A Lumped Parameter Model For Dynamic Simulation Of Energy Control Policies Applied To Small Public Buildings

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ABSTRACT

As public buildings are responsible for considerable amounts of fuel consumption, public administrations are encouraged to adopt interventions for energy requalification of their real estates. In particular, low-cost energy requalification with high return on investments is a good opportunity when resource shortage hampers the adoption of expensive refurbishment. However, in order to properly plan such a process, a detailed energy audit must be carried out. In addition, a reliable model of the audited building is needed to breakdown the whole energy consumption and to simulate prospective energy savings from candidate requalification strategies. To that purpose, this paper will describe a new-generation Dymola™ based simulation approach, that is reliable enough for assessing the dynamic behaviour of public buildings, even when non-standard systems and heat transfer phenomena are involved.

This model provides users with two main advantages: on one hand it facilitates the simulation of interacting physical phenomena (e.g. fluid-dynamics, thermal exchange etc…), on the other hand it allows to simulate even advanced control of existing HVAC systems. This last feature is not typical of standard energy simulation software programs. In addition, it is needed when we deal with low-cost energy requalification, because it is usually aimed at the enhancement of existing regulation devices, so that their behaviour must be simulated in order to find out the best customized control policy. Finally, the paper will assess energy savings which can be obtained through the improvement of the HVAC system's control policy for a case study relative to a small public building, that is used as a community clinic.

Keywords –
Energy requalification; lumped parameter model; low-cost control of heating systems.

1 Introduction

The building stock represents one of the biggest energy consumers, and renovating existing buildings asks for a very detailed energy baseline. In particular, complex strategic buildings, such as public buildings owned by public administrations, ask for the development of a detailed consumption breakdown, in order to accurately analyse the actual causes of current consumption and in order to prospect possible improvements [1]. To this aim, their actual operation must be carefully simulated by means of tailored models. This is the only way auditors can accurately survey, diagnose inefficiencies and quantify energy savings that can be achieved in actual operational conditions. Such evaluations need the adoption of dynamic simulation tools, that are presently under wide consideration by researchers and practitioners [2]. Indeed, they are more accurate than static calculation procedures traditionally used for plant sizing. In a Malaysian public hospital, the energy audit process included collecting information about the hospital's equipment and its energy consumption. As a result, tailored energy saving measures were identified and implemented (e.g. adoption of variable speed drives for electrical motors) [3]. This procedure is compliant with suggestions from the European standard series EN 16247 [4]. However, collecting a complete picture of energy consumption patterns is too often challenging, despite it is well known that the availability of information about water, electric power, gas and heat consumption are very critical to the successful implementation of the energy audit phase. For that reason, in China a number of research projects focused on the development of a building energy consumption platform in support of actions fostering energy efficiency improvements [5].

In this paper, we will focus on a recurring Italian scenario, that is relative to the building stock built around the 1970s and 1980s and we will show a new simulation approach, that can be useful to design intelligent control approaches. In particular, small sized hospitals (e.g. community clinics) are numerous and offer great opportunities for low-cost energy saving enhancement. On the contrary, more expensive interventions are reserved to acute and big hospitals, because these solutions allow to pursue high overall energy savings per hospital. In order for the requalification of small hospitals to be cost-effective, a better management of those hospitals coupled with low cost renovations for energy efficiency may determine meaningful benefits. This is also the case of the community clinic under consideration in this paper.

2 The case study

2.1.1 General description

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, while the second and more recent block 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. The main heating plant was built on the third level below grade, while the next floor upwards hosts the radiology division and some services; the emergency service is located in the first level below grade; offices and clinics are accommodated on the ground level; the physical medicine ward occupies the first level. At the time this study is referred to (i.e. beginning of 2013), level no. 2 hosted a clinic ward. Level no. 3 (i.e. the attic) was unoccupied.

