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Integration of Fault Detection and Diagnosis with Energy Management Standard ISO 50001 and Operations and Maitenance of HVAC Systems

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Abstract
Fault Detection and Diagnosis (FDD) has become a robust scientific field offering proven methods for the optimization and more effective operation of HVAC systems. However, FDD practical application faces several difficulties and barriers: legacy systems may be unable to provide meaningful information for FDD, integration of disparate systems can be difficult but also the organizational culture and existing contractual frameworks may present obstacles for innovation and industry acceptance. This paper presents a practical implementation of an stakeholder-centered solution called the "CASCADE Implementation Kit" that integrates FDD into a comprehensive energy management system. Two major European airports will be the test bench of the CASCADE solution. Airports role as critical infrastructures and main energy consumer is also discussed in this paper. The solution delivers a common integrated platform including several innovative commercial and under development tools including an ISO-50001 [1] energy management software, advanced data visualization, and building performance simulation.

Keywords: Fault Detection and Diagnosis. Energy Management. ISO 50001. Building Management System (BMS). Building Automation Systems (BAS). Airports. CASCADE.

1. Introduction

Airports are essential infrastructures. They handle millions of passengers annually and the number is increasing due to the overall impact of a globalized economy [1]. Airports have become larger and more numerous being one of the largest energy users among large building clusters. Airports also utilize a plethora of Information and Communication Technology (ICT) systems and tools to support flight technology, safety requirements and demanding operative levels. Airport managers constantly operate under

[1] ISO 50001: Energy management systems

pressure to maintain high levels of service that often conflicts with ever increasing environmental obligations. Some recent responses to this challenge are reflected in the airport-focused sustainability programs like the Sustainable Airports Manual in the US [2], or the Airport Carbon Accreditation in Europe [3]. These schemes are aimed to support a significant reduction of CO_2 emissions and a challenging vision towards carbon neutrality. Energy use is often the second operating expense at airports, only exceeded by personnel [4], hence a reduction on energy demand would impact significantly on airport operative results whilst improving sustainability performance.

CASCADE[2] is aimed at developing a facility-specific measurement-based energy action plan for airport energy managers underpinned by Fault Detection and Diagnosis. The next section (Sec. 2) describes the different technologies to be integrated, these are: (2.1) FDD methods, (2.2) Building Management Systems, (2.3) Enerit® Energy Management System, (2.4) Data Logging and DataStorage Tool and (2.5) Airport Ontology. Section 3 reveal some of the challenges addressed during the first stages of the project while Section 4 demonstrates the solution adopted for the final technology integration. Sections 5, 6 and 7 deal with practical aspects, the economic facet and future stages of this research.

2. ICT and Energy Management

ICT play an important role in two major fields as pointed out by the European Commission [5], these are **process efficiency** and **the restructuring of behavioral change**, two aspects covered by the CASCADE solution. The following subsections describe the pieces of the integrated solution, each one playing a specific role in the whole strategy.

2.1. Fault Detection and Diagnosis (FDD)

The goal of fault detection and diagnosis is to detect and identify the causes of a system failure or underperformance. It uses a combination of continuous data monitoring, historical data collection, visualization and analysis. The following are the most common faults in HVAC systems and represent a starting point in CASCADE:

- Simultaneous heating and cooling;
- Faulty, deactivated or falsely set controls;
- Lack of calibration;
- Lack of maintenance;
- Lack of hydraulic balancing;
- Under/Oversizing.

[2] CASCADE has received funding from the European Community's Seventh Framework Programme (FP7/2007-2013) under grant agreement No. 284920. Project website is available from http://www.cascade-eu.org/cms/

In combination with an ISO 50001 based Energy Management System, FDD will be used as a tool not only to recognize faults, but to optimize the operation, redesign or fix faulty equipment, rearranging what is configured improperly and providing maintenance guidance as to failure to maintain tolerance thresholds.

