A NOVEL MONITORING AND CONTROL SYSTEM FOR HISTORICAL BUILDINGS

J. L. Hernández[1], S. Reeb[2], G. Paci[3], H. Garrecht[4], D. García[5]

ABSTRACT

Monitoring and control concepts are the basis of energy savings and comfort improvement because they occur in the analysis and diagnosis phases. However, in historical buildings it is more complex to determine the best system for the monitoring concepts because of conservation issues such as aesthetic aspects. For this reason, wired sensors are not adequate for such kind of buildings and a new concept of wireless sensors has to be adopted. A major problem is providing a power supply without the need to change batteries frequently. The ZigBee is an appropriate solution due to its low energy consumption.

On the other hand, the sensor network has to be complemented by software, that is to say, a Building Management System adapted to the requirements of monitoring and control for these buildings. Sculptures, frescos and drawings have to be maintained in a specific condition in order to avoid degradation, therefore, a management system helps to keep the best conditions for historical buildings. For the implementation, a service-oriented architecture is developed which favors the inclusion of further services. Moreover, the usage of new technologies gives an added value to the system in order to facilitate advanced implementations.

Keywords

Monitoring, control, wireless sensors, ZigBee, Building Management System, historic buildings, comfort, 3EnCult.

1. Introduction

The research European Project 3EnCult, which is funded by the 7th Framework Programme from the European Commission, aims to establish a methodology for improving the energy efficiency and comfort conditions in European historical buildings.

In the the EU-27 context, about 40% of the housing stock was built before the 60s and the other 40% between 1961 and 1990 (Buildings Performance Institute Europe 2011). Therefore, a large proportion of the building stocks are old constructions belonging to the historical heritage which presents a high level of energy consumption and low comfort conditions. Apart from the aesthetics, the heritage and other conservation issues must be borne in mind.

Thus, through a discussion about energy efficiency, comfort and conservation of the historical value, this project works on a methodology for diagnosis and evaluation of the interventions based on these three issues. Several times, the interventions are strictly needed for the building conservation from the structural point of view, such as the moisture problems in the historical wood structures or the maintenance of the environmental conditions in the spaces with unique paintings or architectural elements. However, other times it is not possible the actuation, therefore it has to be applied another kind of solution. In such cases, the Information and Communications Technologies (ICT) play an important role in energy savings by integrating management systems which improves the performance of the systems in order to save energy. On the other hand, for the preliminary analysis and diagnosis before the intervention, the monitoring phase is required so as to understand the current behavior. In this case ICT is important for enabling the measurements and the collection of data. However, conservation issues must be taken into account as they represent a critical point to be solved. A combination of wireless sensors and a Building Management System [1][2][3] can be used so that the monitoring and control rules and requirements can be developed and deployed in historical buildings.

In the 3EnCult scope, there are eight case studies which were able to deploy the wireless sensors and the Building Management System in order to help the analysis and diagnosis approach for the interventions proposed by the industrial partners, based on research into new materials and/or refurbishment techniques. The case studies belong to diverse climatic areas and different ages (from 16th century until the 60s) and cover a wide range of the issues mentioned.

The consortium comprises 21 partners from various sectors, creating a multidisciplinary group including historians, conservators, architects, civil, industrial and telecommunication engineers, public institutions members and industrial partners. The key for the formulation and evaluation of these strategies for buildings with high potential for energy savings is found in this collaborative and multidisciplinary group.

This paper presents the monitoring and control systems developed in the project for energy saving and comfort improvement of historical buildings. Thus, in a first section the monitoring concept, recommendations and restrictions in

1 Cartif Technology Centre, Spain, josher@cartif.es
2 University of Stuttgart, Germany, simone.reeb@iwb.uni-stuttgart.de
3 University of Bologna, Italy, giacomo.paci@unibo.it
4 University of Stuttgart, Germany, harald.garrecht@iwb.uni-stuttgart.de
5 TyCo, Australia, garciagildaniel@gmail.com

historic buildings are presented. Next, the control algorithms and constraints for automatic actuation in the facilities are explained. The following section highlights the ZigBee wireless sensors that have been developed in the context of the project to comply with the aesthetic and conservation issues. The building Management System complements the previous one with the software system for the management of the building through the ZigBee sensors applying the monitoring and control rules. Finally, the results reached in the case studies where the BMS and the sensor network have been deployed jointly and the main conclusions are reported.