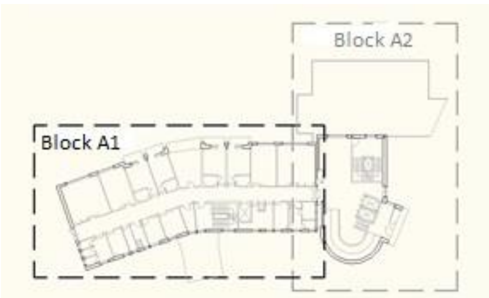

Figure 1. Plan of the community clinic considered as a case study.

2.1.2 Breakdown of energy consumption

As a first step, energy consumption bills were examined. The two kinds of fuel used by the building were: gas methane and electrical power. Both of them were invoiced monthly over the year, so it was possible to estimate the actual consumption experienced every month, whose picture provided the degree of variability during the year (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 for winter months. This assumption is confirmed by the Italian Standard D.P.R. 412/93 [6], 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 (Table 2) was charged to the heating system, thus estimating the monthly distribution of gas methane requested for heating purposes (Table 2).

Table 1 Total consumption of gas methane

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

Table 2 Breakdown of gas methane consumption

	Fuel for heating (m^3)		*Fuel for hot water (m^3)*	
Month	**2012**	**2013**	**2012**	**2013**
Jan	16879	6026	1939	1512
Feb	17817	9781	1939	1512
Mar	8201	6454	1939	1512
Apr	6792	3802	1939	1512
May	0	0	2428	1826
Jun	0	0	1880	1790
Jul	0	0	1826	1474
Aug	0	0	1641	957
Sep	0	0	1919	1050
Oct	1555	0	1939	1512
Nov	4086	3341	1939	1512
Dec	9088	6434	1939	1512
TOT.	64418	35835	23267	18138

As a second step, we analysed the electrical power consumption, which was divided into the sub-categories pertaining to "auxiliary consumption for hot water", "auxiliary consumption for heating" and "building", that – in turn - sums up "lighting" and "facilities". In order to evaluate the electrical power consumption due to auxiliary equipment, lighting and facilities, their behavioural models were assumed, and considered along with the power of each device and its operational time. The corresponding information was collected by means of surveys and interviews to technical personnel dedicated to maintenance.

Then, all these consumption figures (i.e. fuel consumption for hot water and for heating; electrical power consumption for heating auxiliary, for hot water auxiliary, lighting and facilities) were converted into primary energy, using the following conversion factors:

1. in the case of gas methane, the Lower Calorific Value (LCV) is 34.54 MJ/m^3 = 9.59 kWh/m^3 (according to the Italian recommendation AEEG n. 103/03 [7]), which is the amount of heat released by burning a unit of fuel; also, 1kWh$_{fuel}$=1kWh$_{prim}$;
2. in the case of electrical power, 1 Kwh$_{el}$ = 2.34 KWh$_{prim}$ (conversion factor from auxiliary electrical energy to primary energy, according to the Italian recommendation AEEG n. 103/03 [7]).

Thanks to these factors, the fuel's consumption estimations were converted into primary energy and the total primary energy relating to heating, hot water and building were derived as follows:

3. total primary energy for heating was derived as the sum of primary energy of the auxiliary heating system and the primary energy used for heating;
4. total primary energy for hot water was derived as the sum of primary energy of the hot water system and the primary energy used for hot water production;
5. the primary energy of the whole building was derived straight from the conversion of the building's electrical power consumption into primary energy.

As a result, the total primary energy needed by the community clinic in 2012 and 2013, including primary energy for heating and primary energy for hot water, resulted to be distributed over the year as shown in Table 1.

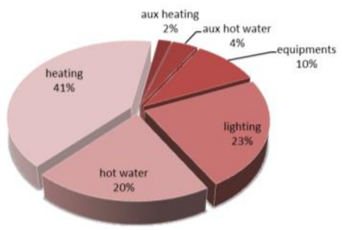

Figure 2. Breakdown of the community clinic's whole consumption in 2013.

According to the European Standard UNI EN 15217:2007 [8], the building performance level is assessed through the Energy Performance (EPi), that is equals to 51.65 kWh/m^3 in 2012 and equals to 38.58 kWh/m^3 in 2013.

