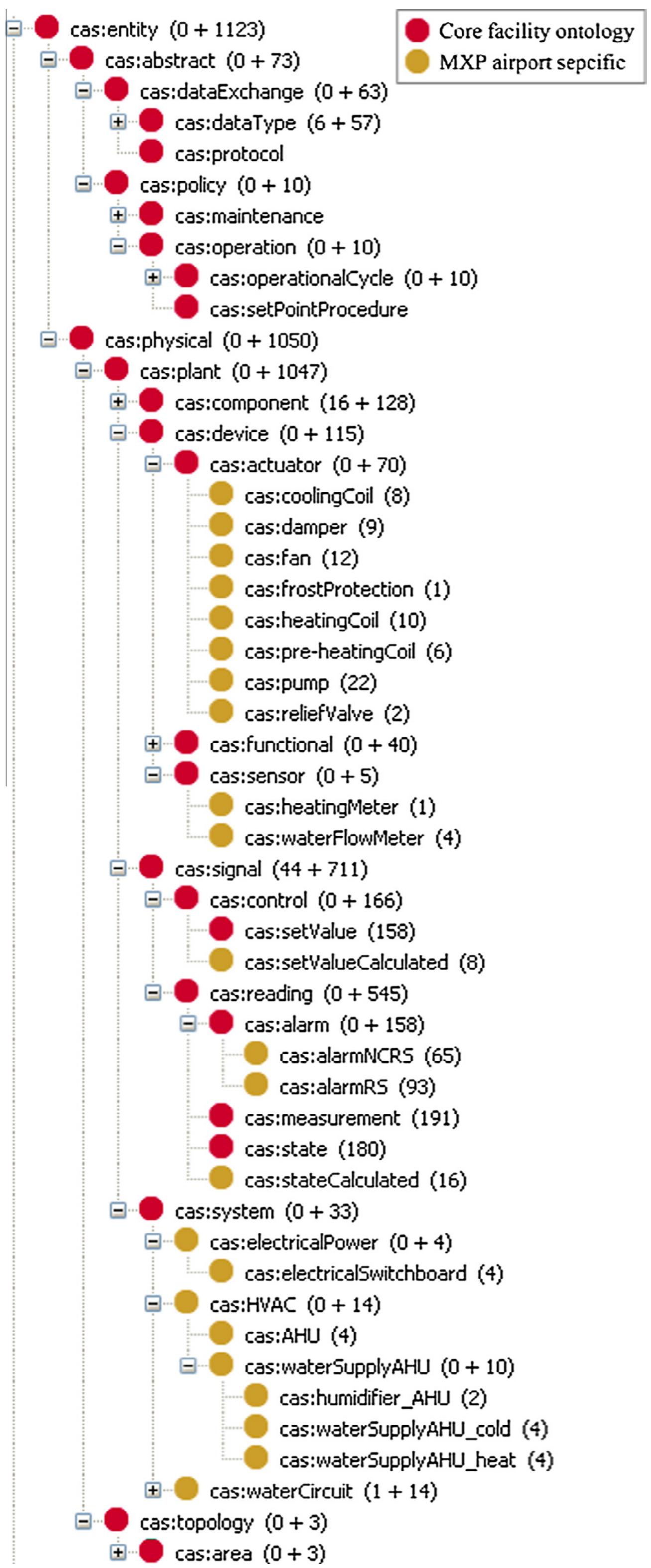

Fig. 6. MXP airport ontology.