2. Monitoring concept

In order to assess the energetic behavior of a historical building, a monitoring phase is required. This also allows an observation of the valuable basic materials and structure of buildings, so that, depending on the type and intensity of building use, an immediate threat to the valuable buildings and equipment can be detected. The monitoring can also give important information on the thermal comfort of a historical chamber.

The aim is therefore, by means of a suitable sensor network, to collect data of all the relevant parameters and metrics in order to characterize the energy behavior of the building, the climate situation and comfort in the rooms, the climate-related stress on valuable surfaces, moisture and heat situation in the energy upgraded building construction and energy consumption. With the evaluation of all these state variables, an evaluation of the energetic and physical behavior of a building can be reliably evaluated.

There are several reasons for implementing a building monitoring. The essential task is to understand the actual condition of the building. It is especially important to collect data of, for example, thermal bridges and other critical design details, as the constructional development of the historical building can have a large impact on the thermo-hygric state of these construction details. The detection of surface temperatures and near field climates in the range of construction details which are considered, allows researchers to assess the structural measures in terms of their structure compatibility. For this reason it is already required in the first monitoring plan to install appropriate sensors on the affected building components. The collected data also allows the validation of any building simulations, which are applied over the duration of the project and can also be used as boundary parameters for coupled thermal-hygric simulations.

Thus, a two-stage implementation of the monitoring tasks is planned:

- Condition of the building: actual state
- Condition of the building: improved state

The monitoring concept will specifically:

- measure information on climatic conditions, comfort and energy consumption
- assess the user's comfort, energy demand and protection of both the historic building fabric and the cultural heritage collection (phase changes and hydration of salts, condensation, shrinkage and swelling, thermal expansion, microorganism, frost etc.)
- integrate dynamic building models and process simulation
- balance out the requirements related to users comfort, energy consumption and cultural heritage protection.

Figure 1 shows the minimum requirements of the first block "Monitoring of Energy Efficiency and Comfort Enhancement". This so-called basic monitoring is suitable for the detection of the actual condition of the building and forms the basis for a survey of future monitoring components.

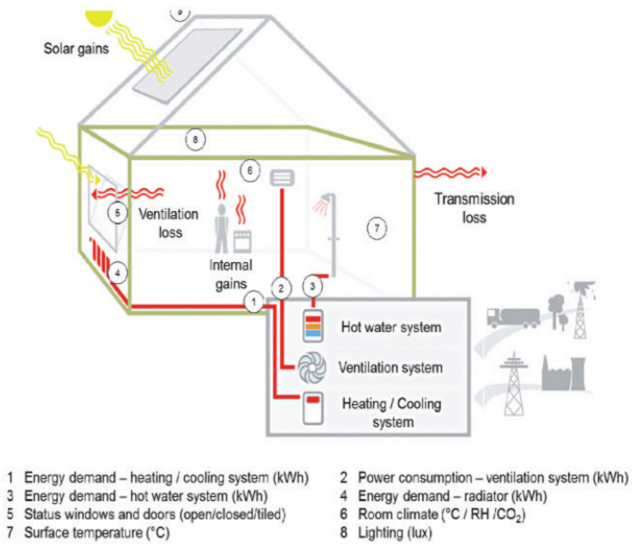

Figure 1: Energy and comfort monitoring – basic system

2.1 Monitoring in historical buildings

The possible interactions between external and indoor climate and the historical surfaces are often ignored. Figure 2 [4] shows the required framework of the investigations. It is the result of an energetic redevelopment whose risks appear in the near field area of valuable historical surfaces, because they are exposed to critical climate fluctuations. This can occur due to, e.g. heating, cooling, ventilating, humidify and dehumidify. Not only do building service equipment-specific measures lead to a change in climatic conditions in the near field of historic surfaces, such as e.g. paintings, but also due to a building activity for energy restoration, for example by installing a thermal insulation of the inside, some extremely complex exposures in the context of transient hygrothermal conditions can appear in the near field area of material layers. A first assessment of the risk of historically significant surfaces is therefore needed to collect data on the climatic near field conditions, e.g. by surface temperature sensors and temperature and humidity sensors in the near field of historical surfaces in sufficient numbers and distributed in the room. Accurate knowledge of hygrothermal material properties, salt loads and also restoration, repair and modernization measures which were carried out in the past, are mandatory in order to evaluate near field stress.

