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MONITORING SYSTEM FOR ENERGY MANAGEMENT OF BUILDINGS: DESIGN OF MODELS AND SENSOR NETWORKS FOR SUPPORTING CONTROL SYSTEMS

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ABSTRACT

Optimal Control is a big opportunity for energy efficiency since it involves much smaller investments than those usually applied to technological building elements integration, by providing new ways for sustainable energy saving solutions. Nevertheless optimal management requires the development of a new class of predictive control logics, behaving consistently in changing environments. This class of control systems embed advanced predictive models, directly coupled with an environment monitoring sensor network, that are capable of interpreting sensed data (both indoor and environmental) and of forecasting future states. The design of the monitoring system is a critical passage as it is subjected to a number of operational and cost constraints, but also has to guarantee a reliable interpretation of the environmental behaviour of the building. This paper discusses this issue and presents the engineering framework and a methodology developed for supporting the design of monitoring networks integrated in optimal control system of large and complex environments. The application of the methodology to the case of a subway station is briefly presented too. This research is part of the European Research Project SEAM4US (Sustainable Energy Management for Underground Stations). The proposed solution is based on the definition and development of the set of models needed for both supporting the definition of the monitoring sensor network and being embedded in the final control system implementation. The development of this class of environmental models for large underground environments such as subway stations involves the elaboration and the integration of different simulation models. The

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simulation results constitute the knowledge that can support an efficient design of sensor networks even in large buildings.

Key words: Monitoring System, Building Performance Models, Building Automation Control Systems.

Introduction

Building Automation and Control Systems (BACS) are spreading rapidly in the Construction sector, as many studies in the last years demonstrated the big impact they can return in terms of Energy Efficiency. Furthermore, in the case of existing buildings, the introduction of BACS is often also more convenient in terms of costs, than other kind of retrofit that would require big investments in refurbishment and building technologies updating. Control systems have to perform mainly three functions: (1) a monitoring function, achieving some data about the current state of the building, (2) a 'control' function, defining in some way (depending on the control policy and control algorithm foreseen) if the current situation is satisfying the imposed constraints (and/or is going to) or if some action is needed for forcing the building towards the expected state, (3) an actuating function, executing the considerations resulting in the previous step.

These function can be accomplished at different complexity levels. Control systems applied to buildings have been traditionally based on suboptimal homeostatic short-term feed-back mechanisms which are applied singularly to each equipment type, without an overall high level controller. These mechanisms usually require a very simple monitoring, consisting mainly in some local sensors placed in the equipment itself. Nevertheless, these control systems cannot take advantage of the knowledge of the overall building. Recently, the availability of pervasive sensor networks, allows us to accurately monitor dynamics of the indoor environment and to implement complex anticipatory optimal control policies [1]. The reliability of this very advanced control systems highly depends on the quality and quantity of information they gather by the monitoring network. Theoretically, the more the sensor network is wide and well-stocked, the more the control system will be reliable. Nevertheless, the installation of a plentiful sensor network has also some noteworthy drawbacks, not only in terms of technical complexity, but especially in terms of economic and environmental costs: the use of monitoring systems for adaptively controlling large buildings risks being jeopardized by noteworthy costs for buying, deploying and managing these equipment. However, especially in large buildings, an optimization of the number of sensor if possible, if the correlation happening between analogous spaces or positions are known. This objective can be achieved through an accurate monitoring system design, but a methodology supporting this process is needed. Furthermore, the design of a sensor network for a building is a complicated task, and it has to be recursive in some way. In fact, the sensor network design would highly benefit of some knowledge about the environmental behaviour of the building. This knowledge has to be gathered in some way before installing a the sensors, for instance through models

