MULTI-CRITERIA OPTIMISATION USING PAST, HISTORICAL, REAL TIME AND PREDICTIVE PERFORMANCE BENCHMARKS

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ABSTRACT

Performance based design, construction, commissioning and operation of buildings requires virtual testing and validation of project alternatives. In the case of environmental and energy management of buildings, whole Building Energy Simulation (BES) models can be used to determine indoor environmental conditions, building energy consumption, system performance, and associated CO₂ emissions etc. BES is currently used at the design and commissioning phases of the Building Life Cycle (BLC) but not during the operational phase. This paper defines a methodology that incorporates predictive BES into building operation while acknowledging present technological limitations with respect to model accuracy and required resources. This predictive model also requires detailed definition and characterisation of inputs including: Historical data from buildings; Real time data such as measurements from meters and wired and wireless sensors underpinned by a Building Management System (BMS) and Future data such as short term weather forecast values and expected occupancy schedules. The paper concludes with a demonstration of the predictive BES model methodology using an existing building at University College Cork, Ireland.

Keywords: Fault Detection, Commissioning, Building Efficiency, Building Operation.

1 INTRODUCTION

Globally, buildings account for approximately 40% of global energy consumption but building performance during operation does not normally reflect the original design expectations (O'Donnell 2009). Research projects have developed IT methodologies and tools to address the complex problem of building performance assessment. The common goal of these projects is to support the building manager in reducing building energy consumption without compromising environmental performance.

European member states are currently implementing formal certification and assessment of Buildings. The Energy Performance of Buildings Directive (EU 2002) prescribes energy certificates for new and existing buildings. Certification is a one time event and subsequent to this evaluation building performance is not continuously monitored, thus making it difficult to maintain optimum operation.

This research work focuses on building energy performance during the operation phase of the Building Life Cycle (BLC) and is an integral part of the ITOBO project (Information and Communication Technology for Sustainable and Optimised Building Operation)(Karsten Menzel et al. 2008). Optimised Building Operation integrates radio frequency identification (RFID), wireless sensors, mobile technologies and building information models (BIM) with repair and maintenance activities.

This paper describes a review of currently available and emerging methodologies aimed at monitoring and reducing building energy consumption. This paper proposes a new performance based methodology that will be adopted as part of the ITOBO project. A brief case study is discussed to demonstrate the application of the methodology.

2 AVAILABLE METHODOLOGIES

Each and every building is unique and its use evolves over time. Operation objectives reflected by building control strategies should be coupled with present building usage. In practice, intended operation may match actual building use at the design and construction stages but during operation building function evolves without a corresponding change to the building management system. In the absence of regular assessments, intended and actual building operation will continue to diverge.
2.1 Commissioning

“Building Commissioning is the process of ensuring that systems are designed, installed, functionally tested, and capable of being operated and maintained according to the owner’s operational needs” (Portland Energy Conservation Inc. (PECI) 1998). Commissioning as defined can be applied for two different case types; 1) standard commissioning for new buildings prior to occupancy 2) Retro-commissioning which is a systematic process applied to existing buildings for identifying and implementing operational and maintenance improvements and for ensuring their continued performance over time.

The four phases of the basic Retro-commissioning process are as follows: Planning phase, where the owner or manager decides which building is selected to be studied and the scope and specific objectives for it. Also, information about the building and current operation conditions are gathered; Investigation phase, in which the building manager and/or commissioning provider review all information in order to determine how each major piece of equipment and building system is supposed to operate (ideal case) and then test and monitor system performance (real case). From this comparison a prioritised list of deficiencies and energy saving opportunities is obtained from which the owner may select various measures for implementation; Implementation phase, all the measures previously selected will be applied at this stage by either the building manager or an outside contractor; Hand-off Phase, the final report which includes a master list of deficiencies and potential improvements, a detailed description of improvements that were implemented and a list of recommended capital improvements for further investigation. Also, it is shown how to sustain efficient operation of the equipment and system.

This practice is typically performed at irregular intervals by expert consultants. It requires specific technical and management skills as well as experience in the field. It’s not a simple task and requires time and knowledge, thus the building manager does not normally possess the necessary knowledge or skills. The key issue is that post commissioning the potential exists for divergences between actual and intended building operation.

2.2 Continuous Commissioning (CC)

Continuous Commissioning (CC) addresses the previously identified weaknesses and has emerged as the preferred method of ensuring that building systems are installed and operated to provide the performance envisioned by the designer (Liu et al. 2003). CC is defined as an ongoing process to resolve operating problems, improve comfort, optimise energy use, and identify retrofits for existing central plant facilities and buildings. The process focuses on current building conditions and requirements while accounting for the fact that adequate information does not often exist at design stage to achieve optimum building operation and also that building use has evolved since design. The CC goals are to optimise HVAC system operation by minimise building energy consumption while maintaining desired environmental conditions. Relevant elements of design intent are only considered as a reference not as the performance target. Yet, this methodology is currently held as a periodic assessment driven by external expertise with domain specific knowledge and experience. Consequently the process is not performed by building managers without the assistance of external experts.

