Preprints of the 19th World Congress
The International Federation of Automatic Control
Cape Town, South Africa. August 24-29, 2014

Improving Energy Efficiency in Large Buildings with Thermal Stratification

Luca Ferrarini*, Giancarlo Mantovani*
Marta Pagliarini*

**Dipartimento di Elettronica, Informazione e Bioingegneria,*
Politecnico di Milano, P.za L. da Vinci 32, 20133 Milano (Italy)
e-mail: luca.ferrarini@polimi.it, giancarlo.mantovani@polimi.it.

Abstract: In this paper the problem of energy efficiency in large commercial buildings is analyzed . In particular, after the introduction of the thermal model with vertical temperature stratification of an existing centre, temperature control schemes are applied with decoupling and feed-forward techniques. It is shown that it is possible to reduce significantly energy consumption and at the same time improve the user's comfort. Finally, the paper highlights also the convenience of introducing some structural changes in the energy distribution plants inside the building.

1. INTRODUCTION

The energy consumption for buildings for both residential and commercial sectors has steadily increased, reaching figures between 20% and 40% in developed countries and nowadays exceeding energy spent for industry and transport. Population growth, increasing demand for construction services and comfort levels, together with the increase of time spent inside buildings, leads to an increase in demand for energy which is expected not to decrease in the future. Along with costs, even CO_2 emissions are steadily growing and the impact of energy consumption in buildings accounts for almost 36% [1]. Thus, the energy efficiency of buildings is a top priority for energy policy at the national, regional and international levels. Directive 2010/31/EU [2] requires that the 27-member European Union to develop national plans for December 31, 2020 will require all new buildings to be Nearly Zero-Energy Buildings which must therefore have a high energy performance. One way to comply with the constraints is to produce energy through renewable sources. The consumption of the non-residential sector, as described in [3], includes buildings used by the services, commercial and the public sector and it is in continuous growth, with an average annual increase of 3.4%. Technological progresses in the field of energy efficiency can play a crucial role for the reduction of fossil fuel consumption. Typical examples are high efficient HVAC (Heating Ventilation and Air Conditioning) plants (like condensing boilers, micro-generation systems, heat pumps, compression and absorption machines), equipment for the reduction of energy losses of heating and cooling systems or constructive techniques improving the thermal insulation of building envelopes. The centralized heating systems installed in large buildings are generally provided with ICT infrastructures for their operation, monitoring and management. An interesting example of their use for reducing energy consumptions is shown in [6]. Their potential, however, is not always exploited, especially for what concerns the control algorithms implemented in commercial application. European regulation EN 15232 ("Energy performance of buildings – Impact of Building Automation, Controls and Building Management") describes the advantages that can be achieved through the adoption of Building Automation and Control Systems (BACS), defining classes of automation systems and related energy savings. However, the regulation does not take into account that the same control architecture can provide very different results on different types of buildings. An interesting study which attempts to tackle this issue is [8] which analyzes the relationship between building energy use and building control system operations to evaluate energy performances versus similar buildings. The indicators described in the paper also quantify potential savings and effectiveness of control system improvements. Instead in [4] a deep and accurate study is performed for applying a set of different Model Predictive Control (MPC) temperature algorithms and it is also applied to different types of thermal zones and HVAC systems. Results related to energy performances are strongly correlated with the type of zone and plant control. The limit of [4] is the fact that control algorithms are thought to be applied to a single thermal zone, without taking into account the interaction between adjacent areas. In many types of buildings, especially the ones with large open-spaces (shopping centers, theatres, cinemas, convention centers) such an interaction cannot be neglected, both for comfort and energy efficiency improvement. An effective application of control techniques to a multi-zone system in the residential sector is presented in [7].

Given the presented state-of-the-art discussion, the purpose of this paper is to examine the impact of traditional control techniques on large commercial buildings. For this purpose, an existing shopping center in Northern Italy is considered and a mathematical model based on energy balance equations is designed in [11]. With respect to the state-of-the-art approaches, the model is designed in a multi-zone fashion and considers the phenomena of vertical temperature stratification, which were proven to be one of the most significant obstacles to the improvement of energy performance in large open space buildings. This work specifically focuses on the design and implementation of different temperature control techniques, based on the model described above, used to improve the thermal comfort and energy consumption of the shopping center.