and preliminary surveys. Nevertheless, both these operations would need, for being efficiently planned, an ‘a priori’ knowledge that could come only from the sensors. This problem can be overcome through the availability of detailed building models that can guide – since the design phase – the definition of a monitoring system consisting in minimum set of sensors correlated to the behaviour of each other space.
This paper introduces the engineering framework used for supporting the design of the monitoring system in a specific case study: the Passeig de Gracia subway station. Even if a subway station is quite an ‘unusual’ building, the methodological framework can reasonably be considered the same for other building typologies. Actually, it has to be considered that, the ‘active building’ perspective introduces in the building design process a notable amount of ‘custom engineering’, as the building move from a passive object to a sort of ‘vital’ organism and this passage requires a specific optimization of all the technologies concurring to the building behaviour and knowledge. BACS design process needs to be supported by building performance modelling [2, 3]. The results of the building performance models then, will drive the system designers towards different choices for the monitoring system. This research is part of the European Research Project SEAM4US (Sustainable Energy Management for Underground Stations), that aims at developing a fully featured pilot system for the dynamic control of energy consumption in Barcelona’s ‘Passeig de Gracia’ subway station.

Methodology for Designing Monitoring Network

In the last ten years BACS have been featured by the spreading over of Model Predictive Control (MPC) [3,4] . MPC is an advanced control technique which, when applied to buildings, employs a model of the building dynamics and solves an optimization problem to determine the optimal control inputs. In the MPC approach, the monitoring system is the link between the control system and the building: monitoring measures are the input data for all the assessment and elaborations of the control system. A sensor-actuator network provides the real data sets for the development and provides feedback to the energy management control algorithms during the operational phase. The smartness of the whole system depends on the capacity of interpreting coherently the data received, knowing their relevance, weight, role in the overall building monitoring. As already highlighted, the overall sustainability of the control system depends highly on the inherent efficiency of the monitoring system, thus the design of the monitoring system has to proceed concurrently to the system model development, as it depends highly on the type of information that the predictive models embedded in the control system need. The presented approach adopts probabilistic models, specifically Dynamic Bayesian Networks (DBN) [5] which provides native uncertainty management, machine learning capabilities and, consequently, offers a good basis for adaptivity and decision support. The choice of embedding probabilistic models was mainly related to the fact that common whole building models cannot be easily embedded into the control system due to the fact that, apart from the issues related to the estimation of the initial state, the very large number of sensors required to keep the model updated would have caused an extremely large, expensive and unmanageable sensor network. Nevertheless, DBNs are graphical representations of probabilistic models, and describe the relations occurring among variables and events through a set of conditioned probability distributions, learnt by a training data set. When, as in this case, the DBN has to be developed in the system design phase – thus before the deployment of the monitoring network, without a meaningful data set retrieved by measured data – an overall running model that could replace the real building system and behaviour is needed. The methodology proposed in this paper is based on the model engineering. A set of different models is foreseen, and they will support both the monitoring of current state and the prediction of future states needed by the control system (Figure 1). Three types of models are foreseen:

- Detailed models of the airflow through Computational Fluid Dynamics (CFD).
- A Whole Building model (WBM) that combines all the different physical aspects, allowing to have a running simulator of the overall building behaviour.
- Probabilistic Models, to be embedded in the control system.

CFD and WBM models are the starting point of the whole process, as they constitute the preliminary knowledge needed for starting the control system design: the guidelines for the sensor network design and the whole system concept, including both monitoring and control parts. The monitoring system is composed by the sensor network, performing measurements, and the software part, aimed at processing the measured data, so that they could be efficiently used by the system.

The first simulations obtained from the CFD and WBM models provide guidelines for the sensor network design in terms of order of magnitude, critical points for sensor positioning, correlation between sensors. Then an environmental survey is needed, for investigating on the field the orders of magnitude of different variables and the sensitivity of the instruments to the actual dynamic processes. On the basis of the data gathered from models and the survey, a preliminary monitoring system can be designed and concurrently the monitoring software part conceived. Once the sensor network and the monitoring software are deployed, the circle with models can be closed, through the validation of the models using measured data. This cycle should be repeated at least twice, for having the possibility of updating the sensor network on the basis of new evidences coming from measured data and validated models. Once the monitoring system can be considered reliable, the measured data sets can be used for training the probabilistic models that will be embedded in the control system for predicting future states.

This methodology was applied in the SEAM4US research project, for designing the monitoring system. Section 3 describes briefly the preliminary monitoring system design phase for the case study of Passeig de Gracia subway station, in its first cycle. The resulting preliminary monitoring system has recently been deployed and now the model validation phase is starting.

