Design and simulation of a fuzzy supervisory control system integrated in a small public building

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Abstract –

Public administrations are encouraged to adopt actions for energy requalification of public buildings, which are responsible for considerable amounts of energy consumption. Low-cost technology improvements for energy renovation with high return on investment is a good opportunity when resource shortage hampers the adoption of expensive refurbishment. To this purpose, the integration of advanced control policies may optimize energy use of buildings with minimum hardware enhancement.

In this contribution, we evaluated the performances of a control system based on fuzzy logic, supervising local Proportional-Integrative-Derivative (PID) controllers, through numerical simulation. First, the design process will be described, with particular concern to the proper selection of the rules in the knowledge base and the design of the inference engine. Then, its performances will be compared with the ones provided by the use of just ordinary PID control units. The fuzzy based control system was simulated as an addiction to the heating system of an existing small public building, that is the "San Elpidio a Mare" community clinic located in Italy. The performances were assessed by means of simulations of an energy dynamic model developed in the Dymola™ environment, that had been previously validated with real consumption measurements. In this paper we will show not only what energy saving can be obtained by means of the fuzzy supervisor, but also its satisfactory performances in terms of stability of the control outputs.

Keywords –

Fuzzy logic; advanced control systems; energy saving; heating system; public buildings

1 Introduction

The survey of appropriate renovation actions to improve the energy behaviour of existing buildings can dramatically contribute to the reduction of the overall energy needs. Indeed, the building stock represents one of the biggest energy consumers, and public buildings were shown great potential for improvement, even by means of low cost renovation actions. As shown in the energy analysis of a Malaysian public hospital [1], the typical assessment procedure includes an energy audit process that collects information about the hospital's equipment and its energy consumption. Then, low cost tailored energy saving measures were identified and implemented, such as the integration of variable speed drives. The arrangement of a very detailed energy baseline is particularly critical in the case of complex strategic buildings, such as those ones owned by public administrations, where the development of a detailed consumption breakdown [2] can be quite demanding, due to the shortage of management systems. The only way auditors can accurately survey, diagnose inefficiencies and quantify energy savings that can be achieved by means of enhanced control is by means of tailored simulations. Such evaluations need the adoption of dynamic simulation tools, that are presently under wide consideration by researchers and practitioners [3]. They are more accurate than static calculation procedures traditionally used for plant sizing and they are compliant with suggestions from the European standard series EN 16247 [4].

In this paper, we will evaluate potential improvements determined by the adoption of advanced control systems based on fuzzy logic, focusing on a recurring Italian scenario that is relative to the building stock built around the 1970s and 1980s. In order for the requalification of small hospitals to be cost-effective, they might take advantage of the availability of low cost energy renovation actions.

In this research, one possible application of fuzzy logic will be proposed, whose performances will be compared both with the reference building in its current operation and with those ones provided by ordinary PID control, that was widely used in HVAC systems, as proved in many research works [5],[6]. Sometimes, fuzzy logic was integrated with PID control units in order to adjust their parameters according to control needs [7]. In this paper we will apply fuzzy logic as the supervisor sub-system of several local PID controllers.

2 The case study

San Elpidio a Mare's community clinic is located in Italy and managed by the public health authority's division, whose headquarters are in Fermo (Italy). The building is made of two blocks. The first one was built in the 1970s (A1), while the second block A2 was built in the 1980s (Figure 1). All the wards and offices are located in the older block of the building, whereas staircases and the elevators are accommodated in the other block. The clinic is arranged on seven levels, three of them located below grade, but at the time this study is referred to (i.e. the beginning of 2013) not all the levels were occupied. The main heating plant was built on the third level below grade and consists in a centralized system from which branch out the two main pipes of the secondary circuits that serve the various levels of the two blocks. Energy consumption was available in the form of energy bills and due to gas methane and electrical power. Both of them were invoiced monthly, so it was possible to estimate the actual picture that is provided in Table 1.

However, invoices were relative to the whole amount of electrical power and gas consumption and were not separated into sub-categories. In the case of natural gas consumption, it was split into heating consumption and hot water consumption. To this purpose, it was assumed that from May to September the heating plant was being turned off, so all the consumption in this period was charged to hot water only. The corresponding average value was assumed valid even over winter months. This assumption is confirmed by the Italian Standard D.P.R. 412/93 [8], because it states that all the heating systems must be turned off from 16th April to 31st October, thus supporting the validity of this approach. The difference between the total consumption and the estimated hot water consumption was charged to the heating system, thus estimating the monthly distribution of gas methane requested for heating purposes and shown in the two rightmost columns in Table 1.