The local energy control strategies here presented are a first and important step in our research, which goes towards an integrated micro-grid energy control. In other words, the controlled building will be incorporated in a smart micro-grid, where thermal and electrical energy is consumed and produced to serve a well-defined urban area (shopping center, business center, small district). In this scenario, renewable and distributed energy sources (photovoltaic, wind) will be exploited along with storage systems (batteries, hot water tanks) in order to minimize overall micro-grid operation cost given a set of predefined constraints. Nevertheless, this approach obviously requires a radical rethinking of the management model of the current electrical network ([3], [9] and [10]).

The results presented in this paper are part of a EU FP7 research project called Cassandra [5], whose aim is to develop a web-based decision support system capable of assessing the behavior of demand response programs with customizable scenarios and different types of consumers.

The paper is structured as follows. In the Sect. 2 the pilot case is described, namely the thermal and physical characteristics of the building and its HVAC plants. Sect. 3 describes feedback controls (PI control and a split-range technique), while Sect. 4 describes feed-forward compensation techniques for disturbances (e.g., external temperature, solar radiation and so on) and decoupling techniques between floors. Obtained results are then analyzed and possible structural changes in the heat distribution system are suggested. Finally, some concluding remarks are given.

2. PILOT CASE MODELING

2.1 Model description

The system under control is a is a medium-size shopping center located in Gavirate (VA), in northern Italy. It is divided in five floors and contains about thirty different shops. The first two floors are partially underground. Floor 1, has a glass roof, separating it from other floors. It hosts a gym with 2 swimming pools (one for adults and one for children), a sauna and a whirlpool. Floors 2 to 5 are not separated by pavements/ceilings, but on the contrary they largely constitute a unique common volume, except for outer corridor rings at each floor. A vast part of the roof surface is made of glass, which was done to increase the brightness of the interior. However in the summer season, when the contribution of the solar radiation is too high, an appropriate curtains system shields the glass cover.

HVAC plants terminals are 2-pipes fan-coils, which are distributed all over the building and fed with hot/cool water generated from a district heating source/chiller plant. The heating plant is also used by the swimming pool to heat the water and the air in the pool area. The system is equipped with a BACS (Building Automation and Control System) for monitoring and control purposes.

In [11] the mathematical models created for the most relevant envelope and HVAC system components are described in detail. A short description of the most important components involved in this paper follows:

1. *Building envelope*. Its structure determines the quantity of heat which should be integrated by HVAC plants and influences energy consumption and indoor comfort at each floor.
2. *Fan-coils.* They are the actuators used to implement the algorithms designed in this research. In [11] the non-linear equations used to compute the thermal power transferred from the plants to the thermal zones are described.
3. *Primary air handling unit.* It allows the replacement and treatment of air in the common spaces. In the case of Gavirate, no humidity control is done.

Exogenous variables are the external temperature, solar radiation, and internal thermal gains produced by customer occupancy and other sources (mainly lights, bars, restaurants).

In the context of this work, first the model described in [11] is improved, second a linear model is developed in order to apply various automatic control techniques and, finally, various control schemes are implemented and evaluated in simulation. In particular, the main improvements with respect to the thermal model introduced in [11] are essentially three:

1. The introduction of an accurate non-linear model of fan coils terminals, with an efficiency that depends on their operating conditions, as provided in the data sheet.
2. The introduction of the air curtains model. Air curtains are large fan-coils placed nearby the building openings in order to limit uncontrolled infiltrations of outside air. As a matter of fact, their energy contribution is comparable to that of the fan coils used for regulating indoor temperature, especially in the first two floors of the building. Air curtains parameters are better with real data over a full year of operation.