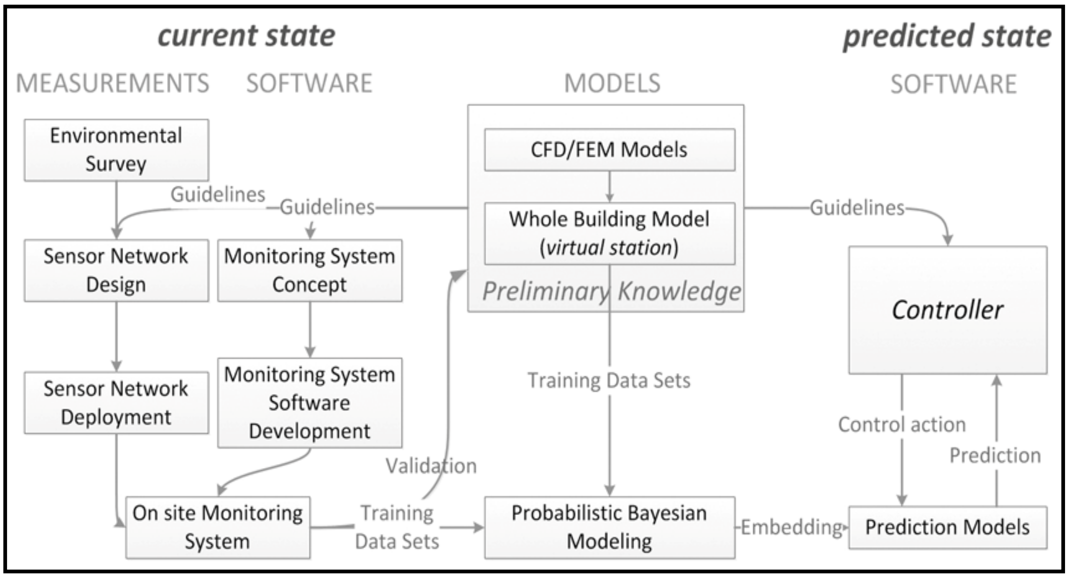

FIG 1. Modeling Framework and Monitoring Design Process.

Application Case: Passeig de Gracia Station

Passeig de Gracia (PdG) station is actually composed by three stations, serving Line 2, 3 and 4. PdG's Line 3 station is the northern one and has five accesses, but two of them are shared with the Adif station (regional trains). A further access is the Station Link, a very long underground corridor that connects PdG-L3 and PdG-L4 stations (Figure 5).

Models supporting Sensor Network Design

This section briefly presents the models developed so far and their role in the monitoring plan. All models presented are a first version and need to be validated through experimental data in the following months.

CFD Models

Different types of FEM models of the Computational Fluid Dynamics (CFD) and Pollutant Transport in the station were developed. They gave mainly four type of results, in terms of both airflows and pollutant concentrations: (1) a preliminary estimation of the entity of the processes, and of the energy saving potentials, (2) a preliminary definition of the boundary conditions to apply in the whole building model, (3) initial insights regarding airflow speed, pressure and contaminant sensor placement and sizing (i.e. accuracy, ranges, etc.), (4) information about the relation between point measurements and average value in a spatial portion.

The first two points are not discussed in this paper. Detail about the models can be found in [6]. All the simulations were carried out by means of COMSOL Multi-physics 4.2, 3D steady state analysis. For the sensor plan, the stream line (Figure 2) and contaminant maps were used to qualitatively evaluate turbulence zones and to provide preliminary data for the sensor specification. For instance figure 2 shows clearly a big vortex interesting the hall and also some differences between the corridors and stairs: some of them (green circle) are interested by regular flows, while others (red circle) by very irregular ones. Furthermore CFD models will be used for correlating the information gathered by the sensors in specific points with average values of the same variables. This kind of information has paramount importance because will allow to estimate synthetic overall values from point measurements. Nevertheless, this process will be done once the CFD models will be calibrated through the measured data.

