An Adaptive Underfloor Heating Control with External Temperature Compensation

Luca Ferrarini, Soroush Rastegarpour and Anacleto Petretti
Dipartimento di Elettronica, Informazione e Bioingegneria, Politecnico di Milano, P.za L. da Vinci 32, 20133 Milano, Italy

Keywords: Temperature Control, Self-tuning Regulators, Building Energy Efficiency, Model-based Control.

Abstract: The paper describes an interesting combination of auto-tuning and adaptive scheduling approaches to design and update a feedback/feedforward control of the temperature in buildings. The focus here is on residential houses endowed with radiant floors, which are intrinsically complex to control due to large inertia and operational constraints, and on the disturbance rejection of the external temperature. Pure auto-tuning techniques may fail to converge if the initialization step is not done properly, due to the wide variety of possible buildings and compensation hard to adapt in closed loop. The proposed approach combines a classification of the typology of rooms based on physical parameters with auto-tuning, so that in a two-step closed-loop procedure, the room cluster can be quickly identified, and consequently the feedback controller and feedforward compensator be tuned. Numerical examples are provided to test the robustness of the proposed approach.

1 INTRODUCTION

The problem of controlling temperature in buildings has seen a growing importance due to the pressure on energy efficiency on the one hand, and on the need to increase the comfort level on the other hand. Although temperature is well understood in many process control applications, in residential buildings with radiant floors temperature control is still an issue in almost all applications, due the large inertia of the pavement itself, to the limitations of the operating range for inlet temperature, and to the many disturbances affecting the system.

On the application side, building automation systems are based on controllers (typically cascaded PID schemes with saturation and linear/nonlinear compensators), which are tuned by hand during the installation phase by some technicians. The results are that days, weeks or months later these systems must be retuned, manually, with users's discomfort in between. The variety of buildings types, materials, orientation and so on, makes the classic auto-tuning techniques ineffective, if proper actions are not taken.

The goal of this paper is to design and test an algorithm that allows to auto-tune a feedback controller and a feedforward compensator, in closed loop, starting from no notion at all of the residential building with radiant panel under control.

Although the technical literature is dense of theory and application of adaptive approaches (Astrom & Wittenmark, 1995), there is a scarce consideration on adaptive compensator in order to achieve a high performance in disturbance rejection. An adaptive control strategy based on RLS method has been developed for a multizone airhandling unit in (Nesler, 1986), but since the most contribution of the collected data from building temperature is due to heating system, the collected data is not rich in information to identify the disturbance dynamics in order to design the proper compensator.

In (Bakker, Brouwer, & Babuska, 2007) an integration of adaptive control and model predictive control has been developed, but the focus is on the occupant behaviour and discomfort aspects and in (Moon, 2012) an ANN-based (Artificial neural network) predictive and adaptive thermal control for disturbance rejection has been proposed. Although the results of these methods are good, they strongly depend on the quality of prediction and estimation, which cannot be guaranteed at all in general, due to the wide uncertainties and disturbances acting on the building. Also, the stability, the quality of estimation and the convergence rate of these methods are affected by initial states and initial control configuration.

Ferrarini, L., Rastegarpour, S. and Petretti, A.
An Adaptive Underfloor Heating Control with External Temperature Compensation.
DOI: 10.5220/0006432906290636
In *Proceedings of the 14th International Conference on Informatics in Control, Automation and Robotics (ICINCO 2017) - Volume 1*, pages 629-636
ISBN: 978-989-758-263-9

