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Extended summary

Model engineering for the adaptive control of energy efficient buildings and components

Curriculum: Architecture Construction and Structure

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Abstract. Recently, new advances in ITC technologies discovered unforeseen scenarios that deeply influenced the original idea of smart home. Smart environments are highly automated living spaces that are controlled through intelligent technologies that are able to optimally configure the space with respect to dynamically changing set of requirements, based on the prediction carried out by simulating models. This research has definitely a broad scope. On one side it involves the development of new active building components, on the other side, the development of intelligent ICT allows the home systems to communicate with one another and with the energy grid, thereby enabling autonomous and/or remote control of the building behavior in adaptive operating modes. Furthermore, both sides share a common redline, regarding the development of a new class of advanced physical models of both building systems and components that can be embedded in the real time adaptive building control system. This dissertation concerns the development of a model engineering process for the development of adaptive models that support the intelligent control of energy behaviors of buildings and components. The term adaptive means that the active building and components should be able to interpret the sensed data (indoor and environmental) and to forecast future states; to evolve its policies as the operating context evolves; to learn from its history and from the end-user interaction so the policies can be adapted to the evolved operating context.

Keywords. information technology, energy efficient building, adaptive control.

1 Introduction

The idea of "Smart House" which aims at getting a more comfortable environmental space reducing the energy consumptions was suggested twenty years ago [1]. Recent advances in ITC technologies discovered new scenarios that deeply influenced the original idea providing new insights that, at the end, generalised to the actual idea of *smart environments*. Smart environments [2] means living/working spaces empowered by information and communication technologies (ICT). Instrumenting spaces with sensors, actuators, micro-chips, micro and nano-embedded systems will allow to collect, filter and produce more and more information locally, to be further consolidated and managed globally according to business functions and services. Smart environment is a general concept that applies at different scales, from the urban context, to the single building, passing through region wise networked systems and infrastructure. Among the smart environments that will work well for the citizens of the future, only solutions which create the greatest synergies between energy efficiency, comfort, safety & security appeared to be the ones that will be sustainable over the long term [3].
This vision is definitely far away from the actual building construction practice, where building control is usually operated on the basis of homeostatic short-term feed-back mechanisms [4], in which the technical equipment (lighting, heating, shades, natural ventilation etc.) are regulated only on the basis of predetermined set points, without any attempt to include the dynamic of the natural environment, the end-user behaviour and mid-long term adaptive energy saving policies. As a result the building control is substantially left to the occupants willing, a situation that in most cases generates high level of inefficiency in the use of energy. The impact is relevant. The equipment and systems providing thermal comfort and indoor air quality for commercial buildings consume 42% of the total energy used in buildings [5]. On the other side, recent studies [6, ,7,8] show that the use of predictive strategies for building control allows an energy saving of more than 20% as for the traditional actuators.
Therefore the investigation of the impact of adaptive technologies in terms of energy saving is in general a relevant issue in the current building technology research scenario.
This research perspective has definitely a broad scope. On one side it involves the development of new active building components. New envelope technologies, like the Active Building Envelope (ABE) System [9] or Variable Transmittance Envelopes [10,11], can significantly extend the thermal control capability of the building components. Internal active heat storage systems, that are integrated in building components through the use of phase change materials [12,13], allow a very efficient control of the indoor thermal dynamic maximizing the positive impact of renewable energy sources. On the other side, the development of intelligent ICT allows the home systems to communicate among them and with the energy grid, thereby enabling autonomous and/or remote control of the building behaviour in adaptive operating modes. Examples, like the InHouse project [14] developed by the Fraunhofer institute, show that the utilization of intelligent ICT technology (including fuzzy logics and neural nets) is able to accurately capture buildings thermal dynamic so as to provide a more reliable basis for the control of the building behaviour. In this scenario, control options have been optimized, as their impact on the buildings dynamic is reflected in the collected information by the sensing system.

Both these sides define precise and complementary research domains, the first being concerned with the evolution of traditional passive building technology towards active multi-functional components that can be seamlessly integrated into the current construction practice, the second being concerned with the exploration/definition of totally new concepts, like that of *building intelligence*, deeply affecting the evolution of the overall construction domain.

