SIMULATION TO SUPPORT ISO 50001 ENERGY MANAGEMENT SYSTEMS AND FAULT DETECTION AND DIAGNOSIS: CASE STUDY OF MALPENSA AIRPORT

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ABSTRACT

This paper describes the use of building performance simulation into a wider implementation of an energy management system (EnMS) based on ISO 50001 requirements. The CASCADE project, funded by the European Union's Seventh Framework Programme (FP7) call "ICT for Energy Efficient Buildings" aims to test different modelling strategies supporting Fault Detection and Diagnosis (FDD). Some of the main challenges includes the integration of new and legacy IT systems, the adoption of a robust calibration methodology, and the systematic verification of energy savings. This paper gives an overview of the CASCADE project and then proposes an approach that defines the use of calibrated whole building performance simulation (WPBS) as a supporting tool for improved building operation. Coupling of WBPS within the CASCADE methodology will increase the functional support offered to energy managers. A case study based on Milan Malpensa Airport that shows the initial model development is also described. Finally a definition of the future steps that will be followed by this research work is described.

INTRODUCTION

Buildings consume an estimated 40% of the global total final energy consumption (IEA, 2008). Studies have shown that building operations does not reflect design expectations leading to an excess of 20% of energy wastage (Mills et al., 2004). Within the building sector, airports can be considered as small cities. They serve as critical nodes in the global, national and local transportation networks connecting people, facilitating businesses and enabling commerce. In Europe, approximately 400 airports that are member of Airports Council Intenational welcomed more than 1.5 billion passengers and handled over 17 t. of cargo, achieving more than 20 million aircraft movements during 2011 (ACI-Europe, 2012a). With respect to the economic impact, Europe's airports employ directly over 1.2 million people, representing €59 billion contribution to EU's GDP. It is also estimated an indirect job creation of 2.1 indirect jobs for 1 direct job at an airport (ACI-Europe, 2012a). Correspondingly, airports are massive energy consumers and emissions producers, being de facto comparable to small cities. As one thinks of airports, they must be considered as open floor plan spaces containing many and varied functional areas which include an "air side" (runway operations) and a "land side" (terminal operations). The former consists of runway spaces and lighting, hangars, maintenance bays, outdoor lighting and navigation aids and the latter comprises the terminal buildings and main concourses, offices, security areas, commercial and restaurant areas amongst others.

Therefore due to the economic impact, their role as the critical transportation infrastructure nodes, and their energy consumption magnitude, airports are excellent candidates for energy efficiency research. Aviation's overall contribution to the global GHG emissions inventory is dominated by aircraft in flight, however these emissions are beyond the influence of airports. On the other hand, there is room for improvement in energy efficiency and emissions reduction originated by buildings and services in airports, both in airside and landside facilities (Baumert et al., 2005). Important actions in this sector can support Europe's 20-20-20 and 50-50-50 policy targets. Airports have displayed a positive attitude towards energy efficiency measures as can be seen by the adoption of sustainability programs like Airport Carbon Accreditation (ACA) by a large number of airports (ACI-Europe, 2012b). Despite the effects of the financial downturn in 2008, airports and airlines are determinedly seeking for every possible cost saving measure that makes compatible both an increasing forecasted demand and the ever growing environmental obligations. Aspects like the need for a "greener" corporate image or the dependency on oil imports also add and additional pressure on airport operators.

Airports also hoard a plethora of Information and Communication Technology (ICT) systems and tools in order to cope with flight technology, safety requirements and demanding operative levels. Airports managers are under pressure to save energy and reduce airports carbon dioxide emissions while buying less carbon credits offsets. Airports already have dedicated personnel for energy management to achieve these goals quickly and to reduce their emissions continuously. Airports managers have to cope with complex building systems and high energy, security and comfort requirements that often conflict with ever increasing environmental obligations. Some recent responses to these problems are reflected in the airport-focused sustainability programs like the Sustainable Airports Manual (SAM) in the US (CDA, 2011), or the Airport Carbon Accreditation in Europe (ACI-Europe, 2009). 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 largest operating cost at airports, only exceeded by personnel (TRB, 2007), hence a reduction on energy demand would impact significantly on airport operative results whilst improving sustainability performance. To answer these needs, the research project CASCADE was funded by the European Commission under the FP7 scheme in order to develop a ICT measurement-based technology solution that is based in ISO-50001 energy management guidelines and integrates FDD methods (PSE.AG, 2012) in their structure.