2.2 State space model

Among other complexity, the system is not that trivial to control due to many facts. On one hand, exogenous variables (disturbances) have a strong effect on the building: among others, the external temperature, solar radiation and internal gains. On the other hand, the inner structure of the model contains a natural strong coupling between air temperature of each floor, in that the temperature of i-th floor strongly influences that of floor (i+1)-th. On top of that, there are non-linarites in the model, as well as saturation constraints on some variables, namely the temperature of the supply water of the fan coils. For the above reasons, in this paper suitable decoupling techniques are implemented and tested, along with feed-forward compensation schemes for all disturbances. Their implementation requires a linear state space model. Thus, such a model is derived, through linearization, where the state variables are the air and the wall temperatures for each floor. The input variables (control variables) are supply water temperature given in input to the fan-coils.

3. THERMAL ENERGY FEEDBACK CONTROL

Particular plant constraints impose the following restrictions on the design of controls:

1. The supply water temperature to the fan coil should be maintained between 42° and 60°. The lower bound is imposed by the swimming pool plant that needs high supply water temperature.
2. The fan coils of each floor have independent switches.
3. Air curtains (relevant especially in the first and second level) must always be switched on during the opening of the center, since they are in correspondence of the entrances.

The control variables are:

1. The supply water temperature to the fan coil that is unique for the entire building, due to HVAC plant structure.
2. Fan coils switch commands at floor level (i.e. five separated command, one for each floor).

In this paragraph two types of feedback control techniques are implemented. The first one is a PI controller of the supply water temperature (T_{in}) associated to a simple control logic to switch on/off the fan coils (if a threshold is exceeded, fan coils in a floor are switched on). The second one is called split-range control and is explained later in the text. Both are compared to the control current practice used in the real building.
For the sake of brevity, the simulations are shown only for the month of January 2012 for all controllers.

3.1 PI control

The supply water temperature is regulated by a PI controller with the addition of the upper and lower limits imposed by the presence of load like the swimming pool, which imposes a minimum supply water temperature value fixed at 42°C. The regulator receives in input the error between the temperature set point and the weighted average of the floors temperatures. The control output is the supply water temperature that the boiler must ensure. Fan coils switches are controlled by a simple threshold: if the temperature of the floor is higher than 20° C (indoor temperature setpoint), then fan-coils group at that floor is turned off.
Floors temperature profiles obtained show that only the first floor is kept close to its set point in the coldest periods of the month. The upper floors, instead, reach an higher temperature and result to be overheated. Technically speaking, we need to cool the upper floors in order to keep temperature close to set point, which is not possible at the moment and which is also apparently a strange activity to perform in the coldest month of the year. In particular, it is the lower constraint imposed on the supply water temperature that prevents the cooling of the inner ambient.

3.2 Split Range

In order to respect the constraints imposed, a convenient architecture is the Split Range control scheme. It is applied when two or more manipulated variables are used to control a single output variable.
The choice of values that the control variable should assume is based on the power required to keep the air temperature at the desired profile.
The structure of the split-range control scheme is represented in Fig 1. There are two main parts. The first part decides the water supply temperature profile, while the second one chooses the fan coils switching command.
The first structure is composed by five PI controllers (R block in Figure 1), one for each floor. Each one receives the temperature error in input (i.e., the difference between the indoor air temperature of each floor and its set point). The control variable is the supply water temperature, computed for each floor, which in turn is used to estimate the power needed to control the air temperature. The average value of supply water temperature computed by all PI controllers is sent to the plant as a request. If it is lower than the temperature limit, the lower bound is assumed as the real control variable.