With all this information available, the actual scenario of San Elpidio a Mare's breakdown was summed up for the year 2013 (Figure 2). Percentages shown in this figure represent the weight that each contribution provides to the hospital's whole consumption of primary energy, considering the actual market price of gas methane and electricity. More specifically, the pie chart splits the global building consumption into six categories. The two most influential ones are heating and hot water, which weighs 41% and 20% out of the total, respectively.

3 Simulation and assessments of energy savings

Considering that the control policy and low cost refurbishment object of this paper was aimed to enhance the efficiency of the clinic's heating system, the model described in 3.1 was validated with respect to the invoiced heating consumption of the building in the same period, as described in sub-section 3.2. Finally, energy savings that can derive from the application of low cost and advanced control policies will be presented in sub-section 3.3.

3.1 The simulation model

The new energy model approach, that we want to showcase in this paper, was developed by means of the Dymola^{TM} development platform, which is based on the Modelica programming environment.

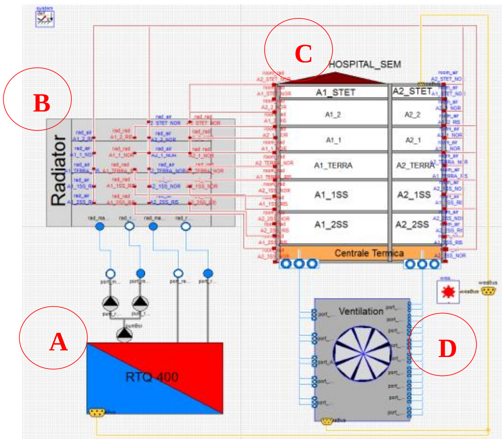

Figure 3. Top layer of the Dymola model

This type of modelling is superior than standard approaches (e.g. whole building simulation) in that it allows users to model in detail and control any device affecting the building's consumption. The "Buildings library v1.3" was used, that is a library made of components specifically tailored for building simulation [9]. Modelica^{TM} is an object-oriented, equation based language to conveniently model complex physical systems containing, e.g., hydraulic, thermal, control and electric power. Figure 3 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 (A), the heating units (B), the indoor space (C) and the ventilation system (D). Each of this top level's components was further detailed into lower levels of the simulation model.

The first top level component, that is the main heating plant (labelled "A" in Figure 3), includes the active boiler (i.e. RTQ 400 with a power of 630 kW), which supplies water through a climatic control system. The lower level's representation of this component is depicted in Figure 4. Here, the pump of the primary circuit (constant speed pump, whose power is 870 W) and the two pumps supplying water to the heated thermal zones (a pump with a power of 1350 W serving the A1 block, and a pump with a power of 375 W which serves the A2 block) were connected to the main plant. They work at their maximum rate over the whole heating period throughout the occupation hours of each day. Regulation is provided by two three-way motorized mixing valves, that are installed on the two supply mains, the first one serving block A1 and the second one serving block A2. They regulate the temperature of supply water by mixing return water with the hot supply water, heated up by the main plant. This process is controlled by a temperature sensor installed in each of the supply mains, as a feedback.

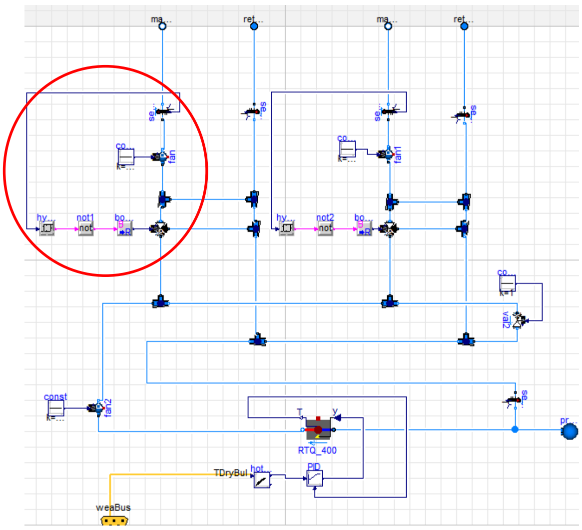

Figure 4. The sub-model of the heating system.