In addition, the adaptive control strategy is used in (Adolph, Kopmann, Lupulescu, & Muller, 2014), (Lauenburg & Wollerstrand, 2014) for radiator heating systems and single room heating system. In these systems, an operator decision is required to adapt the control scheme. These methods are usually named as push-button approach which are not so user-friendly. In (Tanaskovic, Fagiano, Smith, & Morari, 2014), (Landau, Lozano, M'saad, & Karimi, 2011), (Kim, Yoon, & Shim, 2008) an adaptive procedure has been applied on the constrained MIMO (multi input multi output) system to deal with the constrains on the input (for example valve saturation) and output. However, these adaptive control approaches cannot deal with hard output and input constraints and wrong initial states and initial control configuration. And also, the state space structure of the plant needs to be known. In all these approaches, the system and initial control scheme are required to be stable. Among all, gain scheduling is one of the most parsimonious method of choice to rapidly adapt controller tuning to the prevailing operating conditions in a mildly time invariant system. (Yang, et al., 2015) (Leith & Leithead, 2010) (Wilson & Jeff, 2000) (Azwar, et al., 2014)

The approach proposed in the present paper, on the contrary is able to update the compensator based on a recursive cluster selection procedure which can guarantee the stability and robustness of the system even with poorly performing initial configuration for feedback controller and feedforward compensator. The convergence of this approach has been tested in all situations defined by technical literature and it can be shown that by using an appropriate starting point the convergence rate will increase rapidly. According to the adaptive approach the PID controller will be updated to deal with constraints of input and improve the transient behaviour of the system. The main novelty of the presented paper is in the application of a well-known algorithm (adaptive startegy) for choosing the best cluster among a wide range of buildings. Moreover, the new clusterization has been conducted to cover majority types of buildings ranging from old to new ones.

The rest of the paper is organized as follows. In Sect. 2 the reference model and its control scheme are given. Classification of residential buildings is provided in Sect. 3, while in Sect. 4 closed-loop auto-tuning techniques are described and tested inside and outside a cluster. The overall adaptive scheduling approach is analysed. Finally, some concluding remarks are given in Sect. 6.

2 MODEL OF THE ROOM AND ITS CONTROL

A generic building can be seen as a set of zones (rooms) interconnected through heat exchange. Rooms can be described with the same model. In a radiant floor system all the rooms receive a heating fluid (generally water) at the same temperature. The fluid runs through pipelines under the pavement. The returning water from all the rooms is collected and mixed with hot water from a generator to have the right water inlet temperature to keep heating the rooms. The thermal behaviour of a room heated through radiant panels has been here modelled as a four-states dynamic linear system. The state variables of the system are the following:

- T_z: Average temperature of the air in the room [°C];
- T_w: Average temperat. of room walls [°C];
- T_p: Average temperat. of pavement [°C];
- T_{pi}: Average temperature of the pipeline water [°C].

The inputs of the system are:

- T_{oa}: Outside air temperature [°C];
- T_e: Inlet temperature of pipeline water [°C].

The dynamic equations of the system come from the energy balance of the room air, walls, pavement and pipeline. The energy balance equation for the room air is:

$$C_z\dot{T}_z = U_{wci}\left(T_w - T_z\right) + U_{win}\left(T_{oa} - T_z\right) + U_{pavi}\left(T_p - T_z\right) \tag{1}$$

The energy balance equation for the room walls is:

$$C_w\dot{T}_w = U_{wceo}\left(T_{oa} - T_w\right) + U_{wci}\left(T_z - T_w\right) \tag{2}$$

The energy balance equation for the room pavement is:

$$C_p\dot{T}_p = U_{pav}\left(T_z - T_p\right) + P_{TERM} \tag{3}$$

where:

$$P_{TERM} = U_1 A_P L\frac{(1-e^{\alpha})}{\alpha}\left(T_e - T_p\right) \tag{4}$$

$$\alpha = \frac{U_1 A_p L}{\rho A r C_p \theta} \tag{5}$$

The energy balance equation for the pipeline is:

$$C_{wt}\dot{T}_{pi} = -wC_{pwt}T_{pi} + \left[wC_{pwt}\left(e^{-\alpha} - \frac{1-e^{-\alpha}}{\alpha}\right) + U_1 A_p L\left(\frac{1-e^{-\alpha}}{\alpha}\right)\right]T_p + \left[wC_{pwt} - wC_{pwt}\left(e^{-\alpha} - \frac{1-e^{-\alpha}}{\alpha}\right) - U_1 A_p L\left(\frac{1-e^{-\alpha}}{\alpha}\right)\right]T_e \tag{6}$$