Within the ISO 50001 framework, establishing targets for energy savings and identifying Energy Conservation Measures (ECMs) becomes a previous and unavoidable activity that requires not only a sound knowledge of building energy systems, but also of the building end users and its organizational aspects. In this context, simulation can play an important role to facilitate decision making by mitigating risk and uncertainty, guiding energy policy and helping energy managers to ”get the operational logic right”.

CASCADE PROJECT METHODOLOGY

The CASCADE project is aimed at developing a framework and a methodology and tool chain for building customized ICT solutions that coexist with current airport ICT infrastructure and Building Management Systems and assimilate airport operational procedures. CASCADE is aimed at turning Fault Detection and Diagnosis into actionable information by developing an energy action plan that links Actions-Actors and ISO Standards (ISO, 2011) through a web-based management portal. The developed ICT solution will integrate with existing systems and will target an estimated 20% reduction of energy consumption, 20% reduction of CO_2 emissions with an expected 3 years return of investment period. Previous research on FDD estimate that the potential energy-savings varies from 20% to 30% (Yoshida et al., 2001), 10% to 40% (Schein et al., 2006) or 15% to 30% (Katipamula and Brambley, 2005). It is also expected that ECMs generate an additional 10% cost reduction in Operations and Maintenance (O&M) costs. CASCADE will achieve these objectives in time by:

1. Engaging the client, determining their needs, and encouraging organizational change;
2. Integrating new ICT technologies with the systems present at client facilities;
3. Collecting data on user operation and equipment performance;
4. Applying FDD methods across operational scenarios and equipment performance benchmarks;
5. Implementing an Energy Action Plan that links actors, actions, and ISO standards based on facility specific data and providing specific and measurable value.

The CASCADE approach focuses on the actions that airports can take in order to address GHG sources within their control and influence, fully in the line with ACI guidelines and recommendations for the future strategic airport planning and management (ACI-Europe, 2009). Energy management actions in large organizations, such as airports, span across different levels from the top level with the overall energy policy and planning to the bottom with scheduled and emergency based operation and maintenance. In order to support top level energy management it is important to better understand the starting point of an airport in relation to its energy consumption and set reasonable targets. 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 dissimilar technologies and knowledge fields;
- The ability to be easily integrated besides existing BMS system, leveraging existing assets;
- Interest for fetching innovative FDD based automation into a wider energy management standard;
- The search of a pervasive solution that meets standards and stakeholders needs along an entire organization. With this approach, the software development acts as guidance and facilitator rather than a burden.

As shown in Figure 1, the project conceptual inner group is based on four components: FDD tools, energy management software, advanced data logging systems and data handling tools.

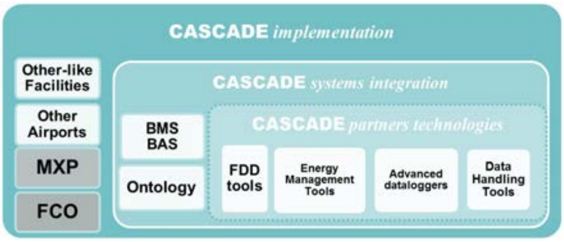

Figure 1: The CASCADE concept

An external layer represents the systems integration group, this is the combination of the different IT solutions with the existing BMS/BAS systems and the airport ontology which will structure data through the different layers, supporting the whole implementation. Finally closing the whole, a methodology for software implementation is being developed, aimed to the adaptation and replication of the tested solution to other airports and similar facilities, learning form the project experience at the project pilots: Rome Fiumicino (FCO) and Milano Malpensa (MXP) in Italy. During the initial stage of the project, a significant effort was put into the identification of the different stakeholders and the characterization of their needs and requirements concerning energy efficiency, their visions on sustainability and the project impact. The resulting picture of different organizational structures, contractual frameworks and operations and maintenance procedures revealed the key aspects this methodology should embrace. The initial investigation comprised a short survey targeted at EU airports and an extensive survey of the two airport pilots participating in the project, aimed to identify significant energy users, current operations and maintenance (O&M) procedures and airport expectations. Figure 2 shows the ”three tiers architecture” initially proposed.