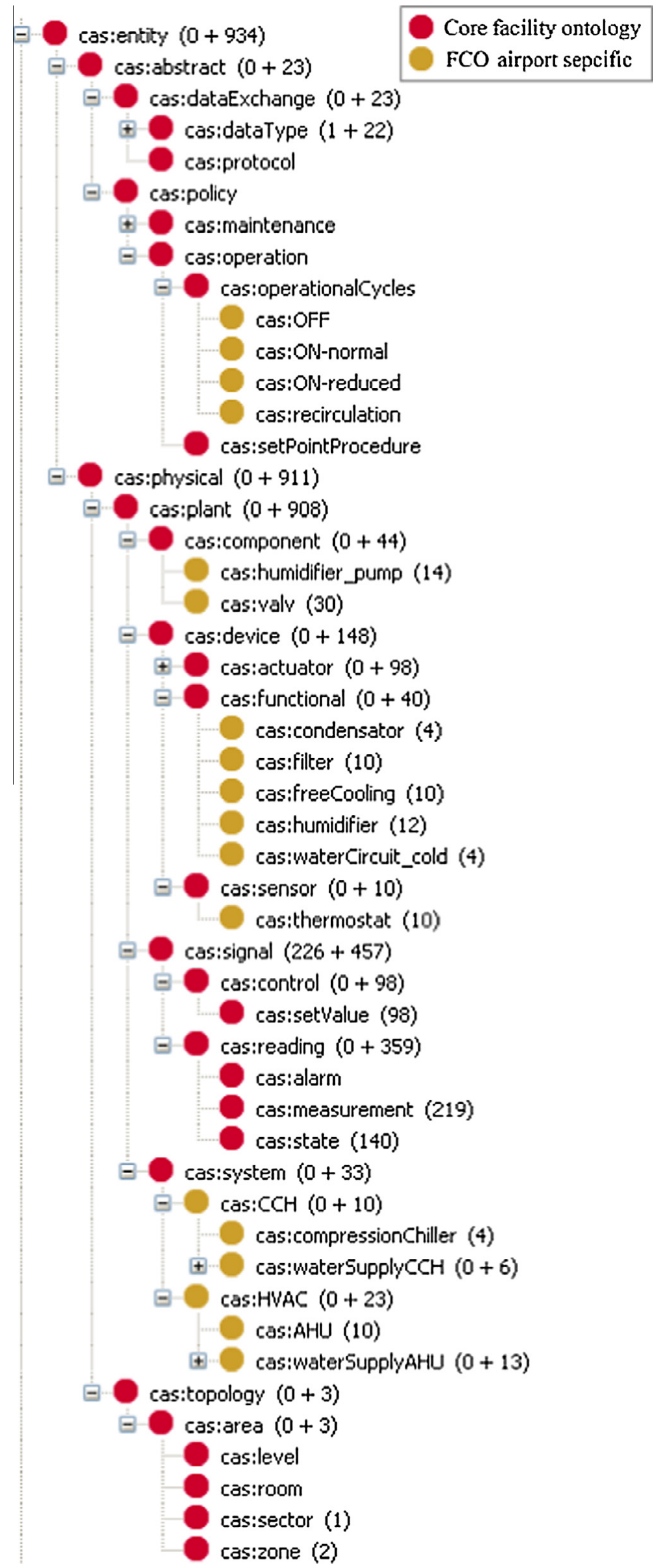

Fig. 7. FCO airport ontology.

the end-user, for FDD system integration and for interactive visualization of the critical device related information.

5.3. Energy saving messages

To increase the awareness and consequently the overall energy efficiency, "content rich" energy saving messages carrying the precise information about the potential energy conservation opportunities detected by the FDDs were developed. Such "content rich" messages were compiled and visualized to the end-user as part of the ISO 50001 energy management guidelines [26,37]. They were composed by extracting the additional semantics, i.e. parameters listed in Table 2, from the ontology. These parameters were

Table 1
Airport ontology statistics.

	Classes	Properties		Instances
		Object	Data-type	
MXP	119	16	46	1123
FCO	73	16	69	934

Table 2
Ontology API parameters.

No.	Parameter	Ontology entity
1	System name	class:system
2	Subsystem name	class:device
3	Device name	class:component
4	Location	class:topology
5	Sub-location	class:topology
6	Location related parameters	property:area_description, property:area_m2, property:volume_m3
7	Technical data sheet	property:technicalSheet
8	Signal type	class:signal
9	Sensor ID	property:signal_id
10	Source	property:source
11	Signal description	property:signal_description
12	Signal related parameters	property:data_type, property:medium, property:position
13	Nearby devices/signals	property:locatedAt

extracted in a fully automated manner simply based on the signal identifier (unique ID of a specific low-level signal) coming from the faulty device and presented in an intuitive and easily understandable manner to the end-user.