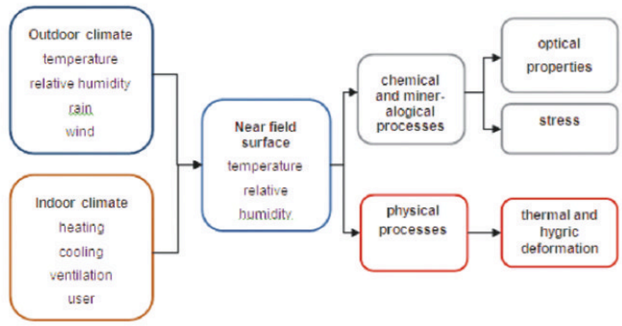

Figure 2: Framework for monitoring concept

Figure 3 [4] shows an example of a sensor array of an internally insulated component. In this case, both the surface temperature on the outside of the building envelope, as well as at the respective material transitions are measured. Additionally, similar sensor arrangements can be installed in the field of thermal bridges and at critical construction dpoints.

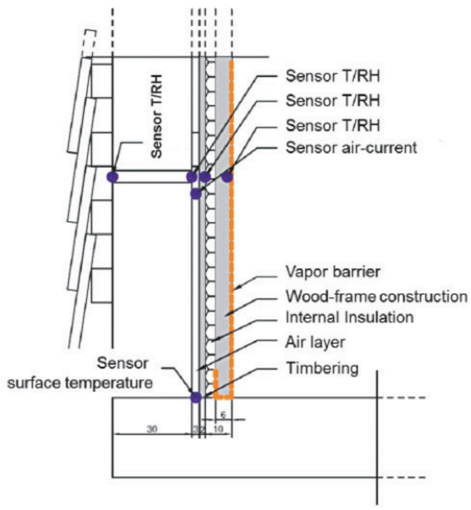

Figure 3: Interaction – Climate and historical surfaces

Other concerns to take into account are related to conservation issues of historical buildings such as aesthetic or conservation aspects. With regard to the aesthetics, wired sensors are forbidden in several cases because it is not possible to modify the visual aspect by making use of cables, therefore the wireless sensor network is used for solving this issue. On the other hand, conservation aspects mean it is necessary to avoid the modification of anything in, the building structure and this is sometimes a problem for the power supply of the sensors. Both concerns define a challenge which has to be faced before implementing the sensor network.

3. Automation concept

The automation concept relates to the control algorithms and the monitoring systems in order to improve the behavior of the facilities and installation in the buildings, after the analysis of the results from the monitoring concept. The main objective in the development of the automation system is the integration of monitoring systems and a Building Management System using a common bus system. The combination of the close monitoring network and the BMS should make it possible to develop optimal building adapted control algorithms, which can then be implemented.

3.1 Control in non-residential buildings

In historic buildings and rooms, there are various organic materials and mineral compositions to be found. Based on their different properties, different risks of damage stress are present through climatic stress. The damaged mechanisms can be as diverse as the occurring materials, so that only significant damage processes can be displayed as an example.