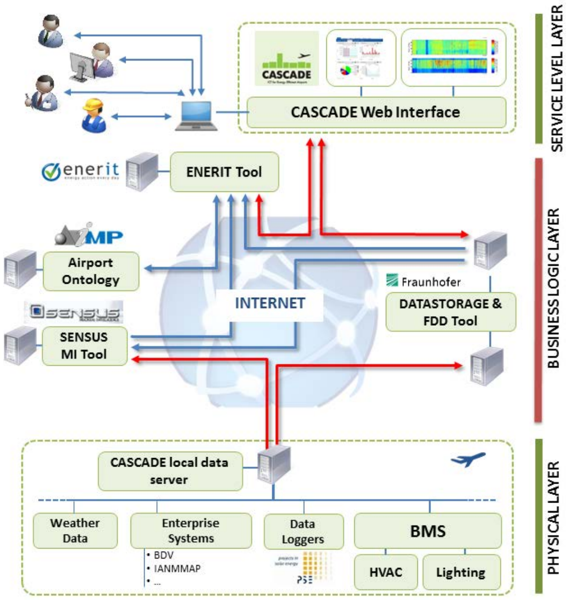

Figure 2: The CASCADE architecture

In the physical layer, the existing infrastructure (BMS, weather station and the relevant enterprise systems data) plus additional sensors and advanced data loggers will gather and concentrate field data into the CASCADE local data server. In the business logic layer FDD will be performed remotely operating conceptually as Software as a Service applications (SaaS). 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 requiring a specific API: First way would be to communicate with the ontology ”locally” so that the ontology is stored in a local CASCADE server simply by calling the corresponding functions for retrieving the needed information provided by predefined API. The second method would be to access the ontology via a web-service by sending the requests and receiving the response carrying the needed information wrapped up into the XML message. The Service level layer provides access and services to the final user application. The main function of the CASCADE Graphical User Interface (GUI) is to translate task and results into information that users can understand and interact. The GUI will support of effective energy action management (in accordance with ISO 50001), and will provide access to advanced visualization to measured data and specific views of performance data relating to detected faults, including their description in terms energy and cost impact and actions needed for repair. This web interface enables effective energy action management for all stakeholders involved in the energy O&M process.

USE OF WBPS FOR ENHANCED BUILDING OPERATION

FDD enables the state-of-the-art energy management because it can be used to suggest problems in system design, equipment efficiency, and operational settings. A measurement framework and minimal data has been established to control and benchmark specific HVAC systems performance. This will help to optimize operational procedures and match energy managers expectations. The research work that starts with this paper focuses on utilizing whole energy simulation models to support fault detection activities at the whole building level and also in supplying a reliable building model to test Energy Conservation Measures (ECMs) in a virtual environment before they can be implemented in real assets. The proposed approach is based on three main steps, as depicted in Figure 3. These steps are described in the next three subsections.

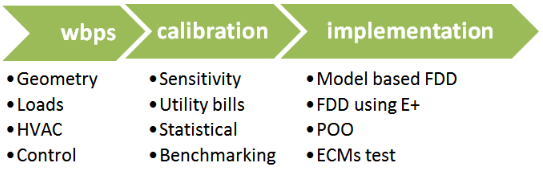

Figure 3: WBPS Plan of work

WPBS Whole building performance simulation

A detailed whole building performance simulation requires the input of geometry, construction, internal loads, weather parameters and HVAC systems. The software chosen for these research is Energy Plus (E+), a state-of-the-art open-source tool promoted by the U.S. Department of Energy. During this first stage, collection and analysis of relevant data was carried out. This included a walk-through visit and the analysis of the original project documentation. Information about the building current HVAC operation was also retrieved and analyzed. These is done in parallel with the CASCADE preparation phase, gathering data of three fundamental aspects: Energy Audit, IT systems (including BMS/BAS in place) and the organizational framework (less influential for modelling but very important for FDD).