The screenshot of the "content rich" energy saving message is shown in Fig. 8 indicating a potential energy conservation action/opportunity. This particular example depicts all the information relevant to the energy conservation measure which should be carried out and corresponding references (next to the data fields in Fig. 8) to the ontology entities listed in Table 2, which were used to extract the corresponding data. As it can be seen from this particular message, the fault was detected on the heating coil valve located at the secondary side of the pre-heating coil of AHU water supply system, within the thermal substation B, serving Terminal 1 of the FCO airport (more precisely, arrivals and baggage claim area). Marked fields represent the additional information extracted from the ontology, based on the signal ID which was provided through the metadata sent from the filed devices and FDDs. However, the information sent through the metadata is usually represented by unintuitive entity acronyms and therefore the airport ontology was used to deliver and present this information in natural language as shown in Fig. 8. For instance, the following is the signal identifier FCO_T1_CCH.02_CTO.TE01___RET_MEA_T representing the sensor measurement of the cooling tower return air temperature according to the unified data-point naming convention which is meant for data exchange among system components and not for the presentation to the end-user. In that way, by extracting the additional semantics related to the detected fault from the ontology, precise high-level information was shown to the end-user in an understandable form in order to initiate appropriate corrective actions and stop further energy leakage on time.

5.4. Ontology validation considerations

Owing to the comprehensive impact of the proposed ontology based facility data model, its validation has to be considered from both internal and external perspectives. These two validation dimensions are elaborated in more detail in the following.

5.4.1. Internal validation

When it comes to the internal validity of the developed ontology, its purpose is to ensure that all defined concepts are viable from a technical viewpoint. This means that consistency verification of the ontology model and its concept interdependencies against the real pilots is necessary. Although the facility model was leveraged based on physical inspection of both facilities, interviews with airports' personnel and available documentation, a certain degree of inconsistencies and errors inevitably emerge during the modelling process. For instance, ontology errors manifest themselves when there is an incorrect association between a particular system and different low-level devices, e.g. between an HVAC system and humidifier. To prevent this, an online validation was performed during the entire ontology design process. This was achieved by using a range of "semantic rules" (SWRL rules) together with an inference engine which provided reasoning over any new entry in the model. As already mentioned in Section 4.1, this represents one of the main functionalities of the developed ontology API. Fig. 9 represents an example of the SWRL rule which ensures that a low-level device or signal which is part of a particular device can only be associated with a high-level system to which that particular device belongs as well. Rules like this ensure that semantics of the facility model, interdependencies between devices, systems, etc., correspond to the actual situation in the field. The critical importance of performing internal ontology validation can be fully comprehended after considering the challenges of the external validation, elaborated in the following.

5.4.2. External validation

While the internal ontology validation aims at providing a facility model that accurately describes the considered building, external validation seeks to prove the purposefulness of the proposed solution in terms of increasing the energy saving potential of the conventional means using FDD algorithms.

FDD algorithms were implemented to detect faults quickly, systematically and, as far as possible, automatically before additional damage to the system occurs, and/or before the system fails or too much energy is wasted [49,50]. This was achieved by a measurement based system as a combination of continuous monitoring, data collection, visualization and corresponding FDD analysis. Both rule-based and qualitative model-based FDDs were implemented leveraging upon acquired measurements and a priori knowledge of a target system (such as AHUs, chillers, and heat exchangers). A variety of faults in terms of type and complexity could be detected by the proposed approach, depending on the number of monitoring points, models of dynamic processes and a priori knowledge of a target system upon which FDD algorithms are operating.

It is important to know that FDD algorithms are commonly applied to a single device and aim at detecting irregularities in their operation without any concern of the wider context in which they operate. However, additional saving potential, both in terms of energy and human resources, can be unlocked by considering, for instance, not just a single AHU but a complex system consisting of several AHUs, serving a common open space, such as those inside terminal buildings of airports.