Neumann and Jacob (Neumann & Jacob 2008) through the BuildingEQ project propose a new CC methodology that consists of periodic analysis of historically measured data that is used as benchmark for efficient building operation. It is structured in 4 different steps, which are: Benchmarking (Operational Rating), Certification (Asset Rating), Optimisation and Regular Inspection. The definition of the required measurements underpins the procedure. A cost effective ‘minimum data set’ has been specifically established and forms the basis of all benchmarking activities. This top-down approach means that the whole system performance is analysed first with subsequent lower level evaluations.

3 PROPOSED METHODOLOGY

The methodology presented in this paper introduces automation of Fault Detection (FD) process to support performance assessment and optimisation. The methodology accounts for
the benefits of automated continuous commissioning tools, which reduce both the costs and time associated with commissioning. The methodology also reduces the level of technical knowledge required, thus making it accessible to building managers.

This systematic methodology will detect the failures or non-efficient performances by a one to one comparison between the measured performance metrics and their associated specific benchmarks. This comparison is carried out on the base of some clearly defined conventions.

3.1 Optimised Building Operation

The proposed methodology defines an overall process that is based on the comparison between measured metrics and their corresponding benchmarks. The key issues are the development of an automated comparison method and the definition of the inputs. Three different inputs are needed and will be described in the following sections (3.2.1, 3.2.2 and 3.2.3).

There are two levels of comparison, the first detects and therefore mitigates “incorrect performance” (incorrect meaning not as prescribed) which is formed on the basis of previous current performance with historical performance. Measurements include operating conditions, operating strategy, building use, etc. Values for current performance that are not in-line with previous performance are registered as a fault.

The second level of comparison is undertaken to improve the efficiency and/or comfort of the building. A static set of rules and calibrated simulation models obtained from the analysis of different building operation strategies may be used. The process is illustrated schematically in Figure 1, where the inputs of measured values, benchmark values and conventions are inputted to the Fault Detection Comparison. The possible results are represented by “Performance as prescribed” when the measured value is in the range defined as valid or “Diagnostic required” when the value is not in the range.

CC is based on available measured data that are usually gathered by Building Automated Systems (BAS)/Building Management Systems (BMS). However these data are used only for real time system control and operation. Therefore they are not structured in a fashion that allows data transformation, performance assessment or fault detection activities. The minimal data set definition takes the measurements normally available from BAS/BMS into account and will consider the installation of new additional sensors exploring both traditional wired and emerging wireless technologies.

3.2 Required Technologies

3.2.1 Measurement Framework

The measurement framework is a key part of this methodology. The origin for the commissioning process of a building is the gathering of the historical data. All conclusions formulated are on the basis of results and are therefore dependant on the reliability of the data on which the analysis is made. The availability of consistent, accurate and reliable data in existing buildings is not conducive to meaningful performance analysis. The costs associated with monitoring the different components of a system require considerable investment. The barrier to defining and
deploying an adequate number of sensors and meters in a building is the installation cost, primarily associated with the cost of wiring. As a percentage of total cost for a new sensor, wiring can account for 45% and 70% for new buildings and retrofit applications (Jang et al. 2008). Currently, the development of new applications that use existing technologies such as wireless sensor networks for building monitoring decrease the installation cost. In response to this need, both industry and academia have been achieving results in developing and deploying wireless sensor technology in the construction sector. Several studies have been carried out regarding the possibility to extend this wireless technology to sensors, meters and actuators (BuildWise 2007). The performance framework used by this research work was developed within the BuildWise project, and is currently used and deployed by the ITOBO project.

The ITOBO project is currently using wired and wireless technology in its measurement framework and storing the information in a Data Warehouse. The measurement framework proposed in this paper provides the inputs to the Fault Detection work package within ITOBO: The framework includes: the benchmarks with a range of valid performance values and the real time data for the fault detection process.

3.2.2 Benchmarks

Within the FD process there are three different benchmark sources. The Statistical Analysis is obtained from previously recorded historical performances of the building. The Set of Rules is a list of conditions with which the building and its systems should comply. This list is defined externally and could be applied to other buildings. The third benchmark, the Energy simulation model, has inputs that include historical data and predictive data such as schedules, loads, occupancy etc.

Historical data from the building is statistically analysed to obtain patterns representing building performance. At a system component level it is feasible to analyse performance metrics for different devices, for example, Heat Pump Coefficient of Performance (COP) versus outside temperature or heat given to the system by the solar panels versus solar radiation.

The Static Model defines rules or conditions to be satisfied. The system will monitor measured data and will be an input for the condition or rule previously defined. Then the result will be either ‘true’ or ‘false’, i.e. the condition that ‘simultaneous heating and cooling is not permitted’. The system obtains the values from the heating and the cooling and if both of them are not zero a fault is detected.