Systematic Calibration

The calibration of models against real data brings us an important methodological question. In this work, calibration is understood as the process of searching for input values that produce an output result that fit the observed data. This process can be deployed two ways: (1) reducing uncertainty of the unknown or imprecise inputs by deepening into more precise information or (2) by adjusting the uncertain input parameters until the output results fits the actual observed data.

In the first case, a systematic calibration of the model includes a preliminary sensitivity analysis of the model variables in order to define key parameters influencing model outputs and weight their relative importance in the model behavior. This will minimize embedded model errors and identify parameters that need to be estimated more accurately or retrieved from real systems performance in a preliminary analysis. Sensitivity analysis can also reveal intrinsic operational problems that often go unnoticed, e.g.: uncontrolled outdoor air exchange rate, thermostat inefficient configuration or missing free-cooling periods. These conflicts can be effectively discovered during the modelling stage and avoid that the model is calibrated to a faulty building. This first approach has been formally described by some authors (Raftery et al., 2011) conceived as a methodical process of adjusting a model against actual performance so it can be considered a reliable representation of actual behaviour. Calibration underlying principles according Raftery et al. can be summarized as follows:

- Detailed Building Performance Simulation models should represent the real building as closely as possible with currently available tools;
- Reproducibility as understood from the principles of scientific methods;
- Detailed energy monitoring systems (EMS) and building automation systems (BAS) should supply the measurements needed to perform the calibration.

The emphasis in this approach is in reducing uncertainty in the unknown inputs on the basis of more reliable information. Assumptions, estimations and simplifications are hence reduced based on evidence.

The second method would be and ad-hoc search for input parameters that fits the observed data. In this sense, the calibrated set of input parameters that produces the best-fit outputs is assumed as *"known"* but producing also residual uncertainty in the subsequent adoption of the model when using it to predict output (Kennedy and O'Hagan, 2001). This traditional *ad-hoc* fitting calibration process has been described by Lee et al. consisting in a two stages calibration. The firs stage fits first the consumption profiles with weather sensitive inputs. The second consists in reducing the output gap for cooling and heating energy consumption adjusting inputs that are not affected by the external environment in an iterative process. A third step will use a correction factor to exactly fit the output value of the calibrated model and make it feasible for FDD (Lee et al., 2007).

In a broader sense, the calibrated model must be understood in concordance with the definition of "energy baseline" used by ISO 50001 standard, but not as a equivalent. The baseline defined in the standard is the benchmark against which current performance is compared to determine if energy performance has improved (or worsen). This concept differs from the idea of a calibrated model representing "ideal" or "optimal" performance that has been used by some researchers to discover faults based on an optimal Vs. actual comparison (see next subsection (Lee and Yik, 2010) and (Basarkar et al., 2011)). This baseline is regarded mainly as stable over time, but the standard gives the performing organization flexibility with regards to the updating of the baseline and only demands a newer definition whenever a major change occurs.

The process of model calibration reveals as a valuable tool to detect current faults and or inadequate operation strategies that can show, thus helping the task of identifying "Energy Opportunities". During the implementation stage, the model needs to be updated to reflect the adoption of the different ECMs, evolving in parallel with the real building in contrast with the baseline, that remains fixed. The subsequent ECMs become *"known"* adjusted inputs.

Model implementation

The third stage of the process will make use of the calibrated model to support the below described activities:

- Off-line WPBS to asses impact of faulty behaviour using E+. This approach has been explored previously by Lee (Lee and Yik, 2010) by imposing a set of "modelling strategies" that represent the expected effect of component faults on the model parameters. Researchers at LNBL are similarly developing reusable model fault objects using the EMS scripting language used in E+ (Basarkar et al., 2011). Fault impacts is measured comparing faulty model outputs with a baseline model that is previously established as the optimal performance model. Assumptions should be made both about the baseline model and the varying parameters occurring whenever a fault occurs. A further implementation of this method in real buildings can be difficult as the baseline model maybe already performing below optimal performance, or faults can occur simultaneously. CASCADE provides the opportunity to use WBPS to assess the overall impact of individual faults in real systems.

