A SENCE-THINK-ACT METHODOLOGY FOR INTELLIGENT BUILDING ENERGY MANAGEMENT

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ABSTRACT

The realization of smart and energetically-efficient buildings is contingent upon the successful implementation of two tasks occurring on disparate phases of the building lifecycle: in the design and subsequent retrofitting phases, the selection and implementation of an effective energy concept; and, during the operation phase, the actuation of available energy-influencing systems and devices to ensure parsimonious use of resources while retaining thermal comfort at acceptable levels. Building Energy Management Systems are tasked to continuously implement a three-step Sense, Think, Act (STA) process: Sense, using sensing modalities installed in the building; Think, utilizing, typically a rule-based decision system; and Act, by sending actuation commands to controllable building elements. Providing the intelligence in this STA process – justifying in that sense the epithet "smart" in smart buildings – can oftentimes be a formidable task due to the complex interplay of many parameters and uncertainties. In this paper, a methodology developed within the European FP7-ICT Project PEBBLE, is presented to streamline the effective implementation of such STA processes. The ingredients of the proposed architecture are: (S) a middleware component capable of collecting and aggregating information from a number of inhomogeneous sources (sensors, weather stations, weather forecasts); (T) a model-based optimization methodology to automatically generate intelligent decisions; and (A) the Actuation layer, which communicates the decisions to the building. Information provided through graphical user interfaces, aims at enhancing user energy-awareness and at making building users proactive Actors in the process. The ICT components implementing the methodology are presented and evaluated with corroborating experiments conducted in an office building of the Technical University of Crete.

Keywords: Smart buildings, Model-based control, Simulation, Co-simulation, Optimization, BEMS

1. INTRODUCTION

The topic of saving energy is ubiquitous, and actions supporting more effective utilization of energy along with behavioral changes needed to support transition into a low-carbon/low-energy economy have long been underway. Still, despite all these actions, change is happening at a slow pace. It is estimated that energy consumption in buildings accounts for approximately 40% of the EU final energy consumption, a significant portion of which is used to satisfy space heating and cooling needs.

Achieving high energetic performance in buildings is contingent upon the successful accomplishment of two tasks in different phases of a building's lifecycle: in the design phase, consideration of energy-efficiency aspects in the building design and selection of an effective energy concept; and, during the operational phase, proper operation of systems and components to ensure parsimonious use of energy while attaining end-user thermal comfort objectives. In office buildings today, the latter task is achieved by installing Building Energy

Management Systems (BEMS). A typical BEMS installation comprises a set of sensing modalities, actuating components, and an Energy Management concept typically implemented as a set of rules in the building's Programmable Logic Controllers (PLCs).

It is very often the case that these decisions are not good enough: it is estimated that 20% of the energy consumed in buildings is wasted due to either poor configuration or wrong operational assumptions during the design and commissioning phases. Even in the case of good configurations, it is very hard to encapsulate good strategies as a simple set of rules. The situation is particularly egregious for high-performance buildings or when renewable energy systems are installed, where, in the former case, the complexity of integration becomes formidable as all the systems have to operate harmoniously together, while in the latter case generation patterns strongly depend on weather conditions,.

The objectives of the PEBBLE (Positive-Energy Buildings through Better control dEcisions) project were to develop ICT components that help address some of the problems and shortcomings identified above by implementing a three-step Sense, Think, Act (STA) process: (S)ense, where a middleware component capable of collecting and aggregating information from a number of inhomogeneous sources (sensors, weather stations, weather forecasts is defined; (T)hink, where a model-based optimization methodology to automatically generate intelligent decisions is proposed; and (A)ct, where the Actuation layer, communicates the decisions to the building. Through this process, within PEBBLE the approach to development of BEMS is different compared to existing BEMS solutions: instead of using a static set of rules, the BEMS strategies are continuously and automatically updated based on current and past measurements along with forecast data (e.g. weather). This automatic BEMS generation is obtained by the solution of an optimization problem where a cost function – say, the Net Energy Produced (NEP) – is maximized subject to constraints (e.g. thermal comfort). In that sense neither a priori expert knowledge nor any fine-tuning is required to set-up and configure the system. Instead what is required is an accurate and computationally efficient simulation model of the building, acting as a surrogate to the real building, that correctly models all passive, active and energy-generation elements.