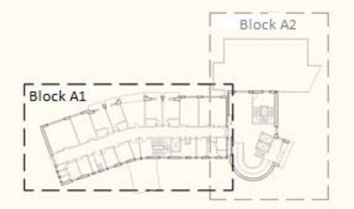


Figure 1. Main plan of the building adopted as a case study.

Table 1 Monthly gas methane consumption

	Total fuel (m^3)		*Primary Energy (kWh)*		*Fuel for heating (m^3)*	
Month	2012	2013	2012	2013	2012	2013
Jan	18818	7538	186125	77811	16879	6026
Feb	19756	11292	195125	113833	17817	9781
Mar	10140	7965	102864	81912	8201	6454
Apr	8731	5313	87893	55015	6792	3802
May	2428	18260	25966	20106	0	0
Jun	1880	1790	20708	19760	0	0
Jul	1826	1474	20192	16728	0	0
Aug	1641	957	18416	11768	0	0
Sep	1919	1050	21083	12660	0	0
Oct	3494	1972	36193	21506	1555	0
Nov	6025	4852	63383	52045	4086	3341
Dec	11027	7945	111370	81720	9088	6434
TOT.	87685	53974	889317	564864	64418	35835

The electrical power consumption was due to "auxiliary consumption for hot water", "auxiliary consumption for heating" and "building", that – in turn - sums up "lighting" and "facilities". A thorough analysis of the building's consumption pattern is presented in the former paper by Pontoni et al. [9]. To sum up, a breakdown of the electrical power consumption was carried out by means of behavioural models and surveys and interviews to technical personnel dedicated to maintenance. Then, all these consumption figures were converted into primary energy, using the current conversion factors for gas methane (i.e. Lower Calorific Value equals to 34.54 MJ/m^3 = 9.59 kWh/m^3) and electrical power (i.e. 1 Kwh_{el} = 2.34 KWh_{prim}), as suggested by the recommendation in AEEG n. 103/03 [10]). As a result, the following figures were derived: total primary energy for heating, total primary energy for hot water, primary energy of the whole building. According to the European Standard UNI EN 15217:2007 [11], the building performance level is assessed through the Energy Performance index (EPi), that in this case is equal to 51.65 kWh/m^3 in 2012 and equals to 38.58 kWh/m^3 in 2013. Hence, both values are much higher than mandatory legislation thresholds (i.e. 14,58 kWh/m^3 in 2012 and 17,71 kWh/m^3 in 2013).

3 The fuzzy controller integrated in the simulation model

3.1 Fuzzy logic

Basically, the approach suggested by fuzzy logic captures the expert's operation design rules in the form of a set of logic rules that would be applied if a human were operating the building control. The main components in a fuzzy control scheme are as follows:

1. the fuzzification interface, that includes the membership functions of each variable considered (both in input and in output) to make possible to convert crisp logic variables into linguistic variables and vice versa;
2. the rule base: simulating the expertise of a knowledgeable operator, it translates the experience of an operator in rules of the kind: "IF premise THEN consequence";
3. the inference engine: it performs decision making in terms of linguistic variables, finding for each crisp variable input those membership functions that are intersected and identifies what rules are active and applicable at each iteration;
4. the defuzzification interface: it turns the linguistic variable values back to crisp logic variable values, which are then applied as a signal to actuators.

A straight way to sum up how fuzzy logic works can be describing it as a procedure. As a first step, actual measurements sent by a monitoring system installed in the building are treated as crisp logic variable values. In the specific case considered in this paper, measurements were relative to ambient temperature and deviation between indoor (i.e. room) air temperature and its set-point (i.e. "error"). These are converted into linguistic variable values by means of previously defined membership functions that were built in the form of trapezoidal or triangular type. The result of this process is that the crisp logic variable values are converted into the corresponding linguistic variable values, that are those ones whose membership functions have the highest value for the measured crisp logic variable value.