- Model based FDD is under development within the CASCADE project. Two model based FDD approaches using an object-oriented framework will be implemented and tested in parallel: (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 quantized system that reduce 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. So far this approach applies MODELICA modelling language and Reduced Order Models (ROMs). A more reliable model will overcome intrinsic ROM imprecisions when dealing with abrupt changes or variable weather data.
- Off-line Predictive Operation Optimization (Set point control and scheduling optimization);
- Testing of Energy Conservation Measures based on key factors methodology by Costa et. al. (Costa et al., 2009). Different operation strategies will be tested with an emphasis on linking occupancy and IAQ requirements. Financial calculations and Carbon Accountancy can easily be implemented using the calibrated model.

CASE STUDY: MALPENSA AIRPORT

The building analyzed is the Satellite A at Milano Malpensa Airport in north Italy (Lat 45.62°N, Long. 8.73°E). An aerial view of the building is shown in Figure 4. The terminal building has been in operation since 1998. Satellite A is a separated segment of the airport terminal linked to the main concourse by a long two stories corridor. It is used as both departures and arrivals hub for passengers and provides access to eight boarding bridges.

Figure 4: Malpensa MXP terminal aerial view

Two additional office buildings were added afterwards (Pallazzine A and B) and have also been considered in the model as their HVAC systems are served from the same heating and cooling production plant. Likewise the model includes the boarding bridges that are also conditioned spaces. The building main areas are open concourses used for the transit of passengers arriving and departures waiting room. Ancillary zones within this building comprise: offices, storage, personnel rooms and plant rooms. Figure 5 shows the initial model geometry created using the SketchUp OSM Plug In. Table 1 summarizes space dimensions and corresponding HVAC systems.

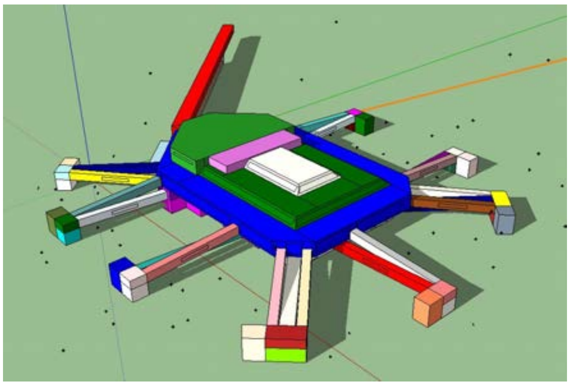

Figure 5: Malpensa MXP terminal SketchUp model

Building envelope

Materials and construction were estimated after a walk trough visit. The building facade is shaped by a metal cladding composite material installed outside the building structure.

Table 1: Zone surfaces of MXP Airport (m^2)

ZONE TYPE	**SURFACE**	**HVAC**
Concourses	10,700	DualD. VAV
Offices/Toilets	2,400	FanCoil
Boarding Bridges	2,612	FanCoil
Conditioned Space	**15,712**	
Non Cond. Space	3,225	

Similarly, the boarding bridges are wrapped with a the same metal cladding faade, also used in roof and floor. The corridor linking the Satellite with the main terminal has its faade made from precast concrete panels. Roof and slabs construction arrangement were estimated based also in data gathered on site.

The resulting U-values for the different surfaces used in the model are defined in Table 2. These were compared with parameters used at the design stage from the original project intent. Design stage U-values refer to the compliance minimum values in the Italian building code at the time and represent the minimum heat transfer coefficient to be used in thermal loads calculation and HVAC sizing. The U-values used in the model are similar from those considered in the original design documentation.