A number of different methods currently under development will be tested during the CASCADE pilot implementation stage. These can be summarized in three categories: (1) Sensor Fault Detection, (2) Rule Based and (3) Model Based Fault Detection and Diagnosis, described as follows:

Sensor Fault Detection algorithms aim to detect sensor failures or inaccuracies that can lead to a biased or incorrect data analysis. They are applied to single sensor data as a pre-processing signal tool before applying plant specific FDD routines. The method developed uses a Support Vector Machine classifier (SVM). A dimension reduction with a discrete Fourier transformation is first applied to reduce the information amount and extract the signal main features.

Rule Based FDD methods will apply a set of expert rules and inference mechanism to check consistency of the targeted system state. For this, an object-oriented rule-based FDD framework will be prearranged and data retrieved from existing systems filtered and analyzed according with a systematic data point convention. For Air Handling Units, a pre-classifier routine based on Mollier enthalpy-diagrams of moist air enthalpy will perform a first analysis step to detect faulty sequences like simultaneous heating and cooling. In a second step, a set of rules based on a-priori knowledge of the specific system, the thermodynamic laws and in previous work developed by Schein and Bushby [15] will complete the detailed analysis.

Two model based FDD approaches using the same object-oriented framework will be developed in parallel and tested experimentally: (1) a black box model based on multiple linear regression analysis will be used to detect possible deviations at a system level from a base pattern using a trained model, and (2) Qualitative Model Based FDD will be developed using quantization techniques. The quantised system reduces the information processed in the application and transform numerical values into qualitative values or states. Secondly, a stochastic automata will determine the transition probabilities of successive states of a faultless system and compare it with the actual system.

In the course of the project, a study of the efficacy of these three different FDD approaches will be completed in order to select the best performing parts to be integrated in the final prototype.

2.2. Building Management Systems (BMS)

CASCADE will deal and coexist with existing BMS, complementing their role in current operation practices. Building automation has evolved from simple controls to the nowadays most common software packages for remote monitoring and commanding. Figure 1 traces the evolution of Building Management and Automation. The primitive "data poor and information poor" paradigm allowed simple on/off controls and information leading to maintenance activities when a system is broken down and unable to operate. Some studies [7] show that still more than 55% of maintenance resources and activities of an average facility fall still in the category of “reactive maintenance”.

Modern BMS built up the "data rich/information poor" paradigm and are aimed to maintain a determined service level compliance. This leads to potential conflicts in complex facilities, over reactive controls and even the hiding of fault in system and components. At this stage, maintenance performed is based in scheduling and routinely controls.

CASCADE will explore the third age of building operation by embedding FDD knowledge and converting the raw data in elaborated information with an eye in enhancing predictive and preventive maintenance current practices as the main objective. New and innovative data visualization tools will also be explored as instruments to help energy managers understand, interact with data and foster collaborative decision making.

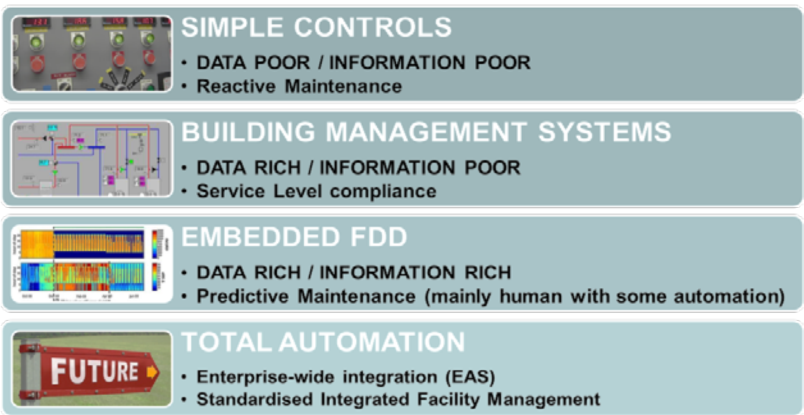

Fig. 1 The four ages of Building Management Systems

It is expected that that future development trends incorporate remote software servicing, integration with enterprise-wide management implementations and the adoption of quality standards toward a total productive maintenance system. From the marketplace some works suggest an influence of Big Data and Cloud Computing Paradigms, and even more interesting a recent move towards “cooperative competition” and sharing of competitive knowledge [5].