The parameters used in equation (1) to (6) are the following:

- C_z: Heat capacity of the room air [J/K];
- U_{wci}: Internal heat transfer coeff. of walls [W/K];
- U_{win}: Heat transfer coefficient of windows [W/K];
- U_{pav}: Heat transfer coefficient of pavement [W/K];
- C_w: Heat capacity of walls [J/K];
- U_{wceo}: External heat transfer coeff. of walls [W/K];
- C_p: Heat capacity of pavement [J/K];
- A_p: Pipeline external perimeter [m];
- U_l: Pipeline thermal conductivity [W/mK];
- A_r: Pipeline section [m^2];
- L: Pipeline length [m];
- θ: Velocity of water in the pipeline [m/s];
- ρ: Water density [Kg/ m^3];
- C_{wt}: Heat capacity of pipeline water [J/K];
- C_{pwt}: Water specific heat [J/kgK];
- w: Water mass-flow in the pipeline [kg/s].

The control scheme here used is shown in Figure 1 with a PID as feedback controller (FBC) and a compensator (FFC) of the outside temperature disturbance (T_{oa}). The aim of the control is to keep the zone temperature equal to a set point chosen by the user. The control variable is the reference (T_{erif}) of the inlet temperature of the water inside the pipeline T_e while the controlled variable is T_z. The PID computes T_{ePID} based on the error between the zone set point (T_{SP}) and the actual zone temperature T_z. The sum of T_{ePID} and of the contribution of the compensator T_{eComp} is T_{erif}. A second (inner) control loop, consisting of a PID, controls the opening of the valve mixing return water from the radiant panels (T_{rit}) and hot water from the generator in order for T_e to follow T_{erif}. Clearly, there are saturations in both cascaded controllers (each endowed with clamping anti-windup), as well as ON/OFF valves combined with a thermostat. All of these have been here considered.

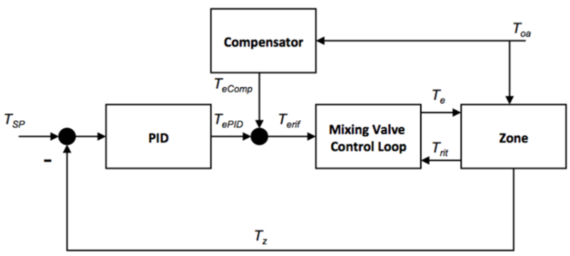

Figure 1: Temperature control scheme.

3 CLASSIFICATION OF BUILDINGS

3.1 Clusterization Procedure

The control scheme previously described is the one widely adopted in practice, with many possible customization (e.g. in the compensation procedure). One of the main problems is that the system under control has a large inertia so that uncertainties and disturbances can create overshoots and oscillations which dramatically compromise the comfort. However, buildings can be of very different types, due to the wide range of their physical and geometrical parameters. A purely adaptive approach to control a generic old or a brand new building is not effective and shows convergence problems. So, the proposed approach is based on a suitable combination of classification and adaptation.

Clusterization of buildings, i.e. the classification of buildings based on the values of the most relevant physical parameters, is the way here selected to reduce the range of all the parameters. This way, a reference model with contained uncertainty can be computed for each identified cluster. The clusterization procedure is based on historical and statistical data about buildings and on data sheets of construction materials. At the end of this procedure, one gets to N_c clusters, and, after the design stage, to N_c feedback controllers and N_c feedforward controllers. The main parameters analyzed in the clusterization procedure are:

- u_{pavi}: heat transfer coeff. of the pavement [W/m^{2}K];
- C_{pav}: heat capacity of the pavement [kJ/m^{2}K];
- u_{wall}: heat transfer coeff. of the walls [W/m^{2}K];
- C_{wall}: heat capacity of the walls [kJ/m^{2}K];

The initial range of the parameters (referred to their average value between all the types of buildings) can be seen in Table 1.