As a second step, the actuators must be defined. In the case study, the fuzzy logic supervises the action of the local PID controllers embedded on the actuators, being able to adjust the temperature of the water supplied by the boiler to the primary circuit and by the opening of the three-way valves to the secondary circuit. Thus, three actuators in total, and two actuators per each fuzzy control system, since two separated control systems were designed in each block of the building to overcome the problems of control due to the different behavior of the two blocks of the hospital. All the three actuators were assigned linguistic variables and the corresponding membership functions of the linguistic variables. Then, a set of rules must be defined in order to convert any input linguistic variables combination (whose size depend on the number of controlled variables and actuators) to all possible actuator states. The initial approach for the definition of the rules, and also of the membership functions, was that proposed by Dounis et al [12], then a "trial and error" approach made possible the definition of a set of fuzzy rules relative to every output variable and encoded as a table. Each row in the table represents one rule. To be noticed that each "fuzzy set" represents the value of the respective input/output linguistic variables for the given rule. At this juncture, all the steps needed to implement the inference engine are done. In this case we have a fuzzy system with two inputs and two outputs, that can be written in the compact form as:

$$Y_j = \bigcap_{i=1}^{2} \{X_i \circ R_{ij}\}, j = 1,2 \tag{1}$$

The fuzzy relations R are defined using the rule base according to the formula:

$$R_{ij} = \bigcup_{k=1}^{n} \{X_i(k) \cap Y_j(k)\}, i \ and \ j = 1,2 \tag{2}$$

Where X and Y are the input and output and the symbol operators mean fuzzy set union and intersection. Finally, the defuzzification method called center of area (COA) was adopted for determining the crisp value that corresponds to linguistic values computed by the inference engine. The COA method defines the crisp value as the center of gravity of the average of the values at which the membership function has maximum values.

3.2 The simulation model

The control approach tested in this paper was targeted to enhance the performance of the heating system of the hospital in San Elpidio a Mare. The energy model was developed in the Dymola^{TM} environment, which is based on the Modelica programing language. This type of modelling is more flexible and accurate than standard simulation tools usually used for whole building simulation, because it allows users to model in detail and control any device affecting the building's consumption. The Modelica "Buildings Library" v1.6 was used, because it is a library made of components specifically tailored to building simulation [13].

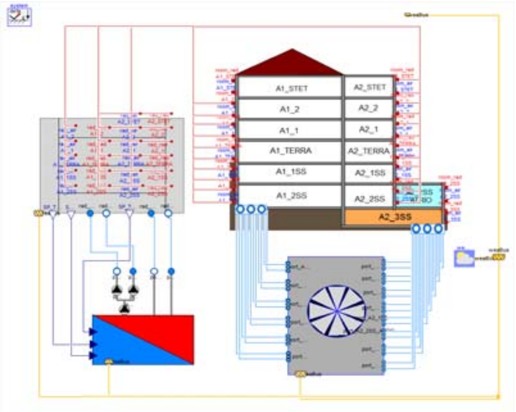


Figure 2. Top layer of the Dymola model.

Modelica is an object-oriented, equation based language to conveniently model complex physical systems containing, e.g. hydraulic, thermal, control and electric power. Figure 2 provides a graphic logic representation of the Dymola model's top layer of the case study. It is made up of four top level components, namely: the main heating plant (bottom left icon on Figure 2), the heating units (top left icon on Figure 2), the indoor space (top right icon on Figure 2) and the ventilation system (bottom right icon on Figure 2). Each of this top level's components was further detailed into lower levels of the simulation model. The indoor space and ventilation system are not illustrated in detail since these units do not include components someway related to the control sub-system. On the contrary, the basic features of the remaining two units will be described here and shown in the following sub-sections.

The heating plant is made of a primary circuit and two secondary circuits. The primary circuits includes the boiler (i.e. RTQ 400 type with 630 W power), which regulates the temperature of supply water by means of a temperature reset control system; one 870 W pump working at constant speed; safety devices imposed by regulations. The two secondary circuits deliver water to the thermal zones of the two building blocks (A1 and A2), whose power is 1350 W and 375 W, serving blocks A1 and A2, respectively. Presently, they work at their maximum rate over the whole heating period. Regulation is provided by two three-way motorized mixing valves, that are installed on the two supply mains and that regulate the temperature of supply water by mixing return water with the hot water supplied by the primary circuit. The valves are activated according to measurements by two temperature sensors installed on the water supply mains.