For the sake of clarity, the red circled component marked on Figure 4, is zoomed as Figure 5. A "hysteresis" class is used to constrain the supply water temperature between 55°C and 60°C. The feedback coming from the temperature sensor (called "sens_T_mandA1" on the same figure) installed in the two water supply mains is used to regulate the three-way motorized valve (red circled on the same Figure), that is a "three way equal percentage linear". In other words, it presents linear opening characteristics between the two input ports. Thus, the opening of the input ports was managed according to the actual need while simulation was running: if the supplied water was getting too hot (i.e. getting close to the upper supply water's temperature limit) the input port's opening connected to the main loop (whose water is heated up by the main boiler) was reduced, so as to mix a higher amount of water from the return line. On the contrary, when the supplied water was getting cold, the input port's opening rate connected to the main loop was increased, so as to supply mainly the water heated by the central plant that is being circulated in the main loop.

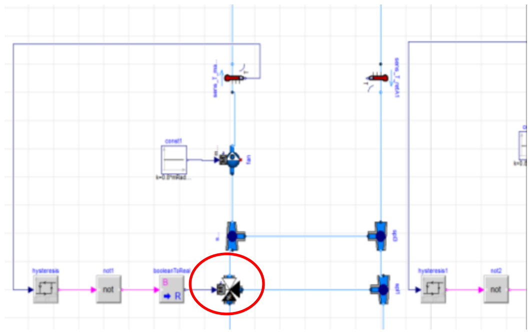
Figure 5. Zoom on one of the hysteresis cycles that regulate the water supply temperature for blocks A1 and A2.

The heating units (B) were modelled through the elements available in the library and called "Radiator". Their water content was regulated by the so called "TwoWayEqualPercentage" valve classes. Characteristics implemented in the model match with those ones typical of a traditional cast iron radiator and each of them has a power equivalent to the sum of the power of the radiators that are in the thermal zone to which the component is connected to. So far, the hospital is not fully heated, so the two-way valves were used either to keep the radiators turned on, or to switch-off radiators according to the real conditions of use.

The indoor space (C) was organized into thermal zones. Each zone was modelled through the "Room" component from the library. As a consequence, 16 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. More details on this issue will be provided in sub-section 3.2. Each “room” (i.e. thermal zone) of the Dymola model was assigned the corresponding thermal characteristics of the envelopes (e.g. thermal transmittance was assumed to be included 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 $W/m^2·K$ and 2.064 $W/m^2·K$) and of the windows (assumed between 2.942 $W/m^2·K$ and 6.281 $W/m^2·K$).

The ventilation system (D) is the last macro-level, which models the air airflow through the windows, that includes both natural air change (due to air leakages) and the windows permeability. These values are set as the sum of the contribution of natural air change and windows permeability for the heated zones (estimated in 0.366 vol/h), while for the non-heated zones only the windows permeability was considered.

3.2 Simulation of the baseline and calibration

The simulation model already described in sub-section 3.1, was then tailored to the community clinic’s actual conditions relative to the month of January 2013. To this purpose, some parameters were updated. Due to this choice, calibration was performed by means of a comparison with invoiced consumption in the same period.

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 January 2013.

The whole building was made up of 14 thermal zones, some of which were heated while some others were not. According to a survey carried out at the beginning of 2013, five heated thermal zones belonged to block A1 and one heated thermal zone belonged to block A2 (Table 3). One non heated thermal zone belonged to block A1 and seven non heated thermal zones belonged to block A2 (Table 4).

Table 3 List of heated thermal zones

Heated area	Net surface (m^2)	Gross volume (m^3)
A1 2SS	475.289	2185.00
A1 1SS	486.886	2240.20
A1 T	487.718	2240.20
A1 1	481.277	2260.70
A1 2	480.941	2208.00
A2 2SS	142.535	669.75

The subdivision of the whole building into heated and non heated thermal zones, was performed in accordance with their use (e.g. hours of the working day every zone is occupied) and level of the building where it was located. Hence, heating times and boundary conditions (e.g. internal thermal gains) were uniform all over each zone. In addition, the geometric and physical characteristics of every building component of the thermal zones (e.g. walls, floors, windows, thermal bridges) could be accurately simulated. The codes listed in Table 3 and Table 4 refer to the type of block (i.e. A1 or A2) and the level where every zone is located (e.g. 1SS means 1 below grade and 1 means “level 1”), while one or more digits at the end of the codes refer to the use of the zone, whenever further detail may be needed.