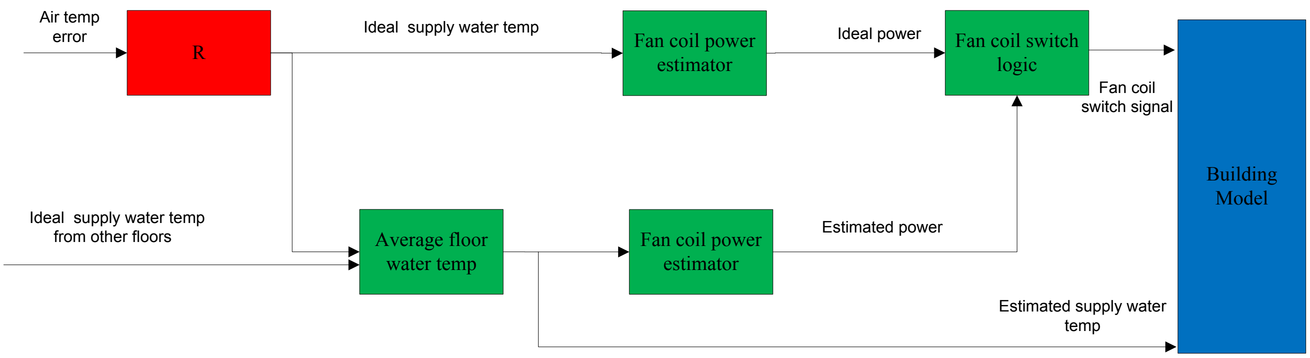

Figure 1. Split Range Scheme drawn for one floor.

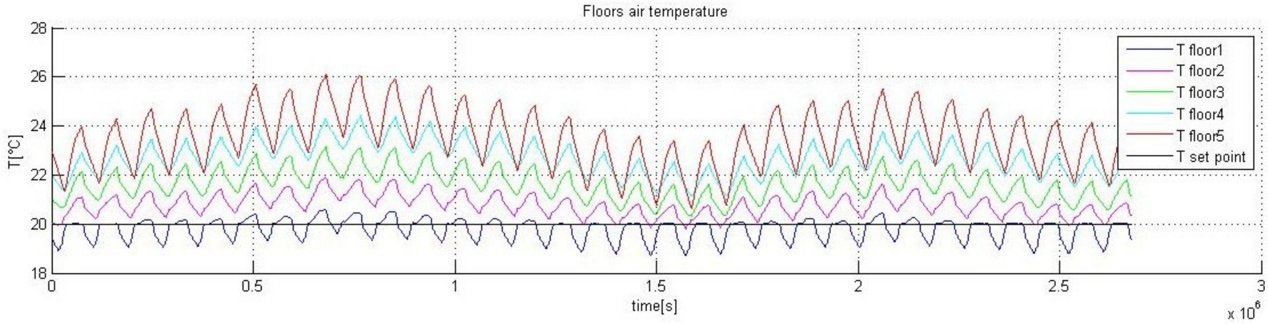

Figure 2. Split Range control, floors air temperature. Simulation time: 31 days.

The second part makes decisions on which fan coils group should be switched on and off. The theoretical powers computed according to the temperature calculated by the five PIs are compared to the power that can be actually produced with the supply water at the mean and saturated temperature which is actually applied. This calculus is represented in Figure 1 by the block "Fan coil power estimator". The ratio between ideal and real power for each plan is calculated for each floor.
If the ratio is greater than 1, the fan-coils are switched on and the temperature is adjusted by varying the supply water temperature. If the ratio is between 0 and 1, a PWM control logic modulates the switching the fan coils by imposing a duty cycle given by the ratio value. Finally, if the ratio value is lower than 0, the control turns off the fan-coils.
Temperature profiles obtained with this control strategy are very similar to the results obtained with the single PI controller, while the energy consumption are slightly higher. The simulation results are shown in Fig. 2.

4. COMPENSATION AND DECOUPLING TECHNIQUES

For each floor both exogenous inputs and energy contributions coming from other floors act as disturbances for the temperature controller.
To reduce all those effects both compensation and decoupling techniques are adopted. As a matter of fact, the fan coils in each floor affect in a consistent way the air temperatures in the adjacent ones, especially the upper floors. This is due to the vertical stratification phenomenon and is clearly shown in real trends collected by the SCADA system, as well as from the computation of transfer function in the state space models.
Compensator and decoupling transfer functions are created starting from the transfer functions between input and output according to the following equation, where the contribution of input- j on the air temperature of the floor-i is canceled by the action of control ij .
Input –j consist on disturbances for the compensator and on control variables from other floor for the decoupling control.

$$L_{ij} = -\frac{D_{ij}}{G_{ii}}$$

L_{ij} is the compensator or decouple control transfer function
D_{ij} is the transfer function between input j and controlled variable i.