Furthermore both sides share a common redline, regarding the development of a new class of advanced physical models of both building systems and components. The implementation of adaptive behaviour of building systems, encompassing a wide range of dimensional and complexity scales, ranging from the single building component up to district/urban wise, requires an in depth rethinking of the traditional modelling approach, being that the accurate simulation of the physics must be easily co-evolved and interfaced with an equally complex control system, and that, at the end, the model will be an integral part of final building, providing the possibility of predicting the near future behaviour of the controlled environment under specific conditions, so that the optimal solution can be sought through scenario analysis [15].

This dissertation concerns the development of a model engineering process for the development of adaptive models that support the intelligent control of energy behaviours of buildings and components. The term adaptive means that the active building/component should be able to interpret the sensed data (both indoor and environmental) and to forecast future states; to evolve its policies as the operating context evolves; to learn from its history and from the end-user interaction so the policies can be adapted to the evolved operating context.

The development of the functional requirements for adaptive building control systems involves a large number of research issues:

- *Sensing* - The control systems must be aware of what is happening around and inside itself through sensing.
- *Interpreting* - The control systems must use models to interpret the sensed data (both indoor and environmental) and to forecast future states.
- *Controlling* - The control systems should know its capacities in terms of controlling actions and actuating power.
- *Explaining* - The control systems should be able to communicate to the end user and explain the reasons of its behavior.
- *Learning* - The system should be able to learn from its history and from the end-user interaction so the policies can be adapted to the evolved operating context.

The objective of this thesis is to define a methodological framework that can allow the integration for multiple physical models of buildings at different levels of representation, allowing for the management of any degree of uncertainty and different adaptive control policies.

In order to create a methodological framework, a series of surveys have been carried out at different scales of the application domain to define the most appropriate modeling techniques and to evaluate these techniques in the perspective of their support to the adaptive control of the overall building.

The main problems analyzed in the chapters of the thesis were:

1. *System Identification*: Identification of analytical models of the thermal behaviour of buildings from experimental data.

2. *High accuracy FEM modeling* of homeostatic control: Integration of a sensor system for feed-back control in the spatial distributed grid.
3. *Concurrent FEM and Whole Building Analysis modeling*: Hybrid concurrent development of a building component model using FEM and Whole Building Analysis methodology, with particular attention to the management of the approximations that are generated in the transition from distributed parameter models to lumped ones.
4. *Statistical Modeling* for weather forecasting: Development of statistical models from data derived from measurements in situ and/or by simulations carried out by means of analytical models.

The methodological framework developed thus far has been applied in the development of models for adaptive control of the station Passeig De Gracia in Barcelona, as part of the project SEAM4US the 7 th Framework Programme.

2 Identification of analytical models of the thermal behaviour of buildings from experimental data.

The first aspect analyzed by the research was that of determine the limits of applicability of the techniques of system identification for the purposes of adaptive control of the building. For our aim these techniques were applied for the determination of quickly methods for the qualification and quantification of the thermal exchange dynamic between the internal surface of the buildings.

This will allow the fulfilment of dynamic exchange models of building components, allowing to obtain a monitoring of these dynamics through a reduced number of sensors.

Observed heat exchange dynamics among room walls show that different parts of the same wall may have different roles in the overall heat exchange behaviour depending on its morphology, on the external climate conditions, on the ventilation regime and, of course, on its recent thermal history.

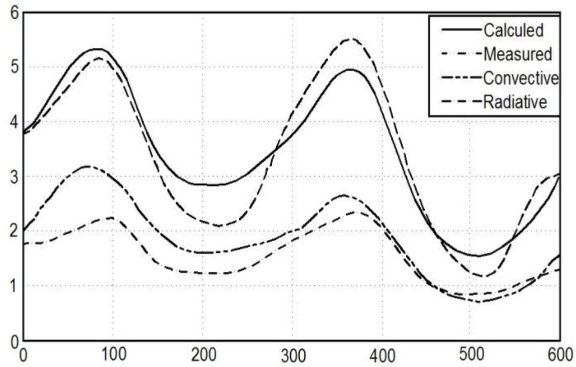
For the purposes of predictive and adaptive control model of buildings a detailed knowledge of each of the exchange dynamics of the walls is required. This requirement is in clear contrary with the need to minimize the number of sensors to be placed in the building at the end of the control.