Table 4 List of non-heated zones

Heated area	Net surface (m^2)	Gross volume (m^3)
A1 STET	510.000	1351.50
A2 1SS	201.000	944.70
A2 2SS	276.500	1299.55
A2 3SS	760.000	3572.00
A2 T	201.000	944.70
A2 1	201.000	944.70
A2 2	201.000	944.70
A2 STET	158.000	418.70

It can be noticed that most of block A1 was heated, while just a small portion of block A2 was. This situation is expected to change in few years, when the whole hospital will be made operational. But the purpose of our model was to accurately depict the actual operational conditions over the time period relative to our analysis.

Other parameters that were customized to the period of simulation are represented by internal gains. Despite they are equal to 7 W/m^2 on the average, as already mentioned in sub-section 3.1, their representation in the model was differentiated according to the thermal zone of interest. In every thermal zone, it was given as the sum of the gains generated by the daily average number of people, by the number of lighting fixtures and by the total power emitted by the equipment. Surveys and interviews allowed us to cluster those gains according to their nature and quantify their intensities. Gains from people and equipment were estimated according to literature and technical data. Gains from lighting were derived from datasheets of manufacturers. These gains were simulated by means of classes belonging to the component C (as depicted in Figure 3).

In particular the class element “intGai4” in Figure 6-a was split into three sub-classes: “intGai_people1”, “intGai_equip1” and “intGai_light1”, as shown in Figure 6–b. These values are all expressed in thermal power and are sent as inputs into the room model, that in this case is labelled “A1_2_RIS”. All the thermal zones were similarly modelled, and the associated gains match with the sum of the contributions generated by every room that belongs to the thermal zone.

Another relevant control that is installed in the building is the climatic control of the main circuit’s loop. Climatic control at the plant level, means that the temperature of the hot water supplied by the boiler towards the distribution sub-system is varied according to the actual trend of outdoor air temperature (which is sensed in real-time by a sensor). The adjustment parameters are set according to an algorithm which is calibrated on the thermal characteristics of the building.

Again, this parameter is part of the "A" top level's component, i.e. the heating plant. The whole excerpt is depicted on Figure 7, whose group is made of the following classes: the "WeaBus", that provides weather data; the "HotWaterTemperatureReset", that computes the best supply water temperature according to sensed weather conditions and to an algorithm that is preliminarily defined in the component; the "PID" component, that adjust the power rate input of the boiler according to the desired water supply temperature, as required by the "HotWaterTemperatureReset" component.

a)
b)

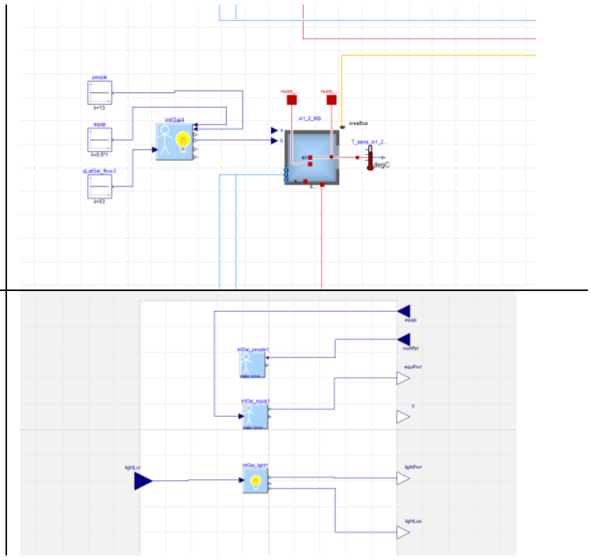

Figure 6. The sub-model used to simulate the internal gains (a) and its subdivision into the several types: people, equipment and lighting (b).