An increase of air humidity or the contact with surfaces moistened with liquid water, leads to water accumulation in the surface layers of material due to hygroscopic or capillary water absorption. An increase of water content is associated with an increase of the volume (swelling). Shape changes by swelling and shrinking lead to stress conditions in the surface layers of materials. These changes effect rapidly exceed the material strength and can cause material fatigue and cracks or voids [4]. The effects of these stresses are particularly strong on materials such as layers of paint on wood. As the various near-surface materials respond in a different ways to climatic changes in the environment, then temperature fluctuations cause local variations of volume changes in the deeper layers,. Furthermore, organic materials have a significantly smaller thermal expansion than hygric expansions by water absorption. Natural and artificial stones pass through these expansions in the same magnitude or values that can even be located occasionally above them. In combination with high material moisture, temperature changes around freezing point can lead to significant structural stresses and in consequence to damage. Frequent freeze-thaw cycles occur primarily in the outer area of the building envelope. However, the temperature can drop below freezing point near the surface layers in unheated buildings, so that the water in the pore spaces freeze and cause damage by expanding without having the required space. With changing humidity and temperature conditions of the indoor air, phase changes of the salts inside the building materials are possible. Depending on the environmental conditions, these salts pass into solution or crystallize. This is accompanied by a volume increase or decrease, which may cause a compressive stress in the material structure. Due to their hygroscopic properties the salts absorb as much water vapor from the surrounding air into the pore space as possible, depending on the humidity level. If high amounts of water can be absorbed until the capacity is reached, after that the water drips and leaks onto the building material surface. Moisture stains can appear on the surfaces by this procedure. Another important aspect is that high air and material humidity in the near field layers of material lead to the development of micro-organisms (mold, algae, etc.), as well as a high proportion of existing organic substances. While inorganic materials such as metals, glass or ceramics are affected only in exceptional cases by organisms, a formation of rust on metal or a tarnishing of glasses can be the result. In this way, the colonization of microorganisms is not just a visual impairment [7], but also has health implications such as asthma, infections or allergies.

Taking into account all the aforementioned premises, the requirements for the indoor climate in historical buildings can be varied depending on the use of the buildings and facilities. Although the desired temperature level or the required relative humidity can vary from object to object, the target must ultimately be indoor climate stability [8]. However, the problem is not only the compliance with the required climate corridor, but also the structural implementation of measures for energy consumption. Since an energetic improvement by building insulation is not possible in most cases, an increase of the energy efficiency and the protection of the physical substance can occur through optimization of existing or in future to the installation of heating and air conditioning. Preventing incorrect manual ventilating and heating can be realized through automation. Opening the windows while the outdoor humidity is higher than the inside humidity can thus be avoided. For these reasons it is sufficient to provide surveillance possibilities by monitoring. The review of the use recommendations can be made through computational fluid dynamics simulations (CFD). The induced flows from heating and ventilation can be shown and verified by simulation. A prediction of the resulting problem areas in the building can be made, which is particularly important to protect historical surfaces such as wall paintings against the currents of the ventilation and heating systems. Moreover, it is possible to heat the seating area more effectively.

3.2 Industrial Engineering School of Béjar Salamanca example

One of the case studies within the project which is used as test suite is the Industrial Engineering School of Bejar, where an advanced control algorithm system has been deployed for controlling the lighting and the HVAC systems. First of all, the lighting system was underused in the demonstrator because the luminaries were poorly distributed, working against the daylight and manually activated. Now, the luminaires are divided into zones according to the occupancy patterns and the control is automated through the presence of light sensors. Thus, the combination of the detection of one or two presence sensors in the same actuation zone as the lux level sets up the control signal. If the occupancy sensors detect anyone and the lux level in the room does not go over the comfort level [7], the luminaires of this zone are switched on. After the timer goes off, the check of occupancy is again performed so as to switch off the lights. The great advantage of this control system is the combination of several inputs in order to determine the best zone to be turned on and optimize the electrical consumption related to the lighting, allowing users to keep at least 50% of the lights off. However, the distribution of the light in the room is non-uniform, which makes it difficult to develop the control algorithm, as it is necessary to combine several inputs, conversion of signals and calculation of the best behavior. This algorithm is a new development created for the case study as there is no hardware for this specific purpose.

On the other hand, the HVAC systems control is centered in the cooling systems, which are based on fan-coil units that are manually controlled without bearing in mind comfort patterns. Thus, the algorithm can be viewed in the Figure 4, where temperature set-points are established in order to decide the working mode. Thus, if the temperature goes over 25.5ºC (25ºC plus 0.5ºC of hysteresis) and the room is occupied, the fan-coils are switched on in cooling mode, but if the temperature goes below 21.5ºC (22ºC minus 0.5ºC of hysteresis) the fan-coils are turned on in heating mode. Moreover, between 22.5ºC and 24.5ºC (0.5ºC of hysteresis) there is the dead band in which the fan-coils units are off because the comfort level [10] is achieved allowing energy savings too. All this control is mixed with a timetable of the usage of the rooms in the building in order to avoid the running of the system outside established time slots.