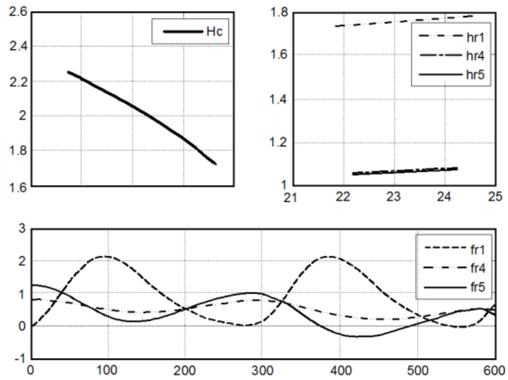
Therefore the analysis made in this phase is aimed to analyze the use of system identification techniques to determine heat exchange models for each typical morphological characteristic of the walls, starting from a small number of measured data.

Observing the general equation of the heat exchange in buildings envelope is seen that indoor thermal exchange between room walls is regulated by convective and radiative dynamics. The measurement of heat exchange coefficients, radiative and convective are very onerous because they change with thermal and fluid-dynamic regimes. In this research has been defined a method for the estimation of these parameters starting from thermographic images by applying techniques of system identification, in order to estimate the thermal exchanges based only of temperature measurements.

An experimental campaign with contact measurements and dynamic thermography techniques has been carried out and a Matlab software has been developed to estimate the coefficients convective and radiative (see Figure 1 a, b) and for the extension of the contact measures to all points identified from the thermographic immage. In order to validate the results we checked if the estimated values were within the ranges published in the literature

and secondly, if simultaneous but uncorrelated estimations on facing walls get consistent results.
In particular we checked if the estimated radiant components of two facing walls converging to a 90° corner are equal in module but opposite in phase.
From the analysis performed, we can affirm that the method considered can be used for dynamic modelling of heat exchanges of the wall starting from simple thermographic surveys and therefore it can be used as a possible techniques of adaptive predictive control of building.





(a) (b)

Figure 1. (a) Measured and estimated fluxes at the wall surface, and the convective and radiative components. (b) Estimated $h_c(T)$ and $h_{ri}(T)$ and the radiative components related to each surrounding wall.

3 Integration of a sensor system for feed-back control in the spatial distributed grid.

The second analysed aspect was the applicability of FEM models to study the integration of a sensor system for the dynamic control of building components. For this purpose, it has been developed and optimized FEM model of a radiant floor integrated with PCM, for the control of the internal temperature of an ambient and for the management of the related internal thermal loads.
An initial 2D finite element model with the same geometry and layers as the specimen and with the mass and conductivity parameters provided by the PCM manufacturer was designed. The construction of same specimens was necessary for the definition of the enthalpy curve of the adopted PCM, the estimation of the resistance caused by the presence of air among the PCM grains, the estimation of the contact resistances at the surfaces of the specimens as well as for the identification of the parameters regulating the heat exchange between the water in the pipes and the PCM layer.
In the FEM model of the active so calibrated component it has been simulated a probe of temperature that would allow the implementation of a control logic. In our case, such logic has turned out to be a PID logic. Moreover, the analysis of simulations allows the optimization of the behaviour of the radiant floor with the insertion of a steel matrix that acting as a thermal diffusor, it allows a reduction of the stratified PCM granular (grains), improving the thermal diffusion both in parallel and in perpendicular (vertical) direction to the floor surface. The high conductivity of the steel allows the matrix to behave as a thermal

diffuser, providing the necessary conductibility to bypass the parasitic resistances introduced by the PCM.

The model of the dry PCM floor was integrated into a larger 2D Multiphysics FEM model of a 16 m² room and compared with a standard radiant floor operating in the same environmental conditions. The extended model allowed the evaluation of the behaviour of the conveniently controlled radiant floor and its impact on the comfort of an environment in dynamic realistic conditions. The FEM model of the floor has been integrated with a sensor of temperature inserted in the layer of PCM. Another sensor was inserted instead into the room to measure the air temperature. It was therefore developed a PID control which acts on turning on/off the system through the definition of the thermal flux entered from the pipe of the radiant panels, in particular the control has been set in such a way as to keep the system is switched off when the temperature of the PCM is lower than that of complete melting of the material. Such kind of control allows the material to stay always in the fusion temperature range (in which it stores and releases latent heat), maintaining the environmental temperature in the comfort zone.