The heating units were modelled through the elements available in the "Building library" and called "Radiator". Their water content was regulated by three-way motorized valves. Characteristics implemented in the model match with those ones typical of a traditional cast iron radiators. Not all the thermal zones were heated and in operation, so the three-way valves were used either to keep the radiators turned on, or to switch them off, according to real conditions of use.

The indoor space was organized into thermal zones, each modelled through the "Room" component from the library. As a consequence, 14 thermal zones were considered on the overall, and only the heated zones were assigned tailored thermal heat gains due to people, equipment and lighting system, that correspond to approximately 7 W/m^2 on the average.

Each room of the Dymola model was assigned the corresponding thermal characteristics of the envelopes (e.g. thermal transmittance was assumed between 1.232 W/m^2·K and 1.443 W/m^2·K), of the floors (whose thermal transmittance was assumed to range from 1.499 W/m^2·K to 2.064 W/m^2·K) and of the windows (between 2.942 W/m^2·K and 6.281 W/m^2·K).

The ventilation system is the last macro-level unit, which includes both natural air changes (due to air leakages) and the permeability of windows. These values were set as the sum of the contribution from natural air change and window permeability for the heated zones (estimated in 0.366 vol/h), while for the non-heated zones only the windows permeability was considered. Weather conditions were set using real data derived by the "APIwunderground" web site, where the plots from the weather station closest to San Elpidio a Mare (Italy) were retrieved from, relatively to the year 2013.

4 Analysis of performances

4.1 The benchmark

The macro-level component modelling the heating units is shown in Figure 3. Out of all the thermal zones, the three-way valves worked to let hot water flow into 6 thermal zones and preventing that flow from the remaining eight not heated thermal zones. This subdivision and the occupancy patterns were determined according to real conditions of usage. To sum up, most of block A1 was heated, while just a small portion of block A2 was. This situation is expected to change in few years, until the whole hospital will be made fully operational. But the purpose of our study was to accurately model the actual operational conditions. The average internal gains mentioned in paragraph 3.2 were differentiated according to the use of every thermal zone under operation. In every thermal zone, it was given as the sum of the gains generated by people, those ones generated by lighting fixtures and by equipment.

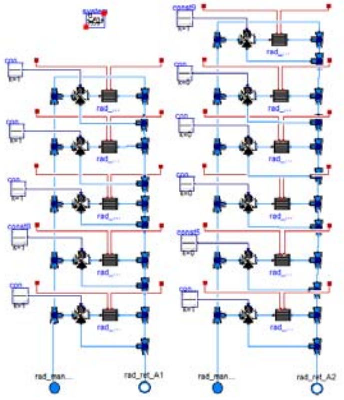


Figure 3. The Heating Units component of the Dymola model shown in Figure 2.

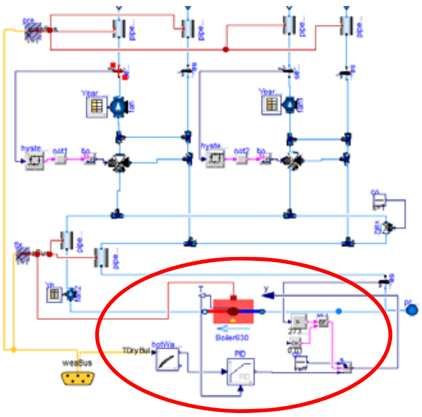


Figure 4. The Heating Plant component of the Dymola model shown in Figure 2.

The Heating Plant depicted in Figure 4 is the last macro-level component that is included in the whole Dymola model. It is equipped with a temperature reset control (circled in red on the figure), that is in charge of adjusting the temperature of the hot water supplied by the boiler and circulated in the primary system towards the distribution system. Such adjustment is varied according to the actual trend of outdoor air temperature (which is sensed in real-time by a sensor). The adjustment parameters were defined as inputs in the “PID_Boi” component displayed at the bottom of Figure 4. The other components between the “PID_Boi” unit and the boiler simulate safety devices that switch off the boiler if either the supply water temperature rises up to 90°C, or the pump in the main circuit is not in operation.

Then, the overall heating energy consumption estimated by this model was compared with the real consumption mentioned in paragraph 3.2 (Figure 5).