A simple, yet descriptive, example of a space conditioned by a pair of AHUs that share common set points and operation strategy can be used to demonstrate our approach. Namely, the consumed energy of an AHU is proportional to the difference between the room temperature and a given set point. If one of the AHUs is malfunctioning, it would fail to reach the requested temperature or simply would not secure enough air flow at the requested temperature, while the other AHU would try to compensate for this deficiency in order to preserve the comfort level. This results in higher power/energy consumption for the remaining AHU although the

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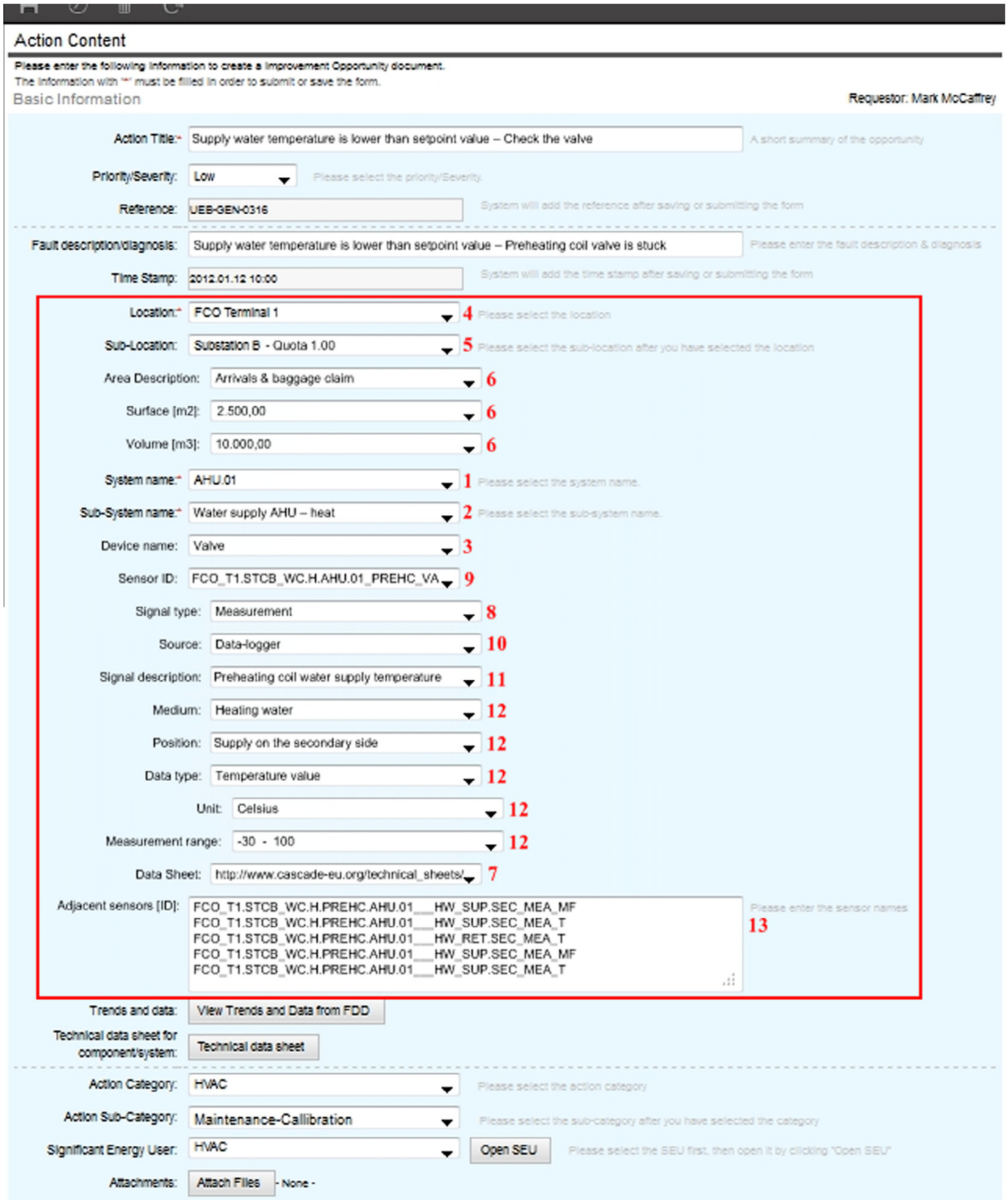
Action Content
Please enter the following information to create a Improvement Opportunity document.
The information with "*" must be filled in order to submit or save the form.
Basic Information
Requestor: Mark McCaffrey
Action Title:* Supply water temperature is lower than setpoint value – Check the valve
A short summary of the opportunity
Priority/Severity: Low
Please select the priority/Severity.
Reference: UEB-GEN-0316
System will add the reference after saving or submitting the form
Fault description/diagnosis: Supply water temperature is lower than setpoint value – Preheating coil valve is stuck
Please enter the fault description & diagnosis
Time Stamp: 2012.01.12 10:00
System will add the time stamp after saving or submitting the form