In summer seasons (see figure 2) the behaviour of the PCM radiant floor affects positively the energy consumption of the cooling system without lowering the degree of comfort. In fact, simulation results show that the PCM floor provides a comfort level that is comparable to that provided by the standard radiant floor with a reduction of the chilled water used equal to 25% less. In intermediate seasons the PCM is able to absorb the internal gain due to the solar radiation, providing a 2-3 days buffer in typical life conditions. This improves the floor integration in systems that use intermittent sources of renewable energies. Finally, in winter conditions the PCM affected the winter warming function of the radiant floor in any way. Both floors behave essentially in the same way and provide the same comfort and energy performances.

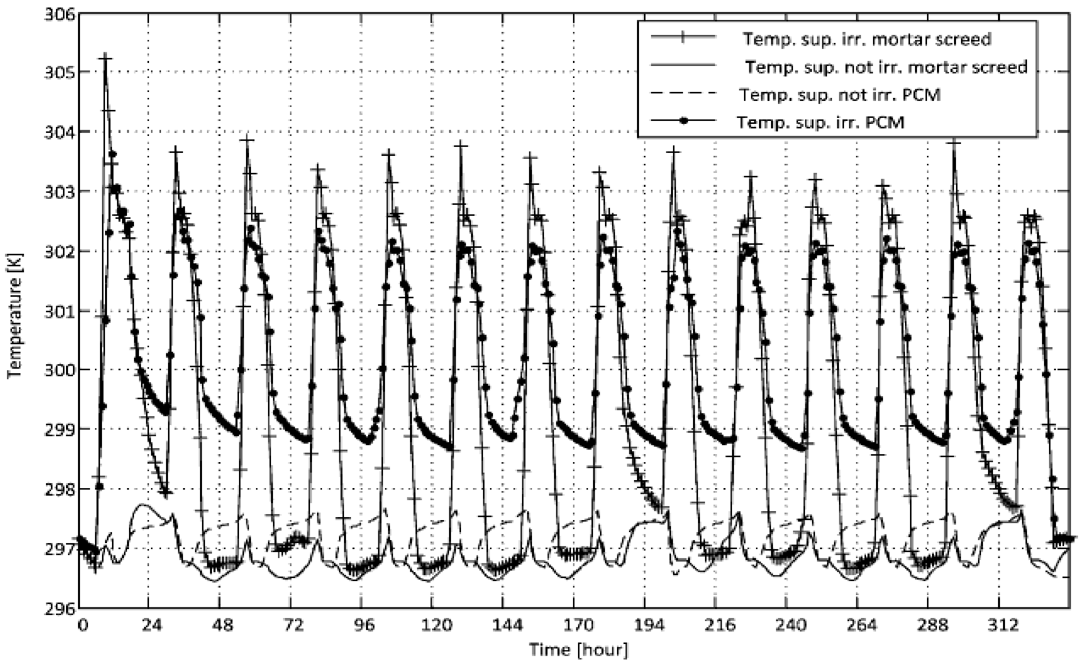


Figure 2. The surface temperatures of the PCM floor and of the traditional radiant floor relative to the irradiated and non-irradiated parts.

On the basis of the results obtained from the research, it has been possible to show how it is feasible to build active components with sensor/actuator systems that allow their use in buildings with adaptive behavior. The studied floor is able to accumulate the internal thermal loads postponing the thermal ri-emission inside the building or its cooling through the fluid, depending both on the future external environmental conditions and on the operation schedule of the building itself.
FEM tehcnologies showed great accuracy in modelling the behaviour of the laboratory specimens, either in passive and active controlled working conditions. However the realization of the FEModels resulted to be onerous due to limitations inherent the FEM simulation and to the high computational workloads. Consequently, FEModels cannot be easily scaled up to the whole building analysis dimensions.