As part of the demonstration activities, the PEBBLE system has been deployed and evaluated in three buildings possessing a variety of design and performance characteristics, located at different places across Europe: the building hosting the RWTH Aachen E.ON Energy Research Center which is an archetype of a complex modern building with many energy systems and renewables installed; the ZUB Building hosting the Fraunhofer Institute of Building Physics, which is the archetype of a very-low energy building with high thermal mass; and the Technical Services Building at the Technical University of Crete, which will serve as an application example throughout this paper. For more information on the outcome of PEBBLE system application in each of the test buildings, please refer to (Kontes et al. 2012b).

Moving to the application presented here, the demonstration site is the Maintenance support building of the Technical University of Crete located in Chania (TUC building), Greece (Dröscher et al. 2010), which is unremarkable in many ways – and in that sense typical of the office building stock in Greece and elsewhere – having no installed BEMS in the beginning of the project. In addition to thermal comfort problems for the building users, the energy consumption of the specific building is quite high, at 130kWh/m^{2}a. Regarding the HVAC system of the building, heating is achieved through a central system using an oil boiler and hot water radiators in each room, while a split unit (AC) in each room is used for cooling.

Figure 1 The Maintenance Support building of Technical University of Crete

Throughout the remaining of the paper, Section 2 analyzes the components of the STA process, with respect to the solutions provided to the application building; Section 3 presents a set of experimental results from the PEBBLE system application; and Section 4 gathers concluding remarks.

2. THE STA PROCESS

2.1 (T)hink

Since the final target of the STA process is the design of intelligent control decisions for the building, this component lies in the heart of the process and determines the efficiency of the proposed solution. Here, a model-assisted fine-tuning methodology to adapt and improve performance of energy management systems has been developed: to start, a detailed building thermal simulation model acting as surrogate of the real building is required, supported by a co-simulation module, along with a naive controller, a "good" initial controller, or even a set of rules with tunable parameters. Given weather and occupancy predictions for a predefined time window, – say a day, – an algorithm is used to create candidate controller parameters, and the simulation model is used to evaluate candidate solutions through a co-simulation module. Controller parameters are updated so that a good-performing controller – in terms of a predetermined cost function – is created. This controller, adapted to the forecasted conditions and the actual building – or at least a comprehensive representation of the real building as obtained using validated thermal simulation models – is used to operate the building until new forecasts trigger a controller-parameter update. Apart from operational performance benefits, updating controllers over short periods, means that simpler in terms of mathematical structure controllers can be used.

The control design problem is posed as a constrained minimization problem, following the Model-Predictive Control (MPC) (Maciejowski 2002) paradigm: a user-defined cost function is provided (say the primary energy, or the NEP) along with constraints (say, thermal comfort (ISO 2005, ASHRAE 2004)); the constrained minimization problem is then solved for a period of time, while the resulting control strategies are applied in the building for a shorter period and a new control design process restarts.