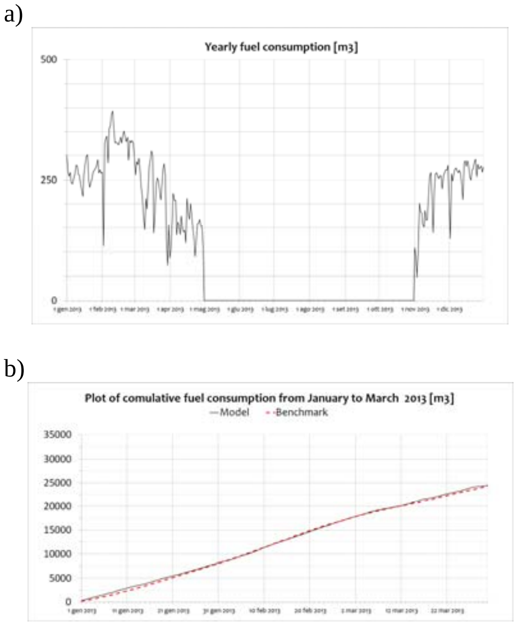


Figure 5: yearly fuel consumption by the boiler (a) and cumulative plots from January to March 2013, used for validation (b).

Table 2: Validation of the benchmark

Date	Measured fuel consum. (m^3)	Estimated fuel consum. (m^3)
2013,Jan 10th	2648.82	2091.46
2013,Jan 25th	3872.47	4226.69
2013, Feb 5th	3020.91	3094.36
2013,Feb 15th	3446.81	3397.00
2013, Feb 25th	3315.41	3172.51
2013, Mar 5th	2405.86	2202.02
2013,Mar 15th	2246.76	2063.37
2013,Mar 25th	2349.09	2318.26
	MBE	-3.28 %
	CV(RMSE)	9.22 %

It can be noticed that no fuel consumption due to heating was experienced during the summer. The validation was performed in the first three months of the year 2013 and was performed by means of the indicators suggested by reference standards. Mean Bias Error (MBE) and Cumulative Variation of Root Mean Squared Error (CVRMSE) were calculated using the formulae [14]:

$$MBE = \frac{\sum_{i=1}^{N_P}(M_i - S_i)}{\sum_{i=1}^{N_P} M_i} \tag{3}$$

$$CVRMSE = \frac{\sqrt{\sum_{i=1}^{N_P}\frac{(M_i - S_i)^2}{N_P}}}{\overline{M_P}} \tag{4}$$

where M_i is the list of measured data, S_i is the set of simulated data, N_P is the size of the database and the average value of the measured data is $\overline{M_P}$. It can be noticed from Table 2 that MBE and CVRMSE are well below the maximum thresholds suggested by ASHRAE, that is 5% and 15%, respectively.

Hence the reference model (i.e. benchmark) was considered as successfully calibrated.

4.2 The PID controlled model

PID controllers are conventional and well-known control systems. As a consequence, a detailed description of their mechanism and tuning methods falls out of the scope of this paper. However, a description of their implementation in the Dymola model for the case study will be provided, in order to clarify the reasons that led to the design and integration of the supervisory fuzzy control.

Besides the PID control that constitutes the temperature reset control at the boiler level and that was embedded even in the benchmark, additional PID controllers were implemented. Two of them were accommodated to adjust the opening rate of the two three-way mixing valves that control water supply temperature values of the two mains in the secondary circuit, and an additional PID controller was added to drive the opening of the three-way valves that regulate the water flow through the radiators in every thermal zone. Figure 6 shows that a set of PID components has been added aside each valves in the heating plant, differently from the benchmark version that is shown in Figure 4.

All the parameters of the PID controllers were estimated by means of the so called “one shot tuning” or “tuning on demand” [15]. This technique can be applied any time the control domain cannot be described by means of a set of mathematical formulas.

As a result, the consumption determined by this new model, whose mixing valves are controlled by PID devices, are lower than the benchmark (Figure 7). Moreover, the comfort conditions are improved even if the local PID controllers are not able to maintain the desired setpoint of 20°C (i.e. required by the mandatory legislations for healthcare buildings) and the internal temperature fluctuates around it as soon as an unexpected external disturb occurs. It was also found that when valves are driven by PID controllers, their activation is smoothed, that is the rate of variation from the position they hold for longer was decreased with respect to the benchmark. In other words, their variations were smoothed. The overall reduction in terms of fuel consumption after the first three months amounts to 5.8 %.