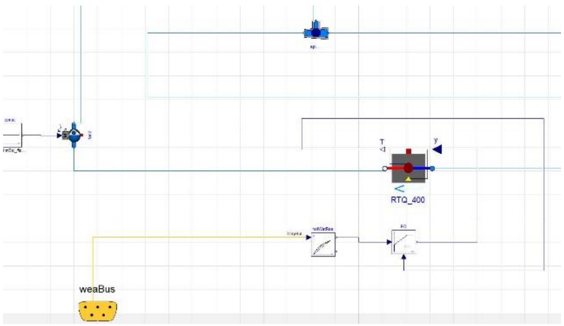

Figure 7. Class components used to simulate the climatic control.

Once the model, including the afore described control elements, was simulated over the month of January 2013, estimated overall consumption was calculated for the month of interest. Then, deviations from measured consumption resulted all to be within the thresholds requested by ASHRAE 14 standard [10], which states that any model shall have a NMBE no higher than 5% if monthly data are used. The calibration phase started through the calibration of some of the input parameters. It was based on the adjustment of the top and bottom limit temperatures in the two hysteresis element in Figure 5, of the parameters of the radiators, that determine the relationship between supply water's temperature and flow rate and ambient temperature and power released into the room. Finally, some adjustments on the water flow rate of the two pumps supplying water to blocks A1 and A2 were done. Thus, the preliminary results achieved so far are good according to the definitions of the standard ASHRAE 14:2002 [10], as shown by Figure 8.

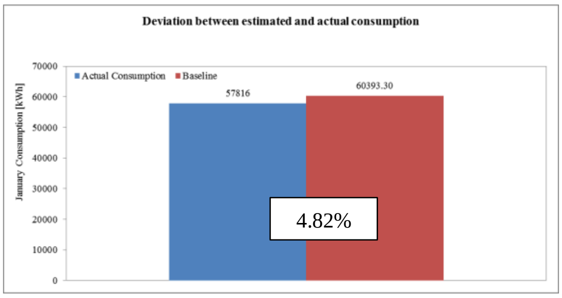

Figure 8. Results from the calibration of the model.

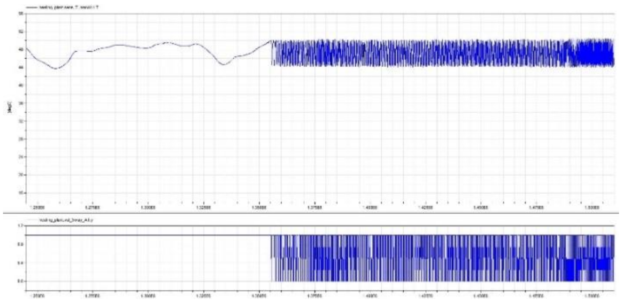

Figure 9. Supply water's temperature supplied to block A1 over three days in January and corresponding valve's opening percentage.

Finally, Figure 9 depicts the plot of the modulating supply water's temperature and of the valve's opening percentage, that is in charge of mixing the water flows from the supply and return lines of the heating system. The frequency of variation is dependent on the use and external actions.

3.3 Description of the requalification strategies and assessment of energy savings

The presently installed regulation sub-systems were enhanced by means of the following additional control devices:

-at the thermal zone level, the two-way valves feeding radiators were replaced with a closed-loop regulation sub-system made up of motorized two-way valves, one temperature sensor to detect indoor temperature and a hysteresis device that control the valve to maintain the thermal zone’s temperature at about 20°C, according to Figure 10-a);

- the motorized three-way valve depicted in Fig. 5 is driven by the average value of indoor temperature in each block instead of water supply temperature, like in the baseline (Figure 10-b).