Table 1: Parameters average values, and range of variations before clusterization.

Parameter	Average Value	Range
u_{pavi}	20	+340% -65%
C_{pav}	100	+60% -60%
u_{wall}	0.75	+75% -60%
C_{wall}	30	+100% -60%

After the clusterization procedure an average value of the parameters is determined for each cluster and their variation range is reduced to approximately 1/3 of the initial one.

3.2 Control Scheme Tuning

The reference model of the generic cluster can be used to tune the PID and the compensator of the control scheme proposed in Sect. 2.2. Starting from the 4-state model described in Sect. 2.1 it is possible to compute two transfer functions:

- *G(s)*: Transfer function from the inlet temperature T_e to the temperature of the room T_z;
- *H(s)*: Transfer function from the outside temperature T_{oa} to the temperature of the room $T_{z;}$

In order to tune the PID controller, a simplified transfer function can be identified from G(s):

$$\tilde{G}(s) = \frac{\mu_G}{(1 + s\tau_G)} \tag{7}$$

According to the transfer function in (7), the PID can be tuned as follows:

$$PID(s) = \frac{K}{\mu_G \tau_G} \frac{(1 + s\tau_G)\left(1 + s\frac{\tau_G}{N}\right)}{s(1 + s\tau_p)} \tag{8}$$

Where K and N can be chosen to act on the velocity of the control loop and τp is a high-frequency pole for the controller feasibility.

As for the compensator M(s) it can be ideally computed as:

$$M(s) = -\frac{H(s)}{G(s)} \tag{9}$$

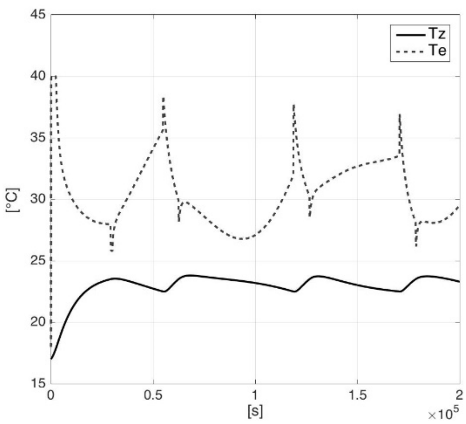

Figure 2: Example of performances when a control scheme of a cluster is applied to a building belonging to another cluster.

For each cluster a low frequency approximation of M(s) can be found and used in the control scheme as compensator of the disturbance Toa.

Notice that applying the control scheme of a cluster to a building of another cluster may result in unacceptable performance, as shown in Figure 2, where Te and Tz are the inlet water temperature and room temperature respectively.

4 CLOSED-LOOP AUTO-TUNING OF ZONE TEMPERATURE CONTROL

Adaptive control techniques are able to self-regulate and update the parameters of a controller in presence of various uncertainties and disturbances. Model estimation is a vital part of the adaptation procedure. The quality of adaptive scheme strongly depends on the quality of the identified models, which in turn depends on initial states and initial control configuration. Apart from that, external disturbances can cause big troubles in the model identification procedure. The proposed adaptive strategy is sketched in Figure 3.

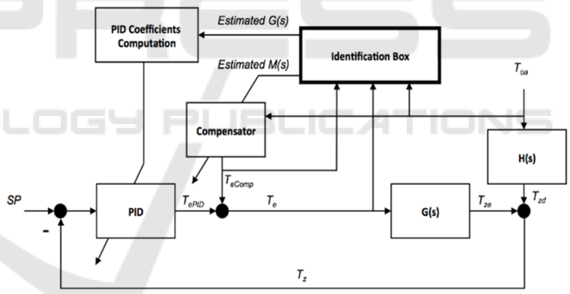

Figure 3: Adaptive strategy block diagram.

The control scheme of Sect. 2.2 is tuned based on an initial guess of the room cluster and applied to the real plant.