2.3. Enerit® Energy Management Tool

This software tool is provides an ISO 50001-based energy action plan helping energy managers measure energy performance and organize subsequent energy actions. The Enerit® Energy Management Tool offers a systematic framework to measure and document actions and results. It will provide the final interface and will shape the user experience. Monitoring and targeting, as well as energy audits are vital ingredients guiding the generation of energy saving opportunities, but this is not enough. Therefore consistent organization and action is needed, this is the main purpose of this tool.

2.4. Data Logging and the DataStorage Tool

Special data logging and data storage will be designed and implemented as part of the CASCADE solution. FDD algorithms are mathematical constructs that analyze historical trends of several variables and parameters. This requires the implementation of hardware and software capable of providing high quality data beyond existing BMS capabilities. Summarizing the main features are:

- High connectivity and interoperability with open standards protocols such as BACnet[3], CAN[4], KNX/EIB[5] or MODBUS[6];
- Interactivity with different database standards like SQL[7];
- Modularity and Scalability.

2.5. Ontology and Semantics

Ontology will underpin CASCADE solution in the form of middleware. Data gathered from the existing building management systems, the physical facilities and the external environment will be structured meaningfully using an ontology layer developed by Institute Mihailo Pupin (Belgrade. Serbia). The ontology will provide a systematic taxonomy framework representing the airport domain data exchange infrastructure. The structured data, its properties, attributes, relationships and governing rules will provide a robust and reliable base to elaborate valuable information, enhancing data exchange and interoperability. The main benefit of using ontologies, as pointed by White [6] is the ability to separate knowledge from system code in a way that can be inspected by humans and can be used by computer programs. This

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[3] BACnet: Building Automation Control Network protocol, developed by ASHRAE.
[4] CAN: Controller Area Network bus, developed by Robert Bosch GmbH
[5] KNX is an International Standard (ISO/IEC 14543-3) as well as an European Standard (CENELEC EN 50090 and CEN EN 13321-1) and Chinese Standard (GB/Z 20965).
[6] MODBUS is a widely used protocol developed by Schneider Electric.
[7] Structured Query Language

way, the CASCADE Airport Ontology will also add value to the project by providing a technology-neutral terminology that will remain regardless of software evolution and mitigate risks of dependency on ever changing applications.

3. Problem Mapping

One of the main objectives of the CASCADE project is to assemble a solution envisioning a new age of Building Management Systems driven by the:

- Integration of a number of disparate technologies and knowledge fields;
- Ability to easily be integrated within existing BMS system, leveraging existing assets;
- Interest for fetching innovative FDD based automation into a wider energy management standard;
- Use of protocols for results verification and measurement;
- Search of a pervasive solution that meet standards and stakeholders needs along an entire organization. Software acting as guidance and facilitator rather than a burden.

As shown in Figure 2, the project conceptual inner group is based on three components: FDD software, Energy management software and advanced data logging systems. An external layer represents the systems integration group, this is the combination of the different IT solutions with the existing BMS/BAS systems. The airport ontology will structure data through the different layers. Finally, a methodology for software implementation will be developed, aimed to support the adaptation and replication of the tested solution within other airports and similar facilities.