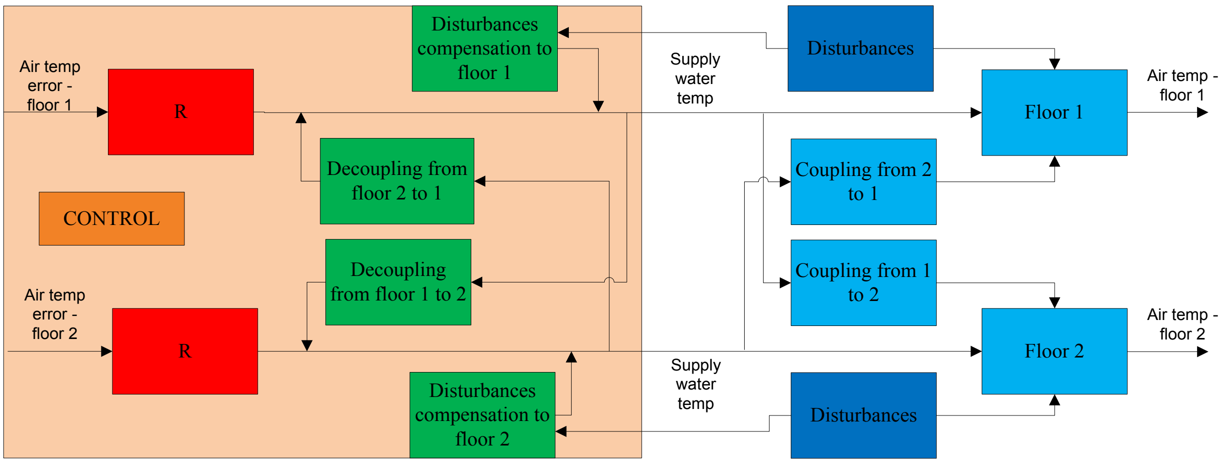

Figure 3. Compensation and Decoupling conceptual scheme for two floors

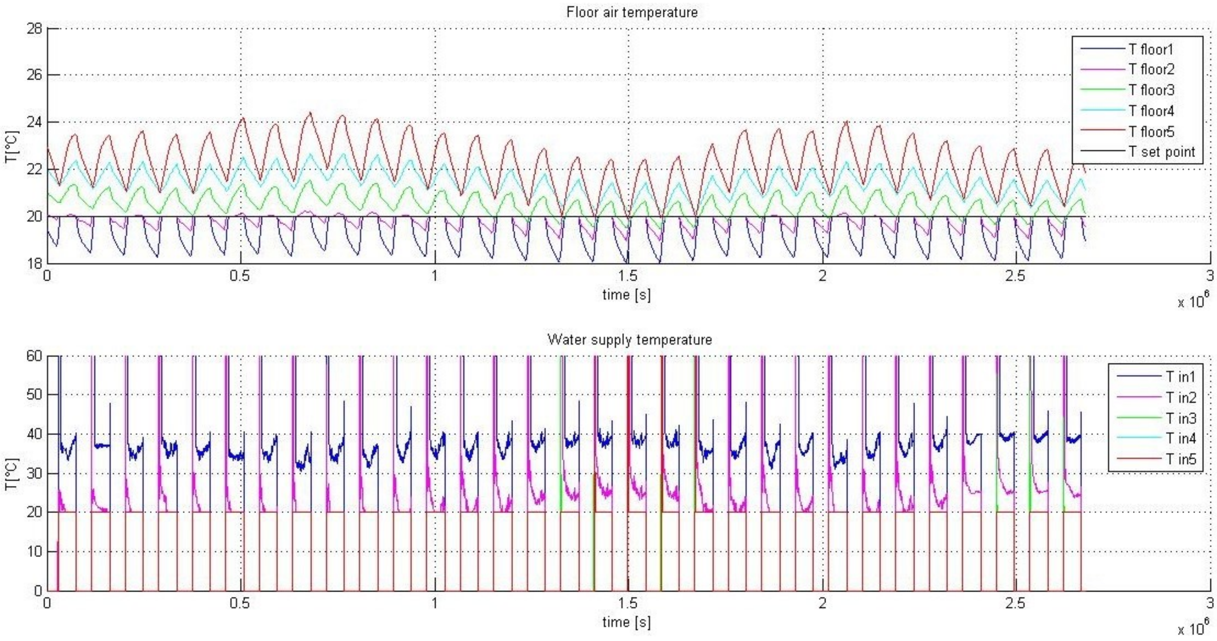

Figure 4. Compensator and decoupling control, floors air temperature and supply water temperature. Simulation time: 31 days.