Input and output data are collected and used in the identification procedure to estimate the plant and disturbance dynamics, i.etransfer functions G(s) and H(s). In order to estimate G(s), which describes just the effects of Te on Tz, a pure output signal without any oscillatory behaviour, due to disturbances (Toa), is required.

In an ideal case, the compensator would guarantee a good disturbance rejection and therefore it could be assumed that the measured Tz is not influenced by Toa but only by TePID. Thanks to the initial compensator, the output signal (T_z) will be pure enough to estimate *G(s)*. However, in the worst case in which Tz is not sufficiently rich, since the most contribution of room temperature is due to the heating loop so the identified model can be acceptable for the first iteration. In an iterative procedure, while the effects of disterbance is alleviating, the estimated G can converge to the optimal one, or very close to it. Once the estimation of *G(s)* is obtained, the output of *H(s)* (T_{zd}) can be calculated (T_{ze}) based on the output of the *G(s)* estimation. The input and output data of the system for the identification procedure can be organized as follows:

$$G(s):\begin{cases}u_p = T_e - T_{eComp}\\ y_p = T_z\end{cases} \qquad H(s):\begin{cases}u_d = T_{oa}\\ y_d = T_z - T_{ze}\end{cases}$$

A method based on state variable filter (SVF) (Young & Jakeman, 1980), (Ljung, 2009) is used to identify G(s) and H(s). Based on these identified models, the compensator and the PID controller are updated.

In order to evaluate how the estimation of G(s) and in consequence H(s) are influenced by this initial guess, the adaptive control strategy is applied to the mentioned plant with different initial guess of the cluster (i.e. parameters of the PID and of the compensator) If the initial control scheme is chosen from a cluster whose physical characteristics are far away from those of the building under control, the estimation of the real plant is inaccurate and,

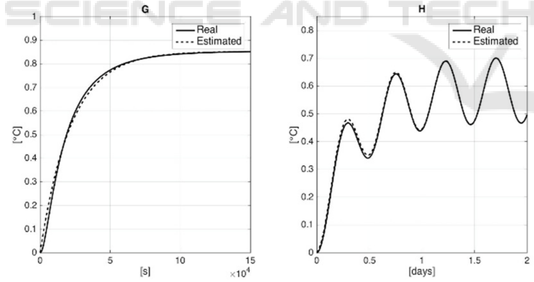

Figure 4: Estimation of G(s) and H(s) with a good initialization.

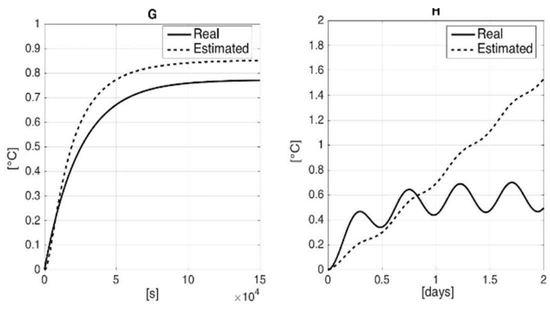

Figure 5: Estimation of G(s) and H(s) with a bad initialization.

consequently, the identified model for disturbance dynamics is completely wrong in the sense of time and frequency properties Figure 5. Both the estimation of G(s) and H(s) are accurate when starting from good initialization
Figure 4. Therefore, to choose the right cluster for the building (i.e. the control scheme) is fundamental.

5 OVERALL ADAPTIVE SCHEDULING APPROACH

5.1 Main Motivation and Possible Solution

A robustness problem in the classical auto-tuning method arises when the estimated plant (*G(s)*) is inaccurate. Because of the strong sensibility of disturbance dynamic estimation (*H(s)*) to the accuracy of estimated plant, classical self-tuning approaches for updating the compensator are unreliable. On the contrary, an adaptive scheduling method (based on clustering approach) is a well-known robust approach to adapt the compensator in a proper way to guarantee the robustness, stability and convergence behaviour of the system even in presence of lack of accuracy in plant estimation.