Location:* FCO Terminal 1 4
Please select the location
Sub-Location: Substation B - Quota 1.00 5
Please select the sub-location after you have selected the location
Area Description: Arrivals & baggage claim 6
Surface [m2]: 2.500,00 6
Volume [m3]: 10.000,00 6
System name:* AHU.01 1
Please select the system name.
Sub-System name:* Water supply AHU – heat 2
Please select the sub-system name.
Device name: Valve 3
Sensor ID: FCO_T1.STCB_WC.H.AHU.01_PREHC_VA 9
Signal type: Measurement 8
Source: Data-logger 10
Signal description: Preheating coil water supply temperature 11
Medium: Heating water 12
Position: Supply on the secondary side 12
Data type: Temperature value 12
Unit: Celsius 12
Measurement range: -30 - 100 12
Data Sheet: http://www.cascade-eu.org/technical_sheets/ 7
Adjacent sensors [ID]: FCO_T1.STCB_WC.H.PREHC.AHU.01__HW_SUP.SEC_MEA_MF
FCO_T1.STCB_WC.H.PREHC.AHU.01__HW_SUP.SEC_MEA_T
FCO_T1.STCB_WC.H.PREHC.AHU.01__HW_RET.SEC_MEA_T
FCO_T1.STCB_WC.H.PREHC.AHU.01__HW_SUP.SEC_MEA_MF
FCO_T1.STCB_WC.H.PREHC.AHU.01__HW_SUP.SEC_MEA_T
Please enter the sensor names 13
Trends and data: View Trends and Data from FDD
Technical data sheet for component/system: Technical data sheet
Action Category: HVAC
Please select the action category
Action Sub-Category: Maintenance-Callibration
Please select the sub-category after you have selected the category
Significant Energy User: HVAC Open SEU
Please select the SEU first, then open it by clicking "Open SEU"
Attachments: Attach Files - None -