G_{ii} is the transfer function between control variable i and controlled variable i.

The implemented control, whose simplified scheme is shown in Fig. 3 for two of the building floors, is composed of a closed loop control with proportional integral anti-windup structure (R in Figure 3), a decoupling controller and a disturbances compensator. To improve performances, simulation tests are performed where different supply water temperatures are computed for each floor and temperature constraints are made less stringent. In particular, the lower limit on the control variable is reduced from 42°C to 20°C. Also different set points for each floor are used, higher for the ground floor and lower for the fifth. Simulation results are shown in Fig. 4.

5. COMPARISON OF RESULTS

Basically, feedback controls setting supply water temperature along with fan coil switching signals reduce energy consumption of 5.4% (PI control with threshold) and 2.4% (split range control) compared to the actual plant consumption, assumed as baseline scenario. From the comfort point of view situation is improved, but the presented control structures are unable to keep the reference temperature for all floors. This is basically because the limits imposed on the control variables are too stringent. The result is that there is a non-trivially controllable stratification of the air temperature in the different floors.

Introducing compensation and decoupling gets marvelous results if some constraints are relaxed. PI control and Split Range control simulated with reduced limitations give similar results for the temperature point of view, but higher thermal energy consumptions However, again, no significantly better results are obtained in terms of vertical stratification (and thus on customer comfort). Again, those techniques allow some energy saving. The addition of control logic to the fan coil switching signals, the relaxation of constraints on the supply water temperature and a change in floors set points lead to higher energy savings. As a matter of fact, comparing with the actual control this configuration reduces the consumption of 25%.

However, the HVAC plant is not designed to allow supply water temperatures different for each floor. Thus, some changes in the heating distribution system are required.

In this view, special attention should be paid to air curtains. If the floor fan coils may require a temperature of 20°C to cool down the temperature, the air doors must receive incoming higher temperatures to ensure their proper operation. So, for the implementation of this changes, supply water temperature of the air curtains is maintained at 42°C. This fact negatively affects the energy consumption of the plant, of course.

To allow a modulation of supply water to fan coils, that are now in parallel, sharing the same feed water and mixing their output in a collector, a simple three-way control valve should be installed at the inlet of the fan coils. In this way, it is possible to change the water path and in particular forcing the outlet water from an upper floor fan coil to warm the inlet water temperature to a lower floor fan coil. Another simple way to reduce the stratification of the air temperature is to force a ventilation stream downwards, to basically extract heat from the upper floors and distribute it in the lower ones. Many other combination between the five floors can be easily investigated through simulation.

As expected, the structural changes proposed do not give the same performance as the ideal control in terms of thermal comfort, which should keep the floors temperature at 20°C during the day and decrease the energy consumption, but

TABLE 1			
Results for the month of January			
Implemented control	**(1) [*10^5 MJ]**	**(2) [°C]**	**(3)[°C]**
Actual control strategy	3,526	1.89	5.25
PI	3.337	1.74	5.51
Split Range	3,442	1.78	5.48
Decoupling and Compensator	2,632	1.05	4.43
Decoupling and Compensator with plant changes	2.884	1.44	3.28

Table 1. (1) Simulated energy consumption ; (2) Air temperature average error from the set point; (3) Difference between the maximum temperature of the first and fifth floor

guarantee a energy saving of about 20%, since energy is recirculated, and thus recovered, among the floors.
Air stratification equal to about 5°C in the baseline scenario, is reduced down to 3.5°C. In Fig 5 the simulated temperature profiles are shown. Table 1 reports the energy consumption needed to heat the floors with the implemented control strategies, not considering the boiler efficiency or the electricity used to power the fans, and other performance indices focused on thermal comfort.
Considering the complexity of the models, the results obtained, especially from the comfort point of view may seem improving. However, considering the limitations imposed by the system, other controls structures incur in lower performance, as shown for example in Fig. 5. So, we may conclude that the techniques described in the paper allow to achieve both the energy consumption reduction and comfort goals maintenance.