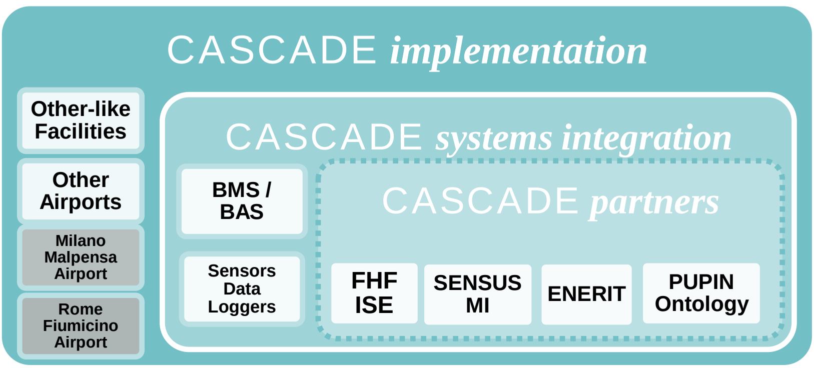

Fig. 2 CASCADE Conceptual Boundaries

4. Gathering Stakeholders Expectations

During the initial stage, a significant effort was put into the identification of the different stakeholders and the characterization of their needs and requirements with regards to energy efficiency, sustainability and project impact. The resulting picture of different organizational structures, contractual frameworks and operations and maintenance procedures revealed the key aspects this methodology addresses.

The initial investigation comprised a short survey targeted at EU airports and an extensive survey of the two airport pilots participating in the project, Rome Fiumicino and Milano Malpensa, aimed to identify significant energy users, current operations and maintenance (O&M) procedures and airport expectations. Rome Fiumicino Airport considered a reduction of between 8% and 15% of energy usage. It is understood that a real time analysis and disaggregation of energy consumption could also help reduce 10% on O&M costs additionally. Milan Malpensa Airport targets a return of investment period (ROI) of three years, thus achieving a reduction of 180 MWh electricity consumption and 1600 MWh of natural gas savings and resulting in a reduction of 437 ton CO_2 emissions.

5. The Architecture of CASCADE

Figure 3 shows the initial approach of the solution three tiers architecture. Some options regarding final user interface and XLM[8] data naming conventions are under investigation. In the field layers, existing infrastructure plus additional sensors and advance data loggers will feed the automation systems currently in place. The automation systems comprehend both field level controllers and automation control triggered by SCADAs[9] and proprietary BMS. A database with historical trends will be installed. FDD will be performed remotely as “Software as a Service” (SaaS) applications. Airport Ontology will be a meta-data layer structuring and describing the airport infrastructure related data, the ontology will be delivered with accompanying application programming interfaces (APIs) for extracting the needed information by querying the ontology.

Querying the ontology can be achieved in two ways (each way would require a specific API). The first way would enable communication with the ontology "locally" (meaning that the ontology is stored in the local CASCADE server) simply by calling the corresponding functions for retrieving the needed information (provided by predefined API). The second way would enable access to the ontology in a web-service based manner by sending the requests and receiving the response carrying the needed information (wrapped up into the XML message).

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[8] Extensible Markup Language

[9] Supervisory Control And Data Acquisition

Concerning the front-end layer, the initial approach will be the one that supports Energy Management Software as the main and final tool providing the Graphical User Interface (GUI). Another possibility proposed would be to use another application to retrieve operations and maintenance guidelines accordingly. The GUI will also convey meaningful information about results of the FDD engine, ultimately allowing access also to some of the FDD visualization tools.