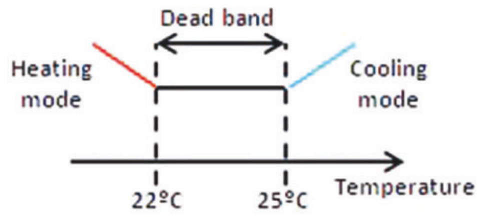

Figure 4: Control algorithm for cooling system

In this second case, the need for translating communication protocols is a challenge to be faced. HVAC system uses a proprietary protocol which is translated in an "opener", similar to LonWorks (the sensor network protocol). Then, the conversion of signals between protocols is needed so that the HVAC system can understand the command. At the moment, no commercial solutions are available; therefore, a new development through Functional Blocks has been made for the control system.

4. ZigBee sensors

Agile, low-cost, ultra-low power wireless networks of sensors, which collect a huge amount of critical information from the environment, become essential tools for building automation. Such wirelessly connected microsystems are defined as Wireless Sensor Networks (WSN) and typically incorporate both sensors and communication functions. Each sensor node monitors its local environment, processes and stores the collected data so that other nodes can use them, transmitting the information through a wireless link. Furthermore, they can include actuators which are able to receive commands issued by a central controller and act accordingly [5].

The current wireless commercial systems do not provide any ability to create interoperability between new applications and pre-existing subsystems. Thus, a new flexible WSN for the real-time monitoring targeted for historical buildings needs to be designed and its performance optimized, with particular attention to the autonomy and reliability of the whole network [5]. Specific objectives can be formulated as follows:

- Physical node size of the WSN not exceeding a few cubic centimeters.
- Sensors lifetime from several years to tens of years.
- The node should be field-configurable and the WSN be modular, have dynamic deployable capabilities, and be easy extensible.
- Optimized Trade-off between lifetime and quality of service (QoS) of the network.
- Standard protocols for WSN and thus ability to communicate with components already on-site.
- Wireless actuators will also be considered which can reduce installation effort considerably in historical building, where existing distributed autonomous components have to work together.

Complying with these requirements, the Wispes W24TH nodes (Figure 5) were selected as basis of the adaptation for the sensor network. All these motes are compliant with ZigBee Pro protocol where there are three types of sensors: coordinator, router or end-device. The coordinator is the main node in the network which manages the information, configuration parameters and so on. This device receives and collects the measurements from the remaining sensors in the network and they are able to communicate any information to each other. The end-device is the sensor which measures the conditions and sends the information to its parent in the network. Finally, the router is an end-device with redirection capability, but with fewer abilities than the coordinator. Basically, it is able to sense data and to redirect the information from child devices to parent ones and vice versa.

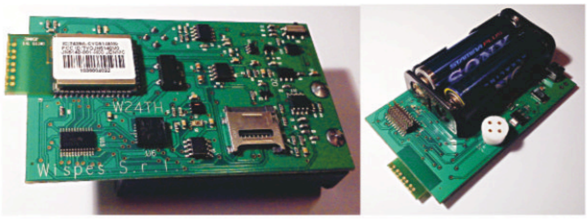

Figure 5: ZigBee wireless sensors

The core of the system is a 32bit microcontroller with a 2.4 GHz radio transceiver and 32 MHz CPU clock that permits the development of complex applications and distributed data processing [5]. The system is provided with a series of on-board sensors:

- Temperature sensor;
- Humidity sensor;
- 3-axis Accelerometer sensor;
- Ambient light sensor;
- Mox gas sensor (VOC, O3, NOx, NH4, CO ...).

Moreover, W24TH is equipped with a microSD card reader for local storing, data logging and backup, a USB battery charger, a 32 kHz quartz oscillator with real time clock library and a 20-pin expansion connector and a power management subsystem. The 20-pin expansion connector features UART bus, SPI bus, I2C bus, 10 GPIOs, 12bit ADC and 3.3V power supply. This allows the W24TH to be connected to several expansion boards such as multi-channels acquisition interfaces, actuators, USB, KNX devices, energy harvesters and more.