4 Use of statistic models to represent the stochastic driving for the control of adaptive buildings.

One of the main components of systems apt to adaptively control buildings is a micro-climatic model, able to provide with good accuracy the trend of the main weather variables for a period of time comparable to the time constants of the building (3-6-9 hours). Because of the essentially stochastic nature of the phenomena, it has been necessary to use probabilistic models and to study their integrability with the traditional analitical simulation models. The weather predictor has been realized through a Bayesian dynamic network of fourth order (see figure 3), which estimates the value of the main weather variables on the basis of the data of such variables in the previous 8 hours.

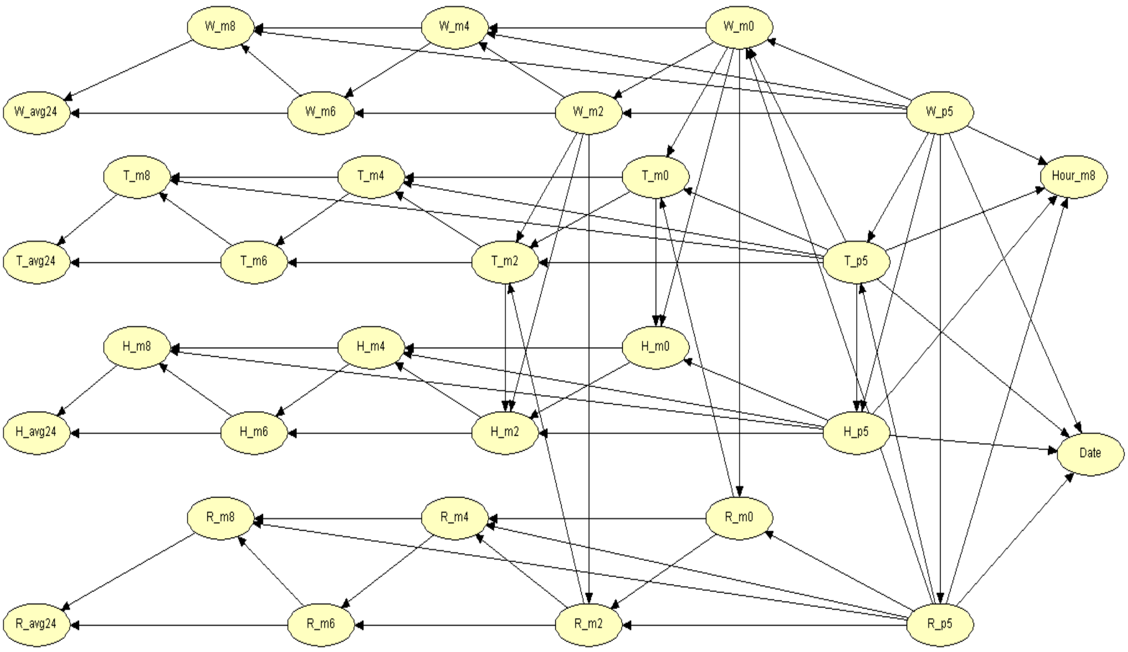


Figure 3. Dynamic Bayesian network for the predicion of weather variables.

The quantification of the relations of conditional dependence among variables has been obtained through the learning statistical algorithm (Learning EM) [16] on the basis of a data-set obtained from local climatic database. The obtained results have been compared to similar results obtained with methods certified in literature, particularly they have been compared to the ones obtained from a deterministic model ARMA of order 64 with previsional horizon of 5 hours, recreated using the same methodology proposed in the Great Energy Predictor Shootout [17]. The results of two models have an average yearly error of the same order of magnitude in support of the validity of our method. The main difference is that the Bayesian method provides the evaluation statistic, so it is in general more informative. The integrability of the model with the traditional analytical simulation systems has been studied by extending the net and including the parameters of comfort and building consumption, simulated through energy plus. In particular, the analytical simulation system operates as a case generator that represents the dataset, from which the bayesian predictor through the learning algorithm builds its schedule of conditioned probability. The results obtained from the probabilistic model and from the analytical one are perfectly comparable. The probabilistic model is less onerous in computational terms and so can be easily included in control systems embedded of buildings

5 Concurrent realization of models of a building using FEM and Whole building analysis methodologies.

Another important aspect of the research was to compare the concentrated parameter LMP models and the distributed parameter ones, analysing to which extent the FEM models could be used in support of the realization of the concentrated parameter models. For this purpose it has been modelled a building component that is a water wall both at the components scale both at the building scale.