For the sake of clarity, in Figure 10 the two control systems are depicted.

a)

b)

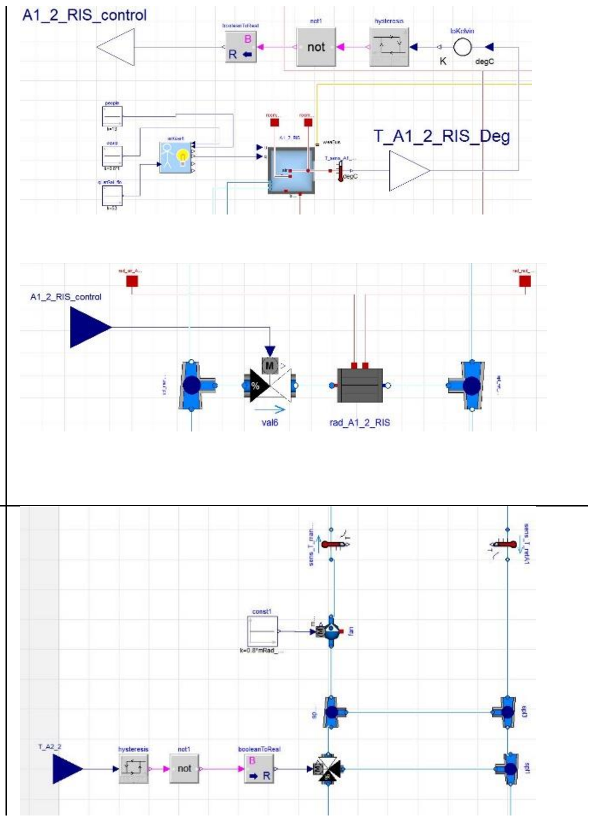

Figure 10. Control systems installed at the thermal zone level and connected to the radiator (a), and logics of the system controlling the motorized three-way valve (b).

To be noticed that while the distribution system in block A2 is split into the several thermal zones and levels that are really served, in the case of block A1 there is no subdivision, but all the radiators are served by the same supply line. Hence, water supply temperatures could not be differentiated according to the thermal zone in block A1. As a consequence, the environmental parameters of level no. 2 were taken as the driving ones, because that level hosts the medicine ward, that is the most critical division in the hospital.

An economic appraisal of the total amount needed to perform the described enhancement of the regulation system is provided by Table 5. It reports the bill of quantities and economic estimation of the major types of devices to be installed, including manpower and health and safety costs. The total cost of the regulation system’s improvement in the hospital was estimated to be equal to 9082 €.

Table 5 Bill of quantities and cost estimation for the low-cost requalification of the hospital.

Description	**U.O.M.**	**Unit Price**	**Dimension**	**Activity Cost (€)**
Indoor temp. probe	no.	119.09	12	1429.08
Interface valve/com. net.	no.	123.07	13	1599.91
Communication devices	no.	160	15	2400
Room valve towards block A2	no.	319.07	6	1914.42
Room valve towards block A1	no.	347.77	5	1738.85
Total Cost				**9082**

Then, another simulation relative to January 2013 was performed with all the regulation enhanced as described in the first part of this sub-section. Figure 11 compares the consumption estimated for the scenarios pre- and post- requalification. It can be noticed that an overall saving as high as 5250 kWh/month is expected, that means 450 €/month, if the fuel cost is equal to 0.823 €/m^3.

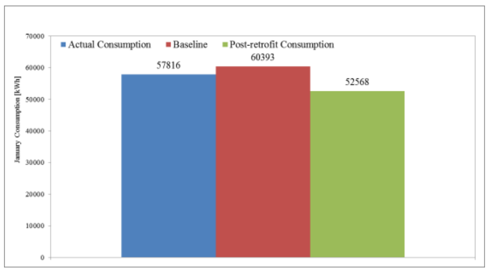

Figure 11. Comparison between the estimated consumption prior to requalification and the post-requalification consumption.

Once a 5.5% interest rate is assumed on this investment, the discounted payback period for the low-cost requalification described above will be 5 years, considering that the heating system will be turned on for 5.5 months/year.

Finally, Figure 12 depicts the indoor air temperature of the controlled thermal zone in block A1 and the power supplied by the boiler in the same period.

It can be noticed that the closed-loop regulation benefits are evident. Indeed the indoor air temperature values fluctuate between 19°C and 21°C obtaining the average temperature right as expected (Figure 12-a). In addition, in order to have a more stable behavior of the heating plant, the boiler works at lower loads (Figure 12-b) while achieving the energy savings seen before.

a)

b)