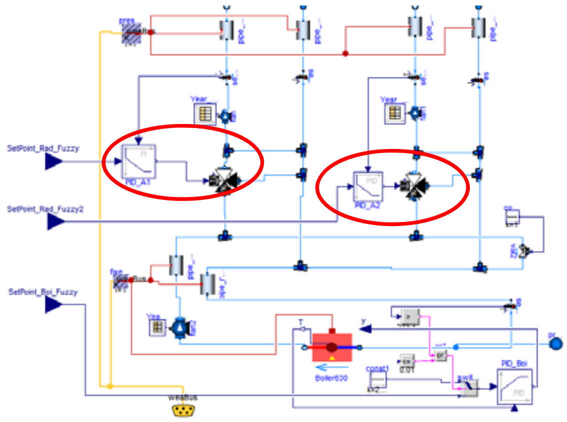


Figure 6: new version of the heating Plant component, where a PID controller was embedded per each mixing valve (circled in red).

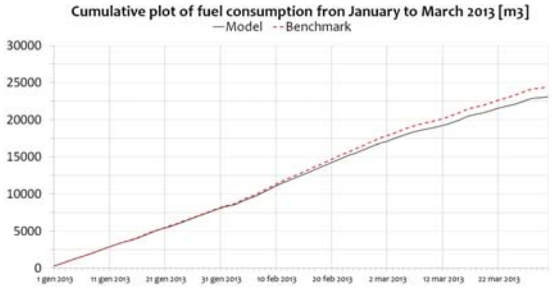


Figure 7: reduction of energy consumption in the first three months of the simulation year.

4.3 The fuzzy controlled model

The fuzzy logic was integrated in the model, in order to assess the potential of a supervisory control, considered as the best solution to overcome the limitations posed by the distribution sub-system of the heating system in block A1. It is served by a two-pipe vertical distribution system, that is unable to differentiate water flow rate and temperature according to the specific needs of each thermal zone. Hence, a conventional local PID control cannot guarantee the best performance, because a trade-off between the several zones can be obtained just in case a supervisor is installed. Moreover, the situation is different in block A2, because its distribution sub-system serves one manifold station on each floor. So, the fuzzy logic was developed as a supervisor, while the local PID controllers in each thermal zone were kept unvaried with respect to what described in sub-section 4.2. Two fuzzy supervisor controls were developed: the first one controlled block A1 and the second one controlled block

A2. Both of them got as input variables the measured crisp variable values: error and ambient temperature. Both fuzzy control units provided the following control signals as outputs: opening rate of the valve located upstream the pumps of the secondary circuits and temperature of the water supplied by the boiler. Considering that two signals were sent by the two fuzzy units at each iteration step, the highest temperature signal was considered as valid to drive the boiler. The linguistic variables associated to the error and ambient temperature are: Negative, Neutral and Positive and Small, Medium, Big respectively. Both the output linguistic variables (PID of the boiler and PID of the mixing valves) were given three states: Small, Medium and Big. A new fuzzy component was integrated in the heating units component of the Dymola model (circled in red in Fig. 8-a), whose architecture is provided in Fig. 8-b.

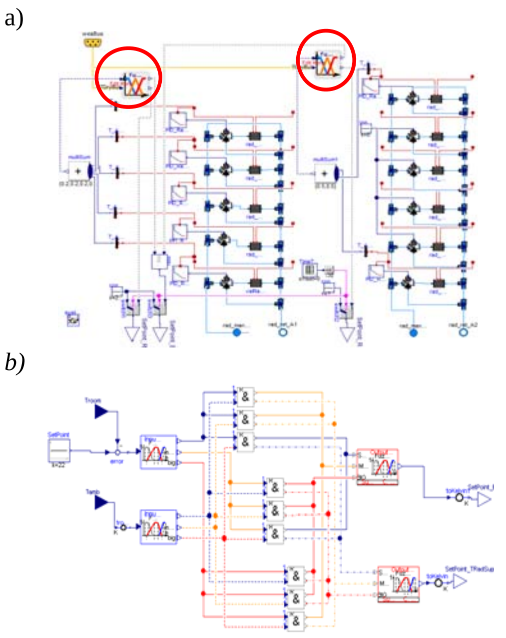
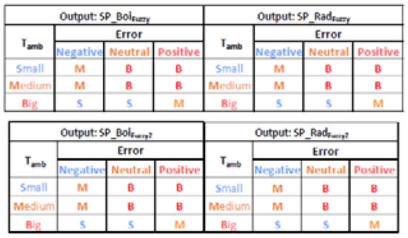


Figure 8: fuzzy component integrated in the Dymola component (a) and its architecture (b).