The FEM models indeed, even if very accurate to the scale of the element, are barely used at the scale of the building, because of both the remarkable difficulty in the implementation of the surrounding conditions and the highly computational effort caused from the latter applied to such a big scale. Conversely, the LMP models allow an easy management of surrounding conditions and thanks to their structure they allow a remarkable reduction of the computational effort for the simulation at the scale of the building.

Through the FEM technics applied at the scale of the component it has then been possible to find out the average speed in perpendicular direction to the water wall that leads/conducts the convective exchange among the border surfaces of the considered water layer.

The comparison between the two simulation methods has been carried out in a simple simulated room with both methods with the same surrounding conditions. It shows how the temperature bends of the air inside the room overlap with an average error of 0.22 K and a SSE (sum of the squares due to the error) equal to 0.07 K, so validating the methodology.

On the basis of the results obtained from the research it has been possible to prove how is it possible to realise concurrent models to simulate the same phenomenon to the different scales by reducing the unavoidable estimates that could be obtained using only one typology of modelling.

6 Hybrid modelling for the building adaptive control.

On the basis of the analysis carried out so far, we can affirm that in order to develop physical models of adaptive buildings, that would be representative of the different dimensional and temporal scales, that would be solid enough and adaptable to variable operative contexts and that would be able to manage the uncertainty inherent in the environmental measurements and produced by the evaluations on the future conditions, it is necessary to implement an articulated modelling process that provides the integrated use of the modelling technics more appropriate to the different scales and for different settings. In particular, we saw that:

- It is possible to use system identification technics to realize concentrated parameter analytical models on the basis of environmental measurement.
- It is possible to use distributed parameter modelling technics to study local phenomena and produce analyitical laws that can be implemented in concentrated parameter models.
- It is possible to use concentrated parameter analytical models to produce data-set to be used as a basis for learning statistical models, that eventually can be included in control systems embedded of the buildings.
- It is possible to use the learning capability of statistical models for the purposes of the adaptation of the model itself to the future dynamics of the building.

Such results have been organized in a model engineering procedure that represents the main result of the present thesis. The model engineering procedure for the adaptive control of building organisms is showed in figure (see figure 4).

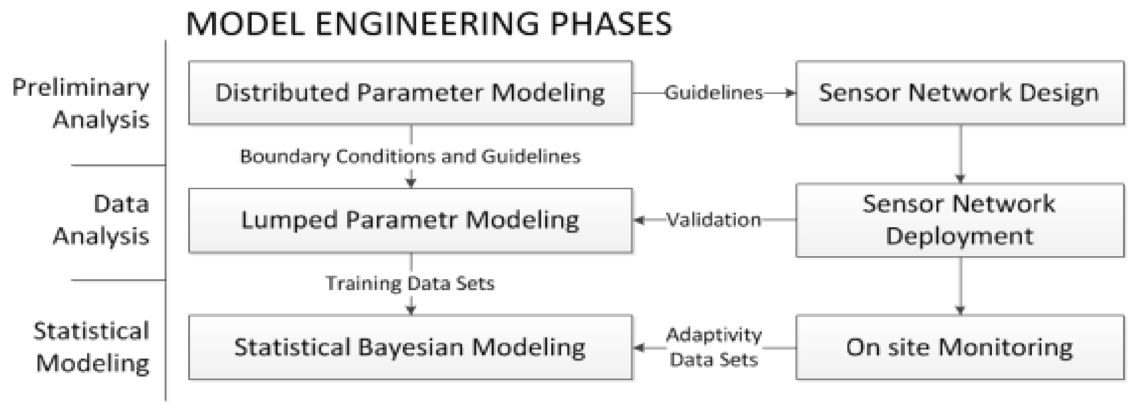
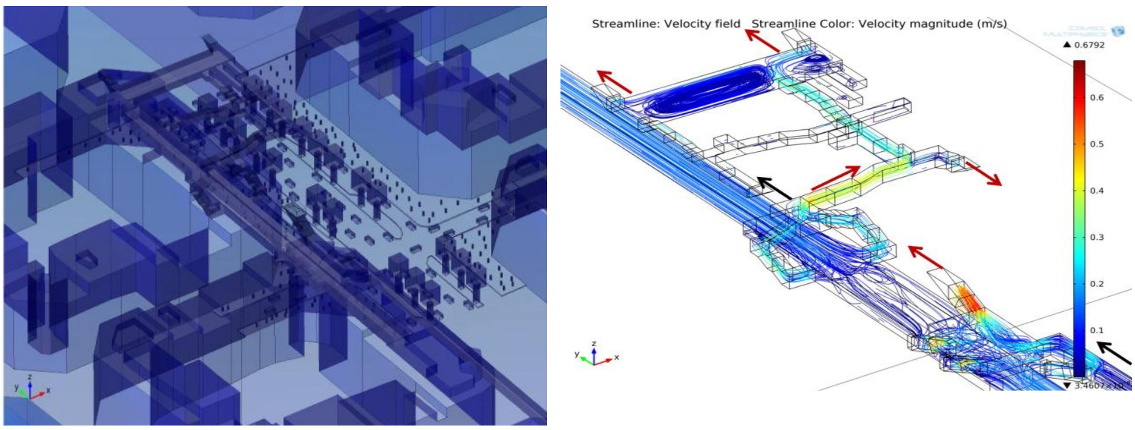