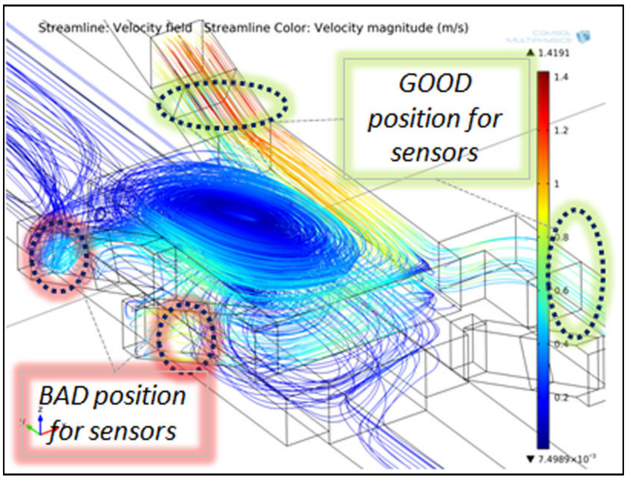

FIG 2. Examples of CFD model simulation results: airflow streamline in HN3.

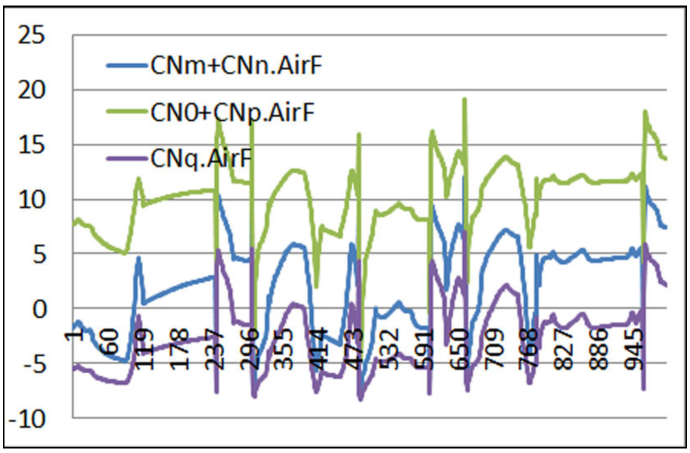

FIG 3. Examples of Whole Building Model results– Airflow rates [m3/s] coming from corridors to platform.

Whole Building Models

WBM model was developed in the Modelica/Dymola simulation environment. A specific library for modelling subway stations was devoleped. Details can be found in [6]. The resulting model for PdG-L3 allowed to identify which are the roles that each process and space play in the final behaviour of the station supporting the identification of the spaces that influence more the building behaviour and guiding the definition of the minimization of the sensor network for the second cycle.
For instance figure 3 shows the airflow curves related to the main corridors linked to the platform. It emerges clearly that the CNo+CNq (green line) are the corridors interested by the highest air flow and they are close to the entrance EN5. Considering that the corridors CNm+CNn are the only corridors connected to the four northern entrances to the station, it appears clearly that the entrance having a major effect in terms of airflow in the platform is EN5.

Environmental Survey

An environmental survey was conducted in March 2012 for gathering a preliminary picture of the amounts and order of magnitude of the variables to be monitored. Also, an evaluation of the quality of the achievable measurement, in terms of noise and disturbances was needed for planning a sensor network. Spot measurements in a number of locations around the station and a continuous monitoring of the platform were performed. A lot of insights about the energetic behaviour of the station were collected. For instance, figure 4 shows the air speed curve in one of the corridors not directly connected to the platform (CNh). The two curves relate to two probes, displace one on the centre of the section (height 1.2 m) and the other in the upper part of the section (height 1.9 m).This kind of graph gives a lot of useful information in the sensor network design perspective. First of all it can be noticed that, even in corridors, the train passage can be observed though air speed measurements (the peaks). Nevertheless, the time sampling should be accurately set, otherwise some noises could be confused. Furthermore, it is clearly visible that the measures in the two different locations diverge when the amount of airflow is higher. This could mean that the sensor placed in the central position could be less ‘sensitive’ than the one placed in the upper position (probably because of the disturbance effect of people walking in the corridor and creating an obstacle to the measure).

Monitoring Network

The public spaces of subway stations are strongly connected in terms of environmental dynamics as they have a spatial continuity (no doors, only grids), even with external environment. It means first of all that the entrances, that are interfaces among outdoor and indoor play a critical role. It means also that ideally not all the internal spaces have to be considered in the control perspective but the main relevant have to be identified.