Table 2: U-Values (W/m^{2}K)

SURFACE	MODEL	DESIGN
Metal Cladding	0.442	0.420
Roof	0.319	0.280
Slab Ground	0.747	0.800
Facade Cavity	0.887	0.720
Facade Precast Concrete	0.977	0.800

HVAC

Thermal energy is produced by a centralized trigeneration plant and distributed across the different building zones, according with a modular design. A set of thermal substations handle the thermal exchange of superheated and chilled water to the local HVAC equipment according with thermal loads. Zone HVAC systems can be divided in two types: (1) Concourses are served by an array of four VAV Dual Duct AHUs. Air is distributed by a duct network at the ceiling and delivered by a set of VAV Dual Duct boxes, and (2) Corridors and boarding bridges are equipped with two pipe fan-coil units operating in groups with their water flow automated by a commuting valve for hot/cold water switching. In this case there is no outdoor air exchange.

Infiltration and Occupancy

Site investigation revealed a potential source of discrepancies between model and actual performance. This consist in the special configuration of the final part of the aerobridges which conforms the entrance to the airplane, this part is normally uncontrolled with regards to air leakage. Operation of HVAC in the bridges was also detected as automatically programmed regardless occupancy or thermostat set point control, this point would need further confirmation. Therefore a sensitivity analysis was performed using parametric object within the E+ software. A series of simulations were run using values of infiltration from 0.1 to 1 Air Changes per Hour only for the aerobridges zones only. Values for the remaining zones were kept unchanged. No air exchange was modelled between different thermal zones, however a glass door between the aerobridges and the Satellite was considered as a way of representing a clear thermal inter-zone bridge. HVAC was modelled reflecting the different types of zone equipment in the building (VAV boxes and Fan Coil Units). A dual duct AHU was modelled for the main concourses. Hot water and chilled water for cooling, heating and pre-heating coils was simplified using DistricHeating and DistrictCooling. HVAC equipment was autosized for the majority of parameters except for water and air temperature set points. The building operates from 04.00 am to 22.00 pm. Zone temperature are controlled by thermostats set to maintain a 20°C to 26°C deadband. Figure 6 shows results of this analysis for the annual thermal cooling and heating energy comprising the whole building. The results demonstrate a clear sensitivity to infiltration values affecting the heating performance, whereas the cooling loads where not significantly influenced and showed an inverse relationship. The influence of the air leakage in this particular part of the building could represent more than 10% of energy consumption increment from 0.3 ACH (moderate leakage) to 1ACH (very leakage). Simulation shows that a further clarification with regard the actual operation of the boarding bridges is needed.

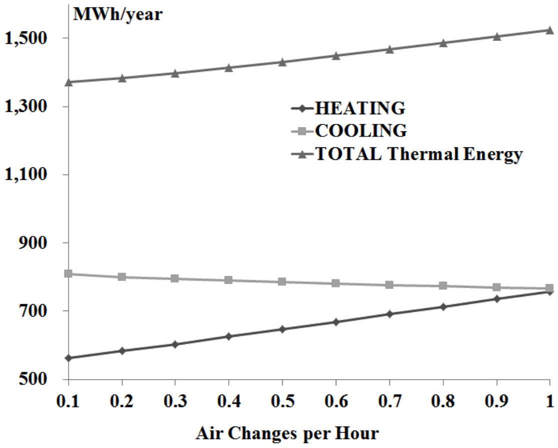

Figure 6: Sensitivity to Infiltration in Aerobridges

In relation to occupancy, it was difficult to work out an adequate value due to the high oscillation of passengers arriving and departing from the terminal. Design documentation showed that design parameters for HVAC sizing varied from 1m^2/person to 10m^2/person according to the different uses, thus representing very high values. The issue of having real occupancy data was addressed by Parker (Parker et al., 2011) creating daily profiles from simple data, while other authors like Suh (Suh et al., 2011) retrieved data from a check-in check-out radio frequency control system. Similarly, occupancy profiles and number of passengers were used in the simulation estimated from the number of passengers and flights, but uncertainty in this parameter remained high. Therefore, a sensitivity analysis was performed. A set of simulations changing occupancy values for the concourses from 4m^2/person (peak load) to 22m^2/person (low season) were carried out. Infiltration was fixed at 0.35 ACH for the all simulations. Ventilation was controlled by the HVAC system by a *DesignSpecification:OutdoorAir* object set to 0.0138 m^3/seg. per person.