According to the analysis conducted in Sect. 3 and 4, a hybrid adaptive approach has been conceived. Basically, first we identify the cluster, then we apply the control parameters of the identified cluster and re-tune only the FBC using the auto-tuning scheme presented in Section 4, maintaining the FFC of the selected cluster. The advantages of this hybrid procedure are: 1) as a first step, it is easier to identify the most accurate cluster to identify *G(s)* or *H(s)*; 2) when estimating *G(s)*, some parts of disturbance dynamics are eliminated before the reaction of compensator; 3) the estimation of *H(s)* is avoided, thanks to the cluster compensator; 4) the identified cluster is used “only” for a correct initialization of the auto-tuning procedure. Thus, this approach improves the robustness and quality of estimated model of the real plant which in turn leads to better re-tune the compensator. The procedure to identify the cluster should be iterative, since the variety of the buildings is very high, so potentially the estimation should be refined in a step-wise manner: first we get data from the closed-loop system with a tentative controller, then, after the plant estimation, better FBC/FFC controllers are obtained and applied, so we can restart, obtaining cleaner data. The closest cluster can be found throughout the iterative cluster selection procedure. The convergence of the mentioned iterative opertaion can be proved due to the cluster selection criterion which is the time constant and DC gain of the estimated linear function. On one hand, the thermal characteristics (thermal capacity and transmitance of the walls and pavement) of the working building are represented by the time constant and the DC gain of estimated transfer function. On the other hand, the clusterization has been done due to difference of thermal capacity and transmitance of the walls and pavement. It can consequantly be claimed that the cluster selection procedure converges to the closest cluster thanks to the accurate clusterization of the possible biuildings. The convergence of the aforesaid operation is also proved by different analysis even with a randomely chosen cluster Figure 7. In the case that the iterative procedure can not converge to the specific cluster, i.e. switching among 2 or 3 clusters, the average compensatore will apply to the system and the proper PID controller will retuned based on the estimated linear model.

As for the initialization of the adaptive scheduling approach, the control scheme is chosen initially as the "average" PID/compensator. This is a standard PID designed for the "average" building, ranging from very old buildings to most recent ones belonging to the Nc clusters. As it will be shown later, the identification procedure of the cluster is affected by the initial control scheme (i.e. a FBC and a FFC), but only for the convergence rate.

Data collection procedure and consequently a preliminary estimation of the real plant are done

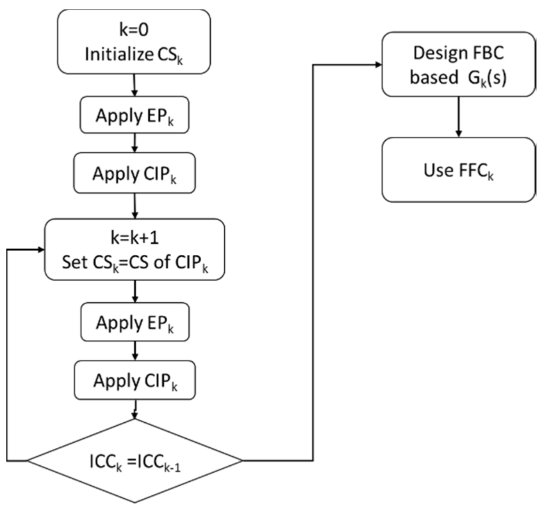

Figure 6: Adaptive scheduling algorithm flowchart.

based on the initial control scheme during a time period Test (Test =2 days in the following analysis and figures). In this step, the closest cluster (ICC, Identified Closest Cluster) is identified iteratively (through the CIP procedure). Once the cluster has been selected, the final FBC is tuned based on the estimation of the plant performed in the last iteration, while the compensator is selected directly from the identified cluster.

The mentioned adaptive scheduling algorithm is summarized in the flowchart of Figure 6. The term CS stands for control scheme, based on a FBC and a FFC. The two acronyms EP and CIP stand for the following two procedures.

Estimation procedure (EPk):

1- Apply the control scheme CS_k
2- Run the closed loop system and collect data for time interval T_{est}.
3- Estimate *G(s)*.