Identifying the most effective sensor arrangement (i.e. number, type and position) capable of capturing all the relevant station dynamics is of paramount importance for the success of the modelling process and, later, for the closed-loop control performances. Therefore, particular attention was devoted to the preliminary environmental sensor network design. In the SEAM4US project, a research group from VTT (Valtion teknillinen tutkimuskeskus – Technical Research Centre of Finland) has in charge the sensor network deployment task, the choice of the specific sensors and the design of the whole sensor network but the identification of the typology, number and position of the sensor was guided by a widen research group at Università Politecnica delle Marche on the basis of the model developed.

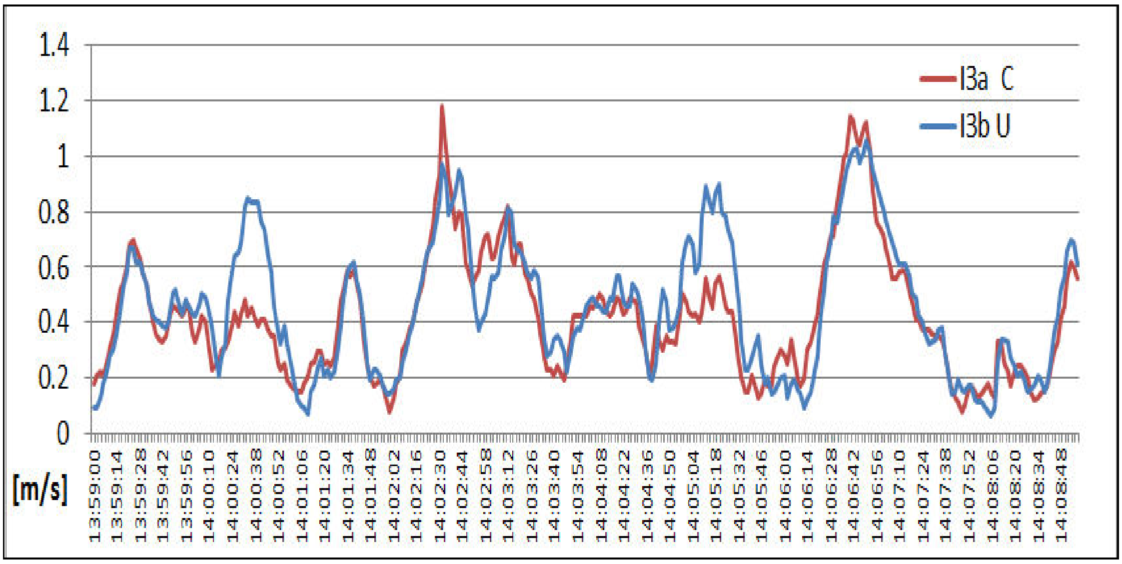

FIG 4. Example of Measurements achieved during the Environmental Survey: Air speed measurements performed in the same section of CNh corridor.

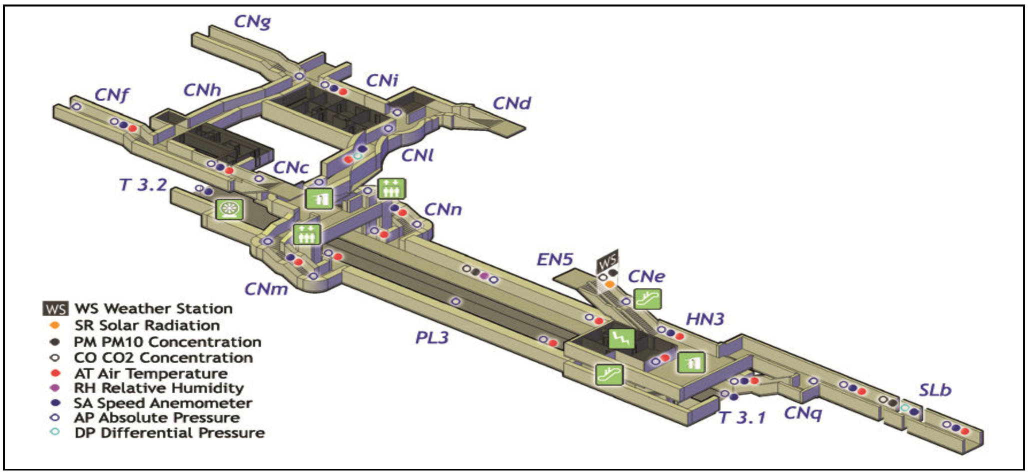

FIG 5. Captions for pictures and graphs. Style: IAHS captions.