An Energy Simulation Model will be used, in simplified or detailed form, to quantify the saving potentials of alternative operation strategies. It is imperative that the model is calibrated, i.e. the parameters must be adjusted so that the results of the model correspond to the actual operation. Only then can a detailed or simplified simulation model be used as a benchmark for the FD process. This allows for virtual evaluation of different operation strategies and selecting the most efficient. Once the strategy is determined, the model itself will be used as a benchmark.

3.2.3 Conventions

The methodology requires the definition of several parameters in order to undertake the comparison. These conventions are based on the experience of the building manager, the Operation and Maintenance (O&M) manuals and past performances obtained from statistical analysis. The tolerance, or upper and lower boundaries, assigned to a linear regression model determine the acceptable performance region. The number of data points outside these bounds can be analysed on a metric by metric basis to establish if a fault actually exists or not. A requirement for fault detection can be the frequency at which the fault occurs over a time period. The functionality of the lightning sensor may be affected by occupant behaviour or changes in the zone layout that may cause obstruction of the light sensor resulting in unnecessary activation of the artificial lightning.

4 CASE STUDY

The Environmental Research Institute (ERI) building, located at University College Cork (UCC), was designed as a green flagship building and a low energy research facility (Pearson 2005). It is a combination of both lab and office space requirements. Such facilities are often dismissed as too complex and
specialized for employing a sustainable design approach. Operation of these facilities while managing low levels of energy consumption is notoriously difficult to achieve (Federspiel et al. 2002). However, recent studies have highlighted lab facilities as the ideal candidate for employing energy saving practices throughout the Building Life Cycle (BLC) (Wirdzek et al. 2004). High levels of energy consumption are magnified during the assessment phases, as it is extremely difficult to qualify the effectiveness of energy use in buildings with disparate activities such as office space, laboratories, cold temp rooms, toilets and conference rooms.

**Figure 2.** High-level image of the integrated Hybrid Heating and Cooling System Installed in the ERI Building

### 4.1 Measurement Framework

A state of the art BMS was installed to facilitate monitoring of the integrated hybrid heating and cooling system (Figure 2), building energy use and indoor environmental conditions. (O'Donnell 2009). In addition to these measurements, a number of wireless sensors were installed and integrated with a Wireless Sensor Network (WSN) as part of the BuildWise project demostrator one. This represents the available measurement framework for the ERI building that exceeds by far what is typically available in buildings. It includes different types of sensors (air and water temperature, air relative humidity, lighting level…) and meters (electricity, heat, water flow…) both at the whole building level and to the system component or zonal level.

### 4.2 Benchmarks and Conventions

The application of the proposed methodology focuses in particular on the overall heating consumption and the heat pump operation. Given the aforementioned measurement framework, the benchmarks adopted in this case study are calculated on the basis of: a statistical model (linear regression model) for the total heating consumption and a static rule for the heat pump COP. These two examples and their respective conventions are described in the following paragraphs.

The heating energy signature was calculated for the period between November 2007 and May 2008. It consists in the interpolation with a linear regression model of the weekly total heating consumption against the weekly average temperature. As explained, this statistical model is a source of a building specific benchmark that can be used for automated fault detection.

In order to identify the fault a convention related to the tolerance has to be defined. The region denoting normal operation was obtained by approximating the model (linear regression line) with a band as illustrated in Figure 3. This band consists of the area enclosed between the upper and lower bound thresholds. In this case the thresholds were obtained with a 20% variation of the average heating consumption. Measured performance can be compared against the region denoting normal operation as represented in Figure 4. In these cases two new values were compared with the benchmark and different results were obtained: the ‘big dot’ represents a measured performance as prescribed whereas ‘the cross’ represents a case in which a fault is identified and diagnosis will be required.

Another example was obtained for the heat pump operation. In this case, the faultless domain was identified with a static rule: *if the heat pump is running its COP value must be greater than 2.5* (Figure 4).
The graph shows how during the first week of May 2007, 4 faults would have been automatically detected. The causes for these faults might be the following: water from the aquifer hasn’t been pre-heated properly, the solar panels aren’t active at that moment…

In relation to the energy simulation based benchmarks, a whole building energy simulation model for the ERI building is currently under development.

5 CONCLUSIONS

This paper analyses the available methodologies for the building operation assessment and proposes a methodology that defines automated Fault Detection to support the application of CC. This automated process is based on the comparison between measured values and building specific benchmarks. A brief case study shows how this methodology will be applied.

The methodology also reduces the level of technical knowledge required, thus making it accessible to building managers.

For the automation of the FD process the biggest effort will be to specify the mentioned set of rules and develop the use of a building energy simulation model to support building operation. Finally the interaction of the different benchmarks will be analysed to avoid conflicts.

Future work will lead to the complete deployment of the described methodology to a building as part of the ITOBO framework.

6 REFERENCES