Cluster Identification procedure (CIPk):

1- Select two clusters with closest dominant time constant based on estimation procedure (EP).
2- Select among those two the one with closest gain.
3- Name this cluster as ICC_k.

5.2 Simulation Results and Comparison

A wide cross-validation between adaptive scheduling and clustering approach and initial control scheme (CS_0) has been performed to illustrate the beneficial effects of proposed adaptation procedure on disturbance rejection, stability and robustness of the system and also the convergence to the most appropriate FFC and FBC in an iterative procedure.

In the first test a modern building endowed with an initial control scheme, randomly chosen among the N_c clusters, has been considered in order to evaluate the robustness of the proposed approach. As shown in Figure 7, this scheme CS_0 generates unacceptable oscillatory behaviour and slow transient response. Nevertheless, after the proposed adaptation procedure, the behaviour of the building temperature is completely smooth and the disturbance rejection is achieved perfectly. The FFC converges to the most appropriate one after 4 iterations (each iteration takes the same time interval T_{est}) and FBC regulates correctly.

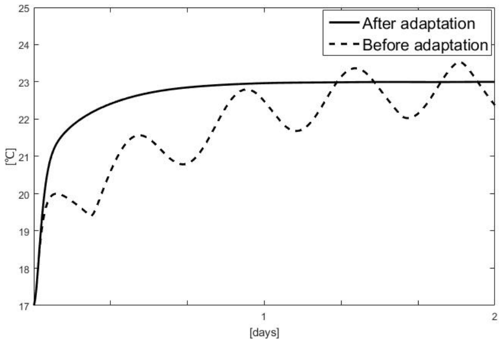

Figure 7: Temperature behaviour of a modern building with a randomly chosen CS0.

In the second test, the same modern building is considered, but this time the CS_0 has been initialized based on the "average" building of the N_c clusters. This initial control scheme is more reliable than the previous one. In this case, the same result of the previous test is achieved Figure 8, but the convergence rate is two times faster: in this second test, the adaptation procedure just took 2 iterations.

In the third test, a very old building is chosen. Once again the CS_0 is initialized based on the average building of the clusters. The adaptive scheduling approach converges to the best working cluster in 2 iterations as shown in Figure 9.

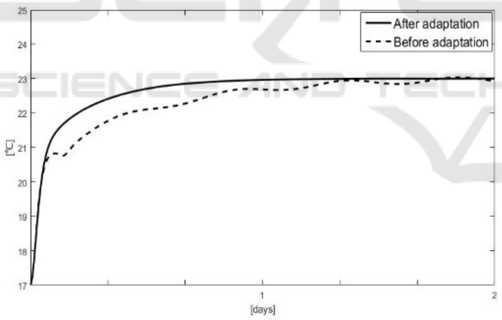

Figure 8: Temperature behaviour of a modern building with CS0 based on "average" building.

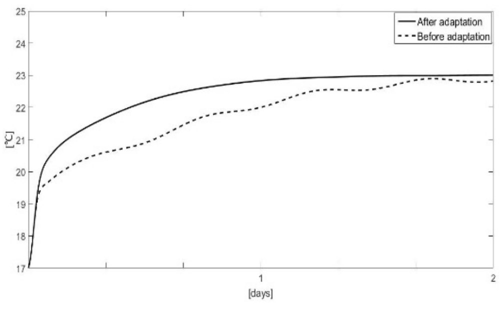

Figure 9: Temperature behaviour of a very old building with CS0 based on "average" building.

Many other similar testing have been performed. So, it can be claimed that, by using an interpolation of all the clusters (ranging from very old buildings to most recent ones) as the initial control scheme for the adaptive scheduling approach, the minimum iterations number for converging to the best working cluster is guaranteed.