Figure 5 reports a schematic view of the foreseen sensors on the station layout. Subway stations in general include five main type of spaces that are: entrances (E), connections (corridors) (C), halls (H), platforms (PL) and staff/technical rooms (R). SL denotes the station link. The monitoring plan so far includes:
Weather Station (WS). A single WS is foreseen and will be placed near the entrance 5. The location was selected on the basis of the WBM simulations, that showed the great impact of the airflow entering airflow in EN5 on the overall behaviour of the station. It includes sensors for: Air Temperature, Wind Speed, Wind Direction, Barometric Pressure, CO2 and PM10 concentrations and Solar Radiation.
Air flow rates (AFL). They are measured indirectly through Air speed and air pressure sensors. Locations are: the five entrances, the corridor CNl and the Station Link. As the two northern entrances are owned by an other company, the related sensor are placed in the corridor CNf and CNg that are the boundary of TMB property.
Air Temperature (AT). AT sensors are foreseen in all the locations where AFL rates are measured (for estimating air density), and in the main Halls (HN2 and HN3). In the platform four AT sensors are foreseen so far, for estimating how many are meaningful in terms of average temperature.
Pollutant Concentrations (PC). The pollutant considered so far are CO2 and PM10, as literature review showed they should be the most critical for these kind of cases. These measures are simply aimed to verify that eventual control measures do not drastically worse the air quality, thus they are placed only in the spaces that resulted critical from the CFD models: Platform and Station Link.
Further sensors are foreseen, only for the model validation scope, that are:
Relative Humidity (RH). A RH sensor will be deployed in the platform, in order to validate the models that will guide the comfort index calculation.
Surface Temperature (ST). Three matrix of ST sensors are foreseen at different depth of the station for validating the model of heat transfer with the ground.
This monitoring plan is just been deployed. On the basis of the measured data, all the models will be validated and fine-tuned and, hopefully, the sensor network further reduced in the second cycle.

Conclusion

This paper presented a methodology for supporting design of monitoring systems to be included in BACS. The criticality and risks related to the design of sensor networks supporting control systems in buildings are discussed. Furthermore the proposed solution overcomes the limits of knowledge related to the fact that any experimental data can be achieved until a sensor network is deployed through the development of CFD and Whole Building Models that could guide the whole process. An application example, in the pilot building of the EU- funded research project SEAM4US is briefly presented.

References

[1] Mahdavi, A.; Orehounig, K.; Pröglhöf, C., *A Simulation-Supported Control Scheme for Natural Ventilation in Buildings*, Proceedings of the 11th IBPSA Conference, Glasgow, Scotland, 2009.

[2] Braun, J.; Kim, D.; Cliff, E.; Burns, J., *Whole Building Control System Design and Evaluation: Simulation Based Assessment*, February 2012.

[3] Wetter, M., *A View on Future Building System Modeling and Simulation*, in Building Performance Simulation for Design and Operation, Spon Press, UK, 2011.

[4] Oldewurtel, F.; Gyalistras, D.; Gwerder, M.; Jones, C.N.; Parisio, A.; Stauch, V.; Lehmann, B.; Morari, M., *Increasing Energy Efficiency in Building Climate Control using Weather Forecasts and Model Predictive Control*, Proceedings of: Clima - RHEVA World Congress, Turkey, 2010.

[5] Murphy, K., *Dynamic Bayesian Networks: Representation, Inference and Learning*, Doctoral Dissertation, University of California, Berkeley, CA, USA, 1998.

[6] Ansuini, R.; Larghetti, R.; Vaccarini, M.; Carbonari, A.; Giretti, A.; Ruffini, S.; Guo, H.; Lau, S.L., *Hybrid Modeling for Energy Saving in Subway Stations*, Proc. of: Building Simulation and Optimization 2012, Loughborough, UK.