The WSN characteristics for for building energy efficiency have to be fully configurable with multi-hop radio link, work for several years with two commercial AA batteries, provide all the network information and be flexible and extensible. To do that, each device is able to check the list of a neighboring device with radio link quality, select the network parent device in order to build up a network custom tree, set the device ID, check sensor state (disable/enable), sample time and batteries voltage.

An example of ZigBee sensor network is deployed in the Palazzina della Viola located in Bologna, Italy, which is one of the case studies in the project. In this network, there are 144 sensors collecting data every 10 minutes with an expected life time of two years. Until now, one stable year of data has been completed, the firmware has been tested and the bugs filled.

5. Building Management System

A Building Management System (BMS) is a computer-based control system installed in buildings that monitors and controls the building's mechanical and electrical equipment such as ventilation, lighting, power systems, fire systems, and security systems [1]. A BMS is a complex, multi-level, multi-objective, integrated, interrelated and complete intelligent design management information system [2], which combines software and hardware for managing the behavior of the facilities of any building [3]. The hardware is the part of the sensor network, as previously mentioned, which is based on ZigBee protocol and deployed in the building. On the other hand, the software part integrates the driver for the communication with the specific protocol (ZigBee, LonWorks, BACnet…), the Internet connectivity and the internal operation (control algorithms, database connection…) setting up an "all in one solution".

Usually, a BMS is monitoring and controlling the building's internal environment, but also BMS systems are sometimes linked to access control (turnstiles and access doors, controlling who is allowed access to and exit from the building) such as closed-circuit television (CCTV) and motion detectors [3]. However, fire alarm systems and elevators are also sometimes linked to a BMS as in the Firesense project [11].

The BMS is centered in four basic functions:

- Controlling: Control algorithms for the behavior of the facilities in the building.
- Monitoring: Continuous monitoring of the status of the sensors measurements.
- Optimizing: Working out the best performance of the system.
- Reporting: Documentation of the intermediate and final results.

Currently, Building Management Systems are commonly implemented in buildings for the management of energy usage and they represent a high percentage of energy savings. Although the controllers and renewable energy resources seem to be the most critical parts for energy savings, the Building Management Systems constitute one of the most important elements. That includes cultural heritage buildings such as the museum of Thessaloniki [3] where a BMS has been deployed and it has achieved a low operating cost, considerable energy and time savings, as well as safety and control levels.

5.1 BMS software architecture

The BMS developed in the 3EnCult context is Service-Oriented Architecture (SOA) based. This SOA is a software design methodology based on structured collections of discrete software modules, known as services that collectively provide the complete functionality of a large or complex software application [12]. Thus, it sets up a multilayer and multiservice platform, shown in the Figure 6 [6], offering high level services for the management of the energy usage in the building.

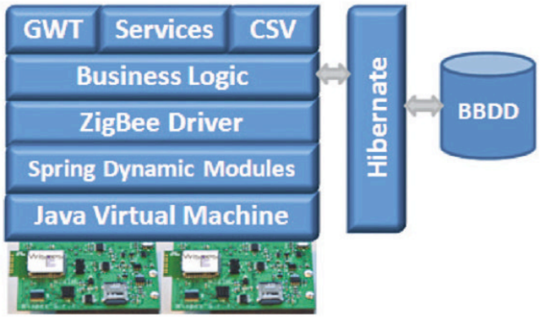

Figure 6: Building Management System architecture

First of all, the physical layer is the correspondent for the ZigBee hardware sensors. Secondly, the system is based on Java; therefore, it needs the Java Virtual Machine for running well, which is directly related to the operating system. The next part is the framework for the platform in order to implement the SOA services. For this reason, the Spring Dynamic Modules has been chosen because it includes the OSGi framework, but also it facilitates the integration of technologies such as Hibernate, the relation between the high level services and so on. Next, the communication with the hardware systems through the framework is represented by the ZigBee driver, which is software able to read and write messages and commands to the sensor network making use of an USB-driven device. The driver sends the commands to the USB dongle which represents the coordination of the ZigBee network and reads the response of the coordinator with the data from the rest of the sensors. These data streams are passed to the Business Logic that makes the decision so that the information can be stored in a persistent permanent way or sent to the high level services. The main functionality of this layer is as a connector between services, databases, drivers and all the elements for the proper behavior of the system. Finally, the high level services are split into three parts: Google Web Toolkit representing the framework for visualization, CSV for formatting downloading files and Services implementing the control logic.