Figure 4. Model Engineering procedure

Starting from the results of an introductory modelling phase a sensor net must be designed and installed. At the same time we develop a thermo-fluid-dynamic concentrated parameters model of the building and we validate it through the standard simulation tools. The main role of the concentrated parameters model is to provide support for the further development of the Bayesian stochastic model, which represents the core of the control system, since it provides prevision, adaptivity and decisional support performances.

This modelling process has been considered as the basis for developing the European project called Sustainable Energy Management for Underground Stations (SEAM4US). It aims to develop a complete experimental system for the dynamic control of the energy consumption of the subway station "Passeig de Gracia" in Barcelona. Such system should be up to significantly reduce the energy consumption of internal environment, on the basis of a system based on previsions related to the external environment in Barcelona, considering both the energetic efficiency and comfort and the control needs. Realizing such a system produces a variety of issues that make the development of the integrated model of a station very complex from an engineering point of view. The steps followed for the modelling are the following:

- Realizing a CFD Model for the air flows evaluation both in the urban canyon and inside the station, depending on the external weather conditions through the FEM (CFD) modelling (see figure 5 a,b). A further development of the preparatory CFD analysis phase concerned the determination of the pollutants distribution in the different scenarios. The results of the stationary analysis have been used to set up a dynamic model of mass transfer, to evaluate those areas with the highest pollutants concentration in order to identify potentially critical zones. Finally, the preliminary CFD analysis leaded to the evaluation of the potentials of natural ventilation in each of the internal spaces of the subway station. The simulated data show how even in the worst conditions the flows are adequate to assume their use through the adaptive control. Particular attention has been given to the study of the sensors net (i.e. their number, type and position), in order to capture all the dynamics of the station in question. The flow line and the contaminants maps have been used to evaluate on a quality level the turbolence zones and to provide an initial general picture of the air flow speed, the pressure and the position of the pollutants sensors and of their precision and accuracy. In particular, for each considered measure point a specific study has been conducted, in order to connect the sensor measure with the value of the size in the volume surrounding it. This strategy allowed to minimize the number of sensors but maintaining the precision needed.

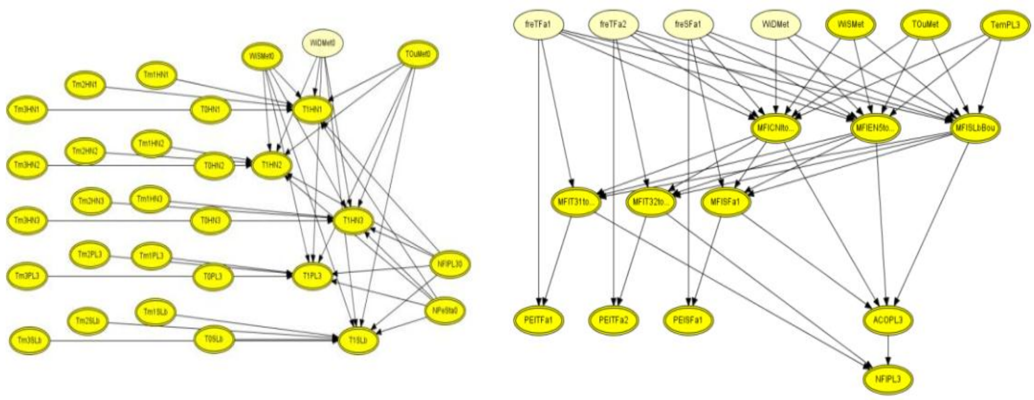


(a) (b)