The component shown in Figure 8-b implemented all the components needed to perform the fuzzy inference (i.e. input and output variables, membership functions and rules) based on the set of rules shown in Figure 9. The defuzzification process was based on the COA approach and the control signals were sent to the heating plant component in Dymola, that was modified accordingly.

As the local PID control in paragraph 4.2 was unable to keep the required setpoint within all the rooms, the comparison was set at a 19°C setpoint, still within the mandatory legislation thresholds. The use of fuzzy logic allows to maintain the desired setpoint without significant variations, achieving a remarkable comfort improvement (Figure 10). Moreover, it determines a reduction in energy consumption with respect to the local PID control estimated as 3.6% (Figure 11).



Output: SP_Bol$_{Fuzzy}$				Output: SP_Rad$_{Fuzzy}$			
T_{amb}	Error			T_{amb}	Error		
	Negative	Neutral	Positive		Negative	Neutral	Positive
Small	M	B	B	Small	M	B	B
Medium	M	B	B	Medium	M	B	B
Big	S	S	M	Big	S	S	M

Output: SP_Bol$_{Fuzzy2}$				Output: SP_Rad$_{Fuzzy2}$			
T_{amb}	Error			T_{amb}	Error		
	Negative	Neutral	Positive		Negative	Neutral	Positive
Small	M	B	B	Small	M	B	B
Medium	M	B	B	Medium	M	B	B
Big	S	S	M	Big	S	S	M

Figure 9: Fuzzy rules in the inference engine.

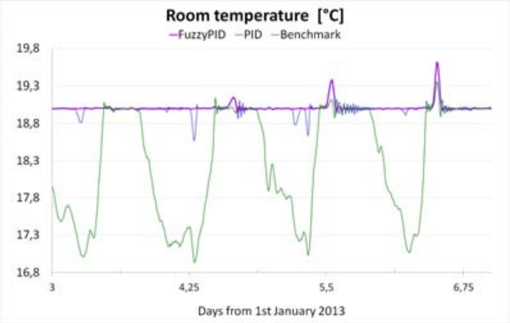


Figure 10: temperature in a representative room determined by fuzzy supervisor (magenta), PID control (blue), the benchmark (green).

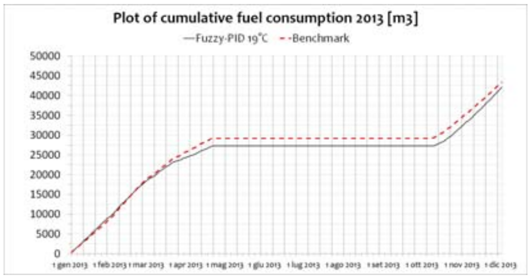


Figure 11: energy consumption reduction due to the fuzzy supervisory control.

5 Conclusions

This paper tackled the problem of HVAC systems improved regulation in order to enhance the energy performances of existing public buildings by means of low-cost hardware improvements and advanced logics.

The benefits of applying a fuzzy supervisory control system were tested on the heating plant of a small hospital, taking advantage of a lumped parameters model simulated in Dymola environment, which has been previously validated through comparison with real consumptions.

The proposed control strategy exploits the fuzzy logic to overcome the limitations pointed out by the implementation of a conventional PID control on a two-pipe vertical distribution system. This kind of plant cannot differentiate water supply temperature in the various thermal zones. The introduction of a fuzzy supervisor actually allows reaching and maintaining the desired thermal comfort, as opposed to the scenario with local PID controllers, which gives back a greater energy saving but also a quite changeable indoor temperature. When fuzzy logic and PID control are compared and applied on the same scenario, that is setting the request internal temperature at 19°C, the fuzzy logic provides a meaningful thermal comfort improvement in addition to energy saving.

The benefits resulting from the implementation of a low-cost control strategy based on logic and simple hardware components as the one shown in this research are easily replicable. Thus, given the large number of old buildings scattered on our territories similar to the one examined, remarkable energy savings could be attained on the overall.

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