Fig. 8. "Content rich" energy saving message.

```
#rule:(?x pref:partOf_device ?y)
(?y pref:partOf_system ?z) -> (?x pref:partOf_system
?z)]";
```

Fig. 9. Example of consistency check rule.

set point temperature would remain unchanged. This would be understood as a device failure if the two faults were to be analysed independently. More precisely, two fault signals corresponding to each AHU, would come from the FDD tool suggesting that, seemingly, the group of AHUs is underperforming. Eventually, personnel on site would inspect the referred subsystem and try to isolate the fault among different devices forming the group, costing precious time and imposing economic penalties. This is exactly where the ontology metadata layer may bring competitive advantage, by providing the semantic correlation between the detected fault and the designated (sub)systems. Furthermore, it should be emphasized that the proposed approach could easily cope with more complex scenarios such as with higher number of AHUs serving entire airport terminals. Owing to the scalability of the proposed approach, the rationale behind it would be exactly the same as in the case with pair of AHUs (as described previously), by delivering the semantic relations from the ontology which imply that all AHUs are serving the same space and that one part of AHUs is trying to compensate the malfunction of another.

6. Conclusion

Contemporary facility management systems are aiming to deliver better insight in facility operation accompanied by more flexible data interpretation and event management capabilities.

However, at the same time, these systems also suffer from increased heterogeneity resulting from employment of various supervision and control systems/devices coming from different vendors. Due to the various, and often proprietary, communication protocols used by these systems, their integration into a common management platform represents a challenging, yet necessary task to solve. This paper proposes a novel methodology as well as an integration solution that offers to bridge the communication gap existing among the aforementioned systems, and provides unlimited sharing of knowledge that is crucial for acquiring high-level energy management decisions underpinned by ISO 50001 energy management standard. The proposed solution is based on a common metadata layer holding a comprehensive facility data model which was implemented using the ontology modelling approach. More precisely, the facility ontology data model was developed by modelling all the static knowledge relevant to the energy related infrastructures operating at a particular facility. In other words, it was defined to accommodate all relevant devices, their technical characteristics, vendor specific data, but also spatial and topological interrelationships, providing a holistic and integrated view of the domain entities and their relationships relevant for the energy efficiency considerations. Furthermore, it enables both data-driven and knowledge-driven analyses, since the ontology contains a plethora of different spatial, topological, structural, functional and other semantic information that cannot be expressed in a conventional data model. In that way, the ontology gives a desired impression of the homogeneous system, solving the challenging task of integration and interoperability of heterogeneous underlying subsystems and alleviates the overhead that is usually encountered in other interoperability solutions.

This paper particularly addresses the definition of ontology concepts necessary for facility modelling from the perspective of energy management and operation, through a detailed explanation of the approach undertaken for modelling tasks. Moreover, the ontology was modelled in such a way as to facilitate the interpretation and semantic enrichment of monitoring signals by providing additional semantics (such as vendor data regarding the equipment characteristics, protocols and standards used, underlying topological model). In order to enable seamless integration and interoperability with the rest of the ICT systems involved in the energy management, the ontology model was interfaced with a custom designed API based on an open source framework which provides for unlimited deployment options. For the purpose of ontology population, two airport infrastructures characterized with a variety of energy related systems were taken into account, the Malpensa airport in Milan and Fiumicino airport in Rome. A simple scenario with a pair of AHUs serving a single space whereby one of them is compensating the defect of another one was specifically used for validation purposes and to demonstrate the usefulness of the proposed ontology based approach. However, it should be kept in mind that due to its scalability, the proposed approach could easily handle more complex scenarios covering, for instance, a number of AHUs serving entire airport terminals, since the rationale behind it would stay the same as in the case with pair of AHUs.

It is also important to mention the challenges and difficulties encountered during the implementation of the proposed approach at test-bed pilots. Mainly, they emerged due to the difficulties in technical integration into the existing technology infrastructure of airport. In the first place, the risk of providing inadequate input data (for instance by facility personnel) could lead to incorrect ontology model and to delivering incomplete information about the target systems. Therefore, several data sources have been taken in combination to acquire and verify required input data such as interviews with facility personnel, questionnaires, technical datasheets, manuals, and desktop research. Keeping in mind that it is important that all obtained data are made available and delivered for further FDD processing and ontology based reasoning, risk of closed legacy BMS/SCADA solutions could have significant impact on feasibility of supporting the integration and interoperability of the overall system. In addition, in case of critical infrastructures such as the airports, security issues should be taken into account due to the confidentiality of facility ontology model and stored data (such as the location of the critical systems, for instance, of the power supply boards/racks). Therefore, adequate measures had to be taken into account to secure the information modelled within the facility ontology model such as providing secure communication means for delivering the information from ontology.

Finally, being developed and tested at these two pilots, it was concluded that the proposed solution improved the integration and interoperability between separate ICT systems, both on syntax and semantic level, thus offering the facility managers to retrieve high-level information regarding the performance of the key energy related systems.

Acknowledgements

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