6 CONCLUSIONS

The paper addresses the general problem of automatic tuning of temperature regulators for buildings with radiant floors. In particular, the problem is here considered for residential buildings of any type (from a flat in a multi-residential building to an isolated villa), of any construction period (from '60s up to 2015), and of any energy labels (classes A to D), which gives rise to a wide variety of physical parameters. Also, the external temperature rejection problem is considered. The basic result here proposed is an adaptive procedure based on a suitable combination of auto-tuning and adaptive scheduling based on a clusterization of buildings. Blind tests show that it proves to be robust to parametric uncertainties always converging to the expected control schemes, for any kind of the above-mentioned rooms. Different sampling time and estimation horizons have also been tested, with similar performance. Models have also been tested in a laboratory facility, where room with heated pavement is build within another bigger room playing the role of external ambient, and the first results are encouraging. Formal proof of convergence will be considered as a further result.

Although the external temperature is one of the most effective disturbances on the building temperature, there are many other disturbances affecting the system, such as internal gains, due to occupant behaviour and thermo-electrical equipment, and solar radiation. The rejection of such disturbances will be considered in the future extension of the adaptive algorithm here illustrated. In addition, future directions include tackling the problem of measurement noise in the zone temperature, inlet temperature and the disturbance signals.

REFERENCES

Adolph, M., Kopmann, N., Lupulescu, B. & Muller, D., 2014. Adaptive Control Strategies for Single Room

Heating. *Energy and Buildings,* volume 68, P. 771–778.

Astrom, K. & Wittenmark, B., 1995. *Adaptive control (2nd ed.).* s.l.:Addison-Wesley..

Azwar, M. Y., Mohd, A. H. & Ahmad, K. A. W., 2014. Modeling, optimization, and control of microbial electrolysis cells in a fed-batch reactor for production of renewable biohydrogen gas. *International Journal Energy Research.*

Bakker, L. G., Brouwer, A. & Babuska, R., 2007. Integrated Predictive Adaptive Control Of Heating, Cooling, Ventilation, Daylighting And Electrical Lighting In Buildings. *International Journal of Solar Energy,* 21(2-3), pp. 203-217.

Kim, J., Yoon, T. & Shim, H., 2008. Switching adaptive output feedback model predictive control for a class of input-constrained linear plants. *IET Control Theory & Applications,* pp. 573 - 582.

Landau, I., Lozano, R., M'saad, M. & Karimi, A., 2011. *Adaptive Control, Algorithms, Analysis and Applications*. New York: Springer.

Lauenburg, P. & Wollerstrand, J., 2014. Adaptive control of radiator systems for a lowest possible distric theating return temperature. *Energy and Buildings,* Volume 72, p. 132–140.

Leith, D. & Leithead, W., 2010. Survey of gain-scheduling analysis and design. *International Journal of Control,* pp. 1001-1025.

Ljung, L., 2009. *Experiments with Identification of Continuous Time Models,* Linköping, Sweden: Linköpings universitet & 15th IFAC Symposium on System Identification,Saint-Malo, France.

Moon, J. w., 2012. Performance of ANN-based predictive and adaptive thermal-control methods for disturbances in and around residential buildings. *The International Journal of Building Science and its Applications,* Volume 48, pp. 15-26.

Nesler, C. G., 1986. Adaptive control of thermal processes in buildings. *IEEE Control Systems Magazine,* 6(4), pp. 9-13.

Tanaskovic, M., Fagiano, L., Smith, R. & Morari, M., 2014. Adaptive receding horizon control for constrained MIMO systems. *Automatica,* Volume 50, p. 3019–3029.

Wilson, R. & Jeff, S., 2000. Research on gain scheduling. *Automatica,* 36(10), p. 1401–142.

Yang, L., Xiaojun, B., Fen, W. & H, L., 2015. A Gain-Scheduling Control Approach for Takagi–Sugeno Fuzzy Systems Based on Linear Parameter-Varying Control Theory. *Journal of Dynamic Systems, Measurement, and Control,* p. 9.

Young, P. & Jakeman, A., 1980. Refined instrumental variable methods of time-series analysis: Part III, extensions. *International Journal of Control,* Volume 31, p. 741–764.