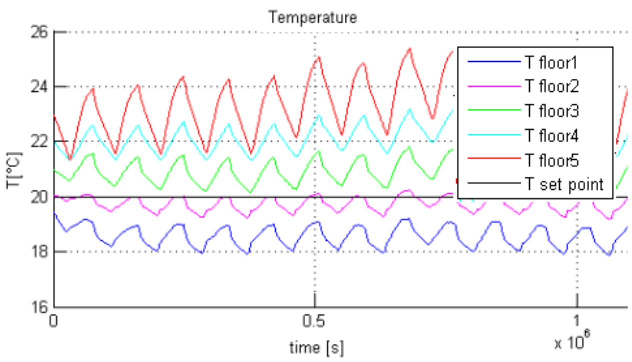

Figure 5. Example of temperature profile obtained with an under-performing control structure

6. CONCLUSIONS

In this paper different building energy control strategies used to improve the thermal comfort and increase energy saving are designed and analyzed in detail. What came out from the analysis is that many control actions can be applied obtaining satisfying results considering temperature trends during the day, with a good set point tracking and thermal power consumption, lower than the current practice in the mall. In addition, the impact of input constraints, which impose important limitations in the goals that can be reached, is analyzed in detail. New plant solutions to bypass these limitations are investigated and proposed. They are based on a different water flow, which provides heat recovery through thermal vector recirculation in the system and a ventilation system to transfer air between the first and the fifth floor.
Another change that can improve the thermal energy control of the building is to modify the water distribution plant which serves the air curtains as well. As a matter of fact, they receive hot water at 42°C and reducing this temperature of some degrees provides further savings without affecting the functionality of this equipment in a limited way.
As a conclusion, the importance of disturbances and coupling among the floors leads to investigate model predictive control techniques in order to anticipate and better compensate the effects of the main disturbances.

REFERENCES

[1] Buildings Performance Institute Europe (BPIE). *Boosting building renovation. An overview of good practices.* 2013.
[2] Directive 2010/31/EU of the EU Parliament and of the Council of 19 May 2010 on the energy performance of buildings.
[3] *RAEE Rapporto annuale efficienza energetica* 2011, (in Italian), ENEA, December 2012.
[4] Oldewurtel F. et alia, *Energy efficient building climate control using stochastic model predictive control and weather predictions*, American Control Conference Marriott Waterfront, Baltimore, MD, USA, 2010.
[5] EU FP7 Cassandra Project http://www.cassandra-fp7.eu/.
[6] S.Katipamula et alia, *Small- and Medium-Sized Commercial Building Monitoring and Controls Needs: A Scoping Study,* Prepared for U.S. Department of Energy under Contract DE-AC05-76RL01830, October 2012.
[7] Cappelletti S., *Modellistica e controllo di impianti termici ad uso residenziale e terziario (in Italian).* Master Degree Thesis, Politecnico di Milano, 2010.
[8] Stephen Treado and Yan Chen *Saving Building Energy through Advanced Control Strategies,* Department of Architectural Engineering, the Pennsylvania State University, University Park, 2013.
[9] N. Motegi et alia, *Introduction to Commercial Buildings Control Strategies and Techniques for Demand Response*, Energy Environmental Technologies Division. LBNL DRRC Report Number 59975. Berkeley, CA, USA. May 2007.
[10] M. LeMay, *An Integrated Architecture for Demand Response Communications and Control*, Hawaii International Conference on System Sciences, Proceedings of the 41st Annual, 2008.
[11] Ferrarini L., Mantovani G. *Modeling and control of thermal energy of a large commercial building,* IEEE International Workshop on Intelligent Energy Systems (IWIES), 14 Nov 2013.
[12] UNI EN ISO 13790, Energy performance of buildings. Calculation of energy use for space heating and cooling, 2008.