Since the proposed control design optimization approach necessitates the utilization of a thermal model of the building, differing model requirements were identified for validation and control-design purposes: in the former case the need for high accuracy along with the potential of use of sensed data (for uncertainty mitigation) is required; while in the latter case "just-enough" accuracy is necessary (because of the need for repeated evaluations and the concomitant constraints imposed by the computational complexity). The thermal model of TUC building was developed in EnergyPlus (Crawley et al. 2001), but when tested, the model complexity and the requirement to run a number of simulations – each with a settling phase to warm-up the model – for the controller optimization process (co-simulation) led to high total computation times. In an effort to reduce the simulation time, the building model was reduced and broken down into representative sub-models (Giannakis et al. 2013), as shown in Figure 2 (left). For this model to be accurate, the boundary conditions of each sub-building had to be passed to the neighboring structures, while a connection between the building model and the predictive control algorithm implemented in MATLAB was necessary. Both these requirements were fulfilled utilizing the BCVTB (Wetter 2011) co-simulation interface. The realization of the connection of the building models with the predictive control algorithm coded in MATLAB is shown in Figure 2 (right). For more information on the simulation model and the co-simulation component, please refer to (Pichler et al. 2011).

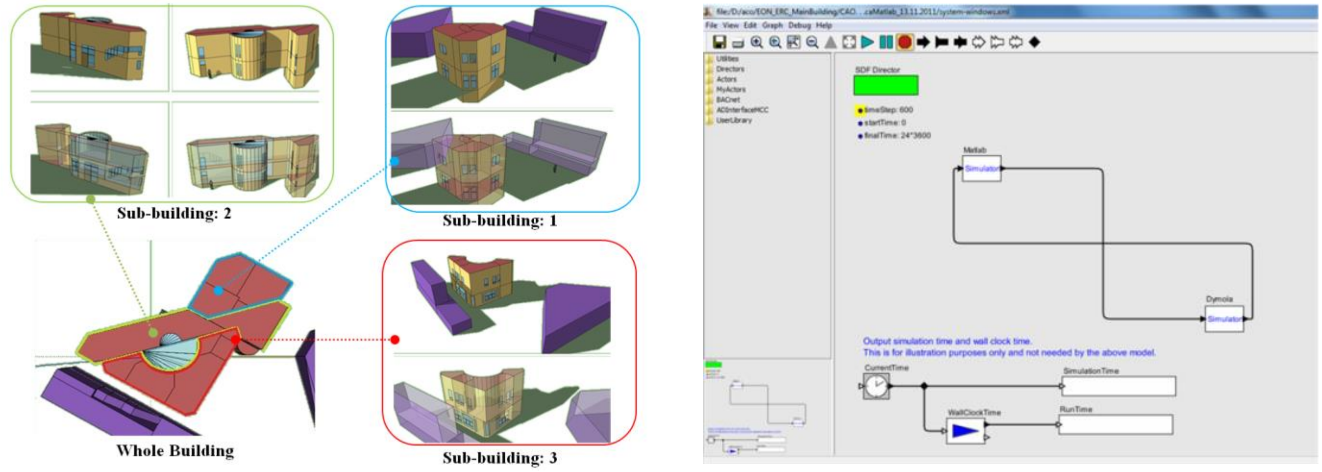

Figure 2 Reduced simulation model (left), connection of simulation models with the predictive control algorithm (right)

Once the reduced model is available and the co-simulation allows simulation using dynamic schedules (e.g. for occupancy and/or weather data) as well as the connection to weather and occupancy forecasting services, the development of the optimization algorithm for solving the constraint optimization problem posed is in order. Here, a new, more elaborate and efficient version of the Cognitive-based Adaptive Optimization (CAO) algorithm (Kosmatopoulos 2009, Kouvelas et al. 2011) for tuning BO&C systems has been developed and tested (Kontes et al. 2012a). This new algorithm will be combining real-life data from the past as well as the elaborate simulation model, to continuously and automatically fine-tune the BO&C systems developed. Extensive simulations using one- and three-zone buildings have demonstrated that this new version of the CAO algorithm provides rapid and convergent automatic fine-tuning of the BO&C system (Kontes et al. 2011). Interestingly enough, the simulation results on medium-scale buildings indicate that the algorithm can provide automatic BO&C fine-tuning (and thus optimization of the building operations) within few iterations even when it starts from zero knowledge regarding the building dynamics.