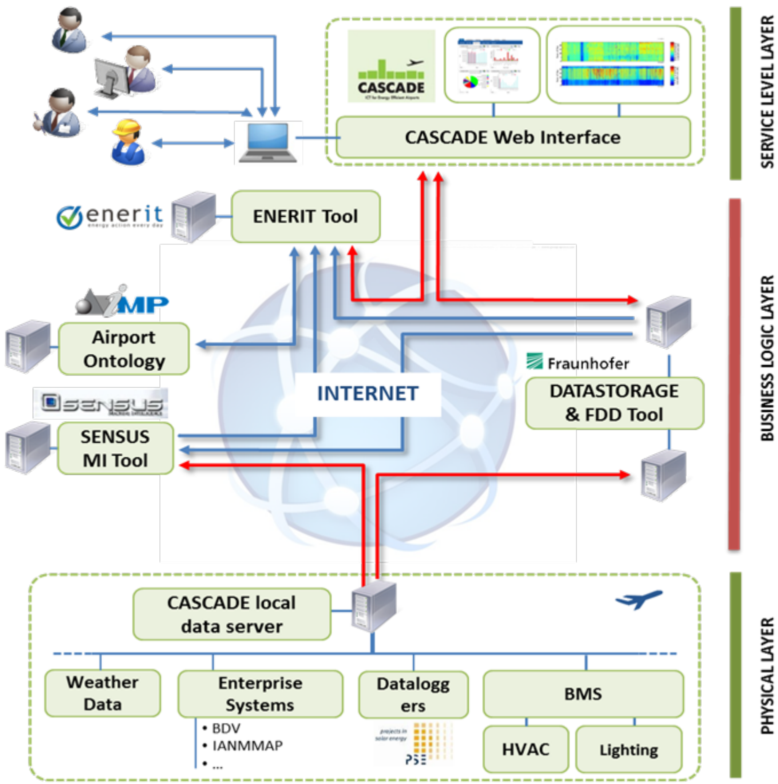

Fig. 3 The CASCADE Architecture

6. Implementation: Pilot Tests

Initial implementation will target HVAC systems at the two pilot airport: Terminal 1 at Fiumicino airport (Rome) and Satellite 1 at Malpensa airport (Milan). This will start in January 2013 till the end of the project in September 2014. The systems targeted will be Air Handling Units (AHUs) and their supporting water loops and chillers.

7. Energy Savings Analysis

On-going commissioning tools have proven to be cost-effective. The average energy savings have been reported at levels greater than 20% with capital expenditure typically achieving payback periods of two years [9]. Some studies in US report the benefits of commissioning tools as a 16% reduction in of the whole building annual energy bill [10]. A comprehensive analysis on the impact of FDD affecting Operations and Maintenance costs, have been developed by Li and Braun [11]. We expect to execute a similar cost-benefit analysis using discounted cash flow methods during next work packages that focus on the replication plan and value proposition. CASCADE cost benefit analysis will evaluate:

- Capital Expenditure (CAPEX): Development and implementation costs;
- Revenues: accounted as energy savings and/or CO_2 credits;
- Effects on improved Indoor Air Quality, linked with user acceptance;
- Sensitivity analysis taking into consideration: Asset lifecycle, Fiscal incentives (accelerated depreciation), Interest rate, Inflation, Energy prices, Energy market liberalization, and influence of Renewable energy on the generation mix.

8. Future Development

Next challenges that need further investigation will focus on the cost-effectiveness of the solution, the discussion about the reliability of the different FDD methods and the development of meaningful key performance indicators (KPIs), described as follows.

8.1. Quality and Extent of the Minimal Data Set

Fault Detection and Diagnosis rely on using data actually available from existing BMS/BAS equipment. Additional capital expenditure on sensors and hardware equipment can be studied as in relationship with estimated savings in order to determine the break-even point which additional sensors, meter or investment provided no added value.

8.2. Quality Assesment of FDD Algorithms

CASCADE provides a good opportunity to prove reliability of FDD techniques over the long term. Methodologies to asses FDD algorithms can be further developed and assessed over real facilities, changing conditions and other influencing parameters. An approach to developing test methods to evaluate FDD systems have already been explored in US for air-cooled vapor compression HVAC systems. CASCADE will perform quality assurance procedures using the International Performance and Measurement Protocol [14]. This task will be performed during the demonstration period and will need at least one year (due to influence of weather data). Verification will be performed in five key areas:

- Physical measurement infrastructure and airport ICT infrastructure;
- Software Reliability;
- Fault Detection and Diagnosis tools;
- Energy Action Plan based in ISO 50001;
- Energy, CO2 and financial savings achieved.

8.3. Key Performance Indicators (KPI's)

New technologies bring possibilities, but also risks. Using big amounts of data without providing meaningful information is one of the risk that ICT adoption faces. The development of standardized KPIs can help improve the deployment of new ICT. We need a more holistic approach to KPI's which links Energy Management, Operations and Maintenance and service level indicators provided by ICT Enterprise systems.

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Project website is available from http://www.cascade-eu.org/cms/

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