In parallel to all the architecture there is the persistent part of the system. It is based on the PostgreSQL relational database that collects not only the measurements of the sensor network, but also the management information of the BMS, such as users, alarms, configuration properties… Furthermore, the platform is developed in object oriented language, it being a necessary adaptation. For that purpose, the Hibernate framework makes the translation into objects and tables.

There are several innovations in this architecture of the BMS. First of all, it is able to communicate the new and specific ZigBee sensors and it is adaptable to other protocols by adding more drivers for different protocols obeying the rules of connectivity between layers. On the other hand, it includes technologies such as Hibernate, Spring Dynamic Modules, Google Web Toolkit in the Service-Oriented Architecture based on OSGi [6].

5.2 Services

In the highest level of the system architecture there are a sub-layer named Services which includes a set of services for the performance of the platform. These have been defined for the ZigBee sensors developed in the project, but they could be extended, if required, because of the advantages of their service-oriented design. The list of services deployed is the following [6]:

- Monitoring service: This is the initial service of the platform and it contains the list of devices deployed in the network and for each sensor its latest value measured (Figure 7).
- Lighting service: It shows the latest value for the lighting sensor of every device in the network, but also it graphs (in a configurable way) the trend of the latest values (Figure 8).
- HVAC service: This service is similar to the previous one with the difference of the values shown. Meanwhile the lighting service records lux levels; this is related to the temperature and relative humidity.
- Energy service: The energy service includes the measures of electricity consumption, as well as the associated costs. Moreover, the capability of trending is also added.
- Alarms service: This offers two functions: the configuration of set-points for the alarms and the list of alarms generated. Also, this service sends a mail when the alarm is launched in order to inform the administrator of the system.
- Download data: This additional service is related to the ability of the platform to download historical data in a “csv” format for some parameters configured by the user.

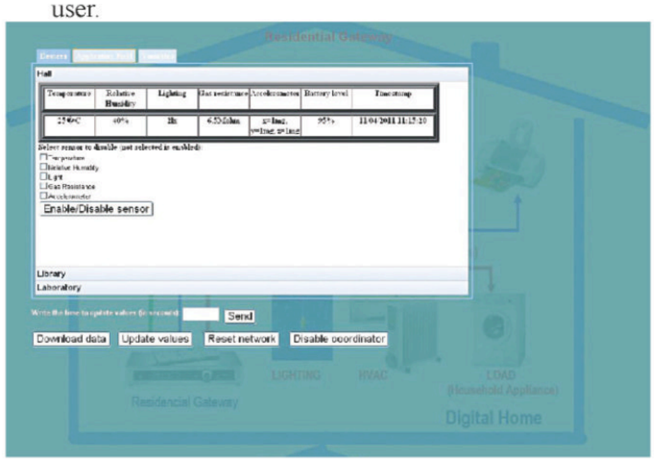

Figure 7: Monitoring service

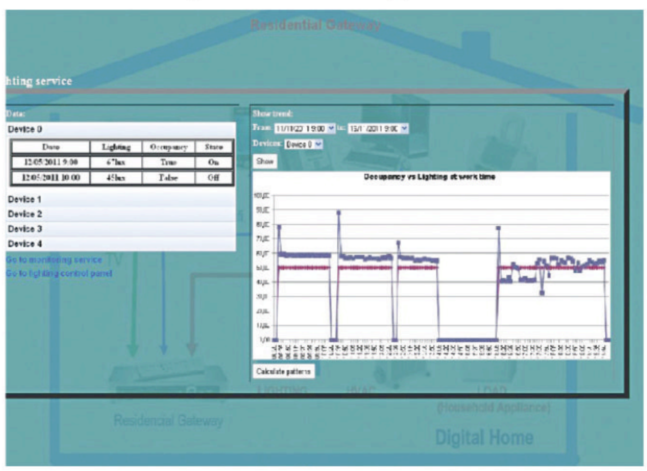

Figure 8: Lighting service

It has to be noted the lighting and HVAC services are able to calculate the best values for the behavior of the facilities through control algorithms.