The main conclusion of the proposed BEMS design approach, is that the goal for "energy-savings" is untimely if treated separated and isolated from parameters, like user thermal comfort; the final target of an intelligent BEMS design mechanism should not be the minimization of a performance index, such as the total energy consumption or the operational cost, but should also ensure smooth building operation, taking into account user comfort. For example, in a real building, a newly-installed BEMS system can consume more energy than the existing system, in order to improve user comfort levels. Since many norms exist for defining user comfort, a BEMS design system has to be able to incorporate the various approaches in an efficient and laborious-free manner. Taking into account this fact, the PEBBLE system is designed in such a way that allows defining accurately and with a simple and straightforward mechanism the tradeoff between the performance index and the posed comfort constraints. In addition, this balance can be altered using a simple set of settings at any point of operation, in case the building manager or the users request it. For more information regarding the implementation and properties of the proposed solution, please refer to (Kontes et al. 2011).

2.2 (S)ense – (A)ct

Even though the control design optimization process along with all the necessary components has been defined, the installation and management of a holistic sensing and actuating platform is essential for successful application of the proposed methodology. This required additional effort for TUC building, since no energy management system was present before the start of the PEBBLE project. As the building was typical of a retrofit scenario, new cabling would be disruptive to occupants (and time consuming). It is for this reason that most room monitoring sensors installed are using wireless technologies, with two types of wireless sensors installed in the building: a set of sensors developed by CSEM for PEBBLE (Hennemann et al. 2010), and wireless EnOcean sensors which are commercially available. Especially for CSEM sensors, the solution is based on the implemented mesh ultra-low power Wireless Sensor Network (WSN). This technology combines ultra-low power operation, ease of deployment, extensibility and flexibility required by the PEBBLE applications. Here, CSEM protocols (WiseMAC) allow each wireless node to act as relay of the information transmitted by the other nodes, thus allowing full and easy coverage of the building and extensions, such as basement, cellars, chimneys, air distribution systems, roofs, gardens, power plants, other secondary buildings, garages, etc. Moreover, to support the constantly varying conditions of wireless propagation, CSEM WSN technology provides automatic reconfiguration of the network for finding alternate routes if some of the previous routes are not usable anymore. This mitigates the typical effects of reflection, diffraction, polarization mismatch and attenuation due to obstacles such as walls and floors. Deployments are therefore made much easier and more robust.

The building in Chania has a significant collection of sensors and actuators, communicating via many different protocols. Data access to the 200 signals originating from the building was initially provided via OPC. It was decided that the needs for an OPC server limited the replicability of the solution and therefore a more direct connection directly to the PLCs via a CGI interface was implemented. In addition, connectivity to external information sources was implemented: this includes receiving current weather conditions from the weather station (via a serial connection) and weather forecasts from two weather services (Greek National Weather Service, online weather forecast site). A number of interfaces for management and user interaction have been developed.

In order to be able to establish a bi-directional communication between the sensing and actuation components, a cloud-based monitoring and control solution was developed. To that direction, it was realized that the need to incorporate weather forecasting and information from other external sources, made it necessary for a generic data aggregation solution. Also the need to provide user interfaces so that building users and operators could interact with the system made it necessary for a generic approach towards generating user interfaces and delivering content to the users. The need for PEBBLE algorithms to have up to date information (and direct access) to all logged building data, also warranted a unified solution. A high level view of the ICT components and the overall PEBBLE architecture is shown in Figure 3 below:

- Building Layer: At the building level the Connector is an ICT component supporting a pluggable driver architecture that enables the communication with the building PLCs and weather stations installed through a variety of connection methods.
- Data Management Layer: The data management layer provides components that functionally support the PEBBLE architecture: this includes a data persistence layer (data logger, database) and connectivity to external services and components (e.g. sources of weather forecast). Physically these components might reside on (or near) the building or in a private cloud. Three main goals have set in the design of these components: generality, openness, and being lightweight so that the parts which are relevant to be able to run in an embedded device. In particular the connector through extensible pluggable driver logic is able to access the PLCs: two such drivers have been implemented, a direct CGI connection to PLCs or a connection via an OPC interface. The data logger is capable of connecting to one or more connectors and to record data to one or more databases. This supports the use case of having a local, short-term storage on a small data base residing on the building, along with a normal data logging to a full-featured database residing at other locations (e.g. at a company's or University's private cloud). The data models and design considerations in developing these components are described in more detail in (Katsigarakis et al. 2011, Kafandaris et al. 2012).
- Application Layer: The application layer is where the components that provide the actual PEBBLE functionalities reside. Two components/applications have been implemented: the Building Optimization Service and Graphical User Interfaces.

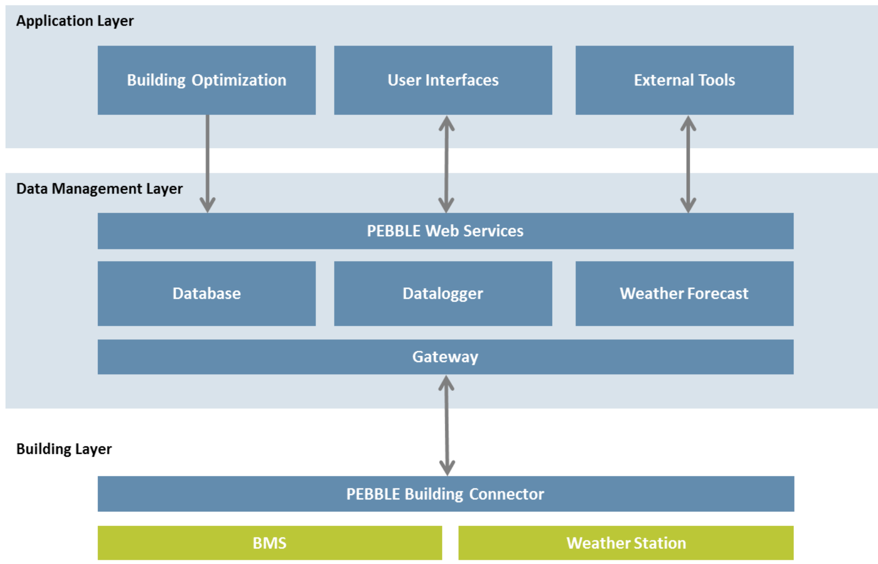

Figure 3: PEBBLE Architecture

The deployment of these components for TUC building is shown in Figure 4; more details on the design of the various components are shown in Figure 5. A web-service interface has been defined allowing the communication between the Application Layer with the Data Management and Data Access layer. Users within PEBBLE act both as sensors and actuators, assisting the control decisions of the system. Within this context, users are allowed limited control on the cooling system, by communicating their preferences and indirectly influencing the AC setpoints proposed by PEBBLE. But in order for the users to make energy efficient decisions, information has to be provided on the impacts of their decisions, using e.g. energy consumption charts. Moreover, in order to promote user-acceptance on the system, a detailed batch of information concerning the conditions in their room has to be provided.

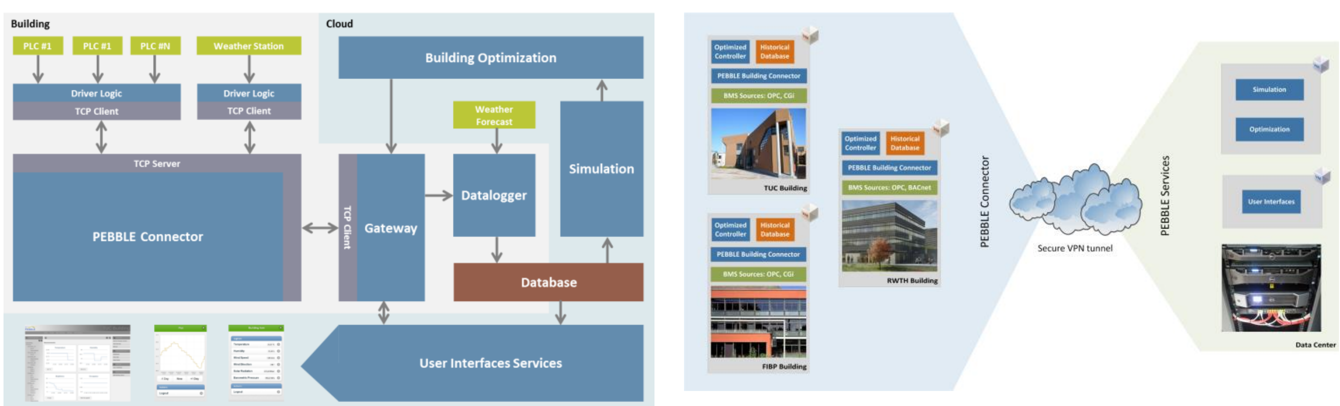

Figure 4: Component Building and Cloud separation

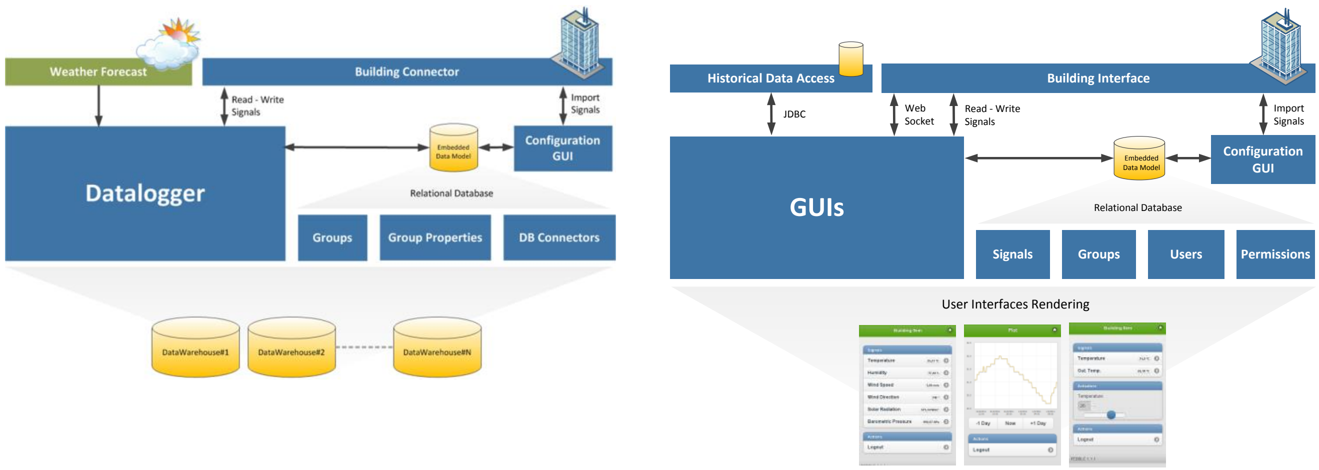

Figure 5: Data Logger service (left); Graphical User Interface Service (right)

To include the above options in PEBBLE System, a set of user GUIs has been developed, supporting different access methods and providing a plethora of available information towards the users. Since not all users should have access in all the sensors and components of the building, user groups have been created, allowing building occupants access only to their office and common space data, while an administrator group has access to all the data available to the system. In fact, the configuration interface allows for fast definition of new user groups, with custom access to various sensors and actuators. Finally, UIs for access through web-browsers, mobile devices and UIs compatible with micro-browsers (VoIP phones) have been developed.

3. EXPERIMENTS

During the demonstration of the PEBBLE system in the TUC building, a set of experiments were conducted: control of the cooling system (split-type air conditioners) setpoints during the summer; and during winter operation, control of water flows to the thermal radiators. A structured demonstration plan was implemented. Initially, “cold” experiments were conducted to test the validity of the PEBBLE controllers: sensor measurements and weather forecasts were used for the warming up of the simulation model and the design of the controllers. Then the controller decisions using sensed inputs were computed but not communicated to the building. This first set of experiments was performed to confirm that the PEBBLE system yields sensible decisions. A second set of experiments where values were actually sent to the building were performed over weekends using artificial occupancy patterns. Finally, cooling experiments which included the building occupants were performed; users could alter the chosen setpoints according to their preferences and their requests were recorded for validation purposes. In winter time, experiments were performed controlling the heating system of the building.

The main development of the PEBBLE monitoring system was performed with the TUC building as a test-bed. Shown in Figure 6 below is the experimental methodology along with the various components that were developed and interconnected so that the experimental work could be performed. The simulation model was run using real sensed data by utilizing the co-simulation interface: past sensor measurements were merged with forecast data to generate automatically occupancy patterns and weather files. Then the effect of various control strategies was tested on the simulation with a warming up period of 4 days and a forecast period of 1 day. A new controller was generated every 3 hours (or 1 hour for winter experiments) and was communicated to the building. The current controller was invoked every 10mins (or 30 mins for winter experiments) to compute values of the A/C setpoints (for cooling experiments) or valve position (for heating experiments).

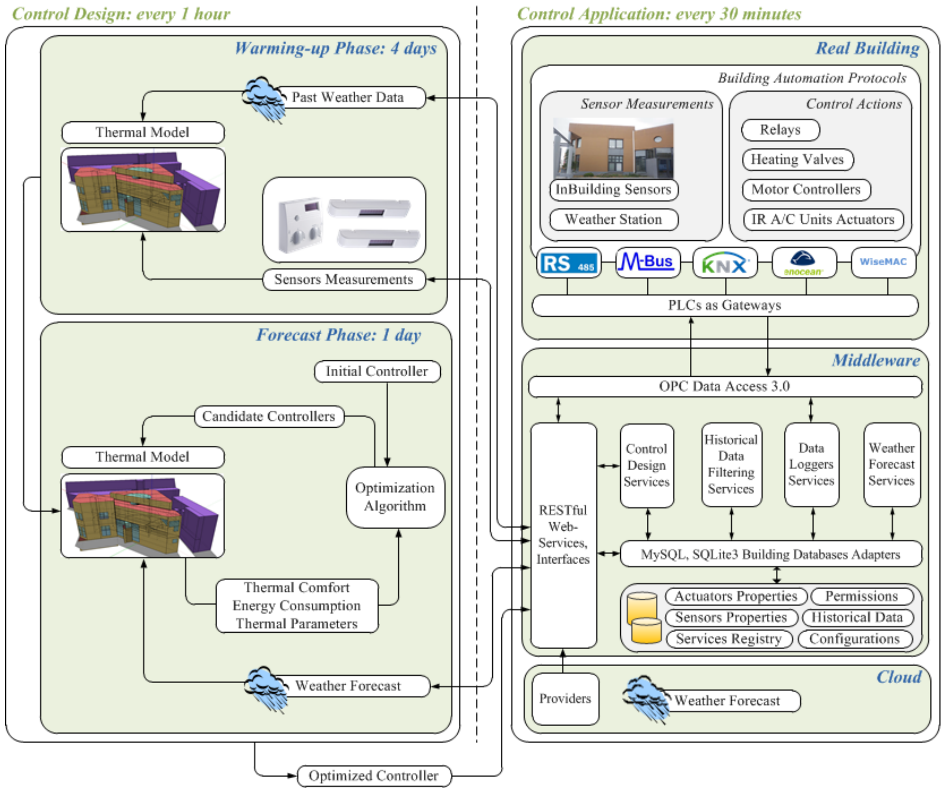

Figure 6: The experimental methodology

The most interesting online experiment is the winter experiment conducted from 22/02/2013 - 01/03/2013. In this experiment two zones of the TUC building were controlled: in zone O4, which had two radiators, one was delivering the base load and PEBBLE was optimizing the operation of the second; at the same time, in office O5 the operation of the one radiator present there was optimized.

A summary of the obtained results is shown in Figure 7: the hot water consumption at each controllable branch and the sum of them, and the hot water consumption at offices O4, O5, as they resulted from the heating experiment by comparing the control strategy produced by PEBBLE system with the rule based controller applied to the building. The implementation of the PEBBLE system leads to 57.77% and 34.85% energy savings for offices O4 and O5, respectively. For more information on the experimental setup and the resulting controllers, please refer to (Kontes et al. 2012b).

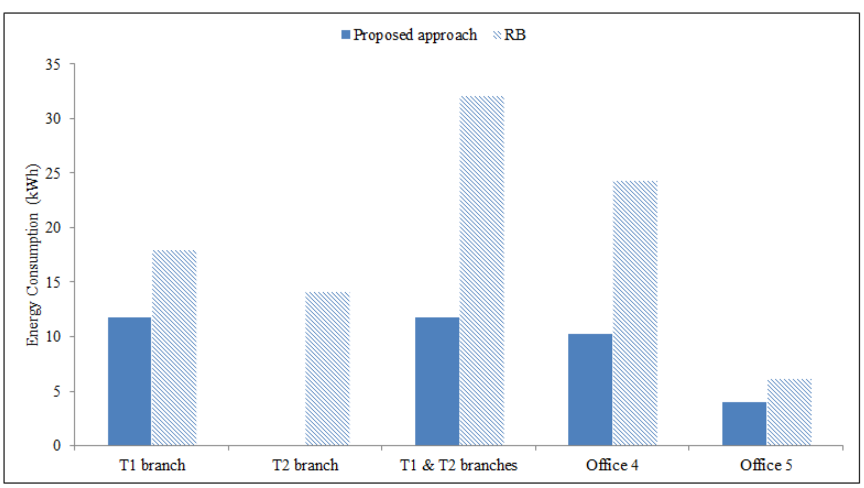

Figure 7: Heating experiment results

4. CONCLUSIONS AND FUTURE WORK

In the present work a methodology developed within the European FP7-ICT Project PEBBLE is presented to streamline the effective implementation of a Sense-Think-Act BEMS design processes. The ingredients of the proposed architecture are: (S) a middleware component capable of collecting and aggregating information from a number of inhomogeneous sources (sensors, weather stations, weather forecasts); (T) a model-based optimization methodology to automatically design intelligent BEMS; and (A) the Actuation layer, which communicates the decisions to the building. Through the model-based optimization approach, PEBBLE system is designed in such a way that allows defining accurately and with a simple and straightforward mechanism the tradeoff between the performance index and the posed comfort constraints, while a cloud-based monitoring and control solution is able to configure transparently the complex interplay of all the sensing and actuating sub-components, as well as to maintain and expand the installed infrastructure, thus supporting the control design optimization process. The efficiency of the proposed approach is presented by demonstration in an office building of Technical University of Crete, located in Greece, where for a heating experiment leads to significant energy savings, compared to the campus central heating strategy, while maintaining acceptable comfort levels.

Even though the proposed methodology has proven to be robust and lead to energy-efficient building operation, it necessitates a laborious hand-tuning configuration process prior to deployment, which includes the implicit mapping of each sensing and actuating component to the corresponding elements of the simulation model, as well as to the respective entries of the data-logging system. In addition, if a simulated model of the building is not available the deployment costs can increase. Therefore, our ongoing work focuses on the utilization of a Building Information Model (BIM) repository, holding all the necessary information for the semi-automatic design of the building model, as well as the transparent configuration of the overall PEBBLE system.

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