Figure 5 (a) A section of the simulation domain of the urban canyon in the surrounding of Passeig de Gratia station. (b) The streamline map for a typical simulation scenario.

- Development of the multiphysical concentrated paramenters (LPM) model of the station. Developing such model was necessary since the CFD modelling of the stations allows an evaluation on a quality level related to the air flows behavior of the station and of the pollutants in different environmental conditions, but it does not offer the flexibility needed to integrate it with models of different kind and to be included in complex control algorithms. Hence, it has been necessary a new modelling type that allows a higher level of abstraction in order to manage the domain complexities. Secondly, the DBN development requires the definition of a training and regulation data-set that can be creaated only through a computational model of the station. In terms of the simulation of the air flows, a input/entrance model has been developed, that involved the definition of the wind coefficients studied ad hoc through the combination of a hybrid modelling CFD-LPM, that allows complementary information. The data derived from CFD scenarios are used to model the air flow in some sections of the station, such as crossovers and hallways that connect to other stations. Finally, an investigastion was carried out to confirm the data obtained from the CFD and LMP models.

- Development of the dynamic bayesian network of the station. This last development has been necessary for two main reasons. Firstly, the DBN natively support adaptivity and uncertainty management, which cannot easily implemented using a standard LPM method. Secondly, the LPM cannot easily be integrated in the control system SEAM4US, since the high number of sensors needed to maintain the model up-to-date would have required an unmanageable sensor net. On the other hand, the LPM is fundamental in the global process of the model engineering, because it provides support for the stochastic model development. We developed two different networks: a net of temperature that was time dipendent to consider the time shift of the building , an air flow one that was istantaneus (see figure 6 a,b). On the basis of this network, using the data of the installed sensor system will allow to control the systems of the station, minimizing the consumtpions but maintaining the environmental comfort unchanged. The control networks will be gradually updated with the new data coming from the sensors, and will then be up to define the best control policies depending also on the new conditions that will gradually occur.



(a) (b)

Figure 6. Bayesian model for the Temperature (a) and Airflow Prediction(b)

7 Conclusions

The aim of this thesis was to define a methodological framework that can integrate multiple physical models of buildings at different scales of representation, allowing the management of any levels of uncertainty and different policies of adaptive control. In order to create the methodological framework a series of investigations at different levels of the building have been carried out to define the most appropriate modeling techniques and to evaluate these techniques from the perspective of their support for the adaptive control. The validation of the proposed methodology has carried out by the SEAM4US project, aimed at energy savings through dynamic control of the metro station Passeig de Gracia in Barcelona. The thesis developed the hybrid modelling solution involving FEM CFD, lumped parameter in conjunction with stochastic modelling. The case study is still in a preliminary development phase and will be validated during the next years when monitoring network and the control system will be fully deployed in the pilot station in Barcellona.
The methodology presented here for a specific application case can be easily extended to other building typologies. Therefore, the results achieved in this thesis are of general interest in the building technology scientific communities, since model-based control of building is one of the most promising approaches that will mitigate the financial impact of any energy efficiency solution.
The critical points that emerged from this scientific investigation, is that both the model development and embedding require a deep understanding of the building energetic and environmental behaviour, that usually is not a competence of the building professional sector. This kind of integrated service could have great exploitation in the building desing and management professional market.

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Appendix A List of style tags

An appendix may be provided for additional material the Author does not wish to include in the main article sections.

The following list briefly summarizes the style tags used in this document:

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- Abstract title (*character*);
- Affiliation (*paragraph*);
- Appendix (*paragraph*);
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- Editorial process (*paragraph*);
- Emphasis (*character*);
- Figure (*paragraph*);
- Figure caption (*paragraph*);
- First paragraph (*paragraph*);
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