6. Results

An important part is the test and deployment of the final system in order to check the behavior and improve the performance of the systems. For that purpose, the project sets up eight case studies where the tests, analysis and evaluation of results can be made. In the current status of the project, the test of the behavior in two of the case studies was performed, but the evaluation of the energy savings and comfort improvements will be measured during the last quarter of the project.

Thus, the selected demonstrators were the Palazzina della Viola located in Bologna (Italy) and the Industrial Engineering School of Bejar, in Salamanca (Spain). In the first case a big sensor network based on ZigBee has been deployed with 144 devices collecting data every 10 minutes. The main result of this is the communication in a complex network of all the devices is one year of data employing heterogeneous sensor configuration.

In the second case study, the complete system was deployed in a small sensor network with seven ZigBee devices working together and the Building Management System collecting stable data. The BMS included the aforementioned control algorithms in order to achieve some recommendations in the use of the facilities. The improvement has still not been evaluated, but it will compare the same months of the school timetable.

7. Conclusions

During the course of the project we have had the chance of studying the monitoring and control concepts adapted to historical buildings. These buildings present a challenge because the conservation issues such as aesthetics, historical value or structure have to be faced. In order to solve them, the ZigBee sensors were developed for monitoring while keeping in mind the cultural heritage thanks to the wireless sensors that do not damage any part of the building. On the other hand, the combination of sensors and control systems allowed the improvement in the behavior from an energetic point of view so as to save energy, raise comfort conditions so that the indoor climate avoids damaging the historical value. These control system manage the main variables measured by the ZigBee sensor for working out the best solution though defined control algorithms.

The combination of the wireless sensors with the Building Management System fills the gap between the requirements for retrofitting a building and the conservation aspects. The sensor network is able to measure the parameters whereas the Building Management System gathers all the information and works out the control algorithms in order to improve both comfort levels and the behavior of the facilities.

8. Acknowledgements

We would like to thank the European Commission for Project funding and the EWCHP organizers for the opportunity to participate in the conference.

9. References

[1] Dr. Abdulmohsen Al-Hammad, "Building Management System (BMS)", College of environmental design, http://faculty.kfupm.edu.sa/ARE/amhammad/ARE-457-course-web/Building-Management-System.pdf, last visited on 1st of July, 2013.

[2] Cser, J.; Beheshti, R.; van der Veer, P., "Towards the development of an Integrated Building Management System," Innovation in Technology Management - The Key to Global Leadership. PICMET ‹97: Portland International Conference on Management and Technology , vol., no., pp.740, 27-31 Jul 1997.

[3] D. Karolidis, "A report on Building Management Systems in museums, with a reference to the Archaeological Museum of Thessaloniki," BMS Group meeting, Amsterdam, 2009.

[4] 3EnCult, "D4.1. Recommendation on variables and sensors", Work package 4: Monitoring and control

[5] 3EnCult, "D4.3. Wireless sensor network", Work package 4: Monitoring and control

[6] 3EnCult, "D4.4. Report on the Building Management System", Work package 4: Monitoring and control

[7] WTA-Merkblatt 6-3-05: Calculation prognosis of muld growth risk; WTA-Publications, Edelsbergstraße 8, D-80686 München

[8] WTA-Merkblatt E 6-12: Climate and climate stability in historic buildings; WTA-Publications, Edelsbergstraße 8, D-80686 München

[9] UNE EN12464-1:2011 Light and lighting - Lighting of workplaces. Part 1: Indoor work places.

[10] UNE EN-ISO7730:2006 Thermal comfort.

[11] Firesense project, "FIRESENSE (Fire Detection and Management through a Multi-Sensor Network for the Protection of Cultural Heritage Areas from the Risk of Fire and Extreme Weather Conditions, FP7-ENV-2009-1-244088-FIRESENSE)," http://www.firesense.eu/, Firesense WebSite, last visited on 1st of July, 2013.

[12] Velte, Anthony T. (2010). Cloud Computing: A Practical Approach. McGraw Hill, ISBN 978-0-07-162694-1.