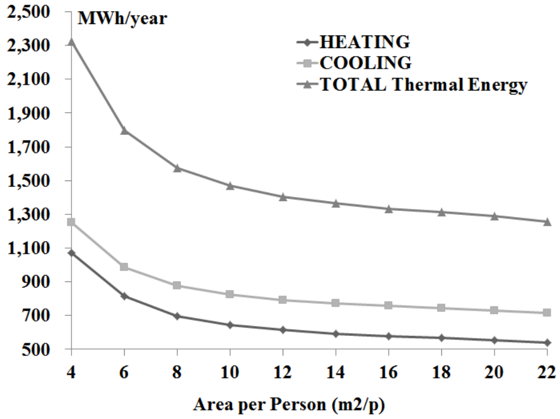

Figure 7: Sensitivity to Occupancy

Figure 7 show the results for the different occupancy values. It is clear that thermal energy increases dramatically for high occupancy values both for cooling and heating. This can rise high as 65%: from 1,406 MWh (12m^2/person) to 2,324 MWh (4m^2/person), while it has a negligible effect for low levels off occupancy. It must be said that high occupancy values simulated are likely to occur only during short periods of time, therefore a better understanding of high/low season periods both in summer and winter is of paramount importance for the calibration process.

Calibration Process and Model Implementation

Next stages will complete the calibration process using the approaches described previously. There are two main areas to look at: One is the investigation of better and evidence-based quality parameters and their influence in the model outputs (high level), and the second refers to the data gathered using the CASCADE implementation itself (low level) more focused at the fine tunning of systems and subsystems. FDD using WBPS is currently at the expense of short time resolution performance data coming from the CASCADE solution, and is still not available. The effort will be focused in the coupling of the different simulation and FDD applications, their run-time and the identification of main ECMs and problems detected during the modelling phase.

CONCLUSION

In this paper airports are identified as significant targets for energy saving technology solutions supporting the EU 20-20 and 50-50 challenges. We also presented an overview of energy management in airports and the development proposed by the EU FP7 CASCADE project that focuses on ICT solutions for energy efficient airports. CASCADE project will help to reduce their energy needs by developing an ISO 50001 Energy Management System, based on advanced Fault Detection and Diagnosis tools. With this paper we particularly defined how calibrated WBPS models can be utilized to support FDD and improved energy management activities and presented the initial results of our case study. Actual performance data were not available at this time. Thus far we described the results of a primary stage of the model analysis.

NEXT DEVELOPMENT

In relation to the future work we will focus on the following aspects:

1. Integration of a predictive sensitive tool that can analyze and workout the optimal operation strategy based in actual performance and forecasted conditions such as weather and occupancy.
2. Methodology to simplify the building model allowing for lower computational resources and shorter simulation time.
3. Integrating real time data acquisition of meteorological data and occupancy for control schedule optimization using Building Control Virtual Bed Test (BCVBT) similarly as described by O'Neill (O'Neill et al., 2011) and Pang (Pang et al., 2012) with the use of the BCVBT and synchronized data acquisition from the CASCADE business logic layer.
4. Using the model to detect faults by linking energy signature (or other parameters) with faults in the HVAC system.
5. A model input update is needed whenever ECMs implementation takes place, introducing also a maintenance duty. Automating this process or creating an easy to use application for the manual update by the non modelling expert .

NOMENCLATURE

t = tonne (1,000 Kg)

ACA = Airport Carbon Accreditation

AHU = Air Handling Unit

TMY = Typical meteorological year

AMY = Actual meteorological year

MXP = IATA code for Milano Malpensa Airport

FCO = IATA code for Rome Fiumicino Airport

GHG = Green House Gas

WBPS = Whole Building Performance Simulation

ACH = Air Changes per Hour

BMS/BAS = Building Management System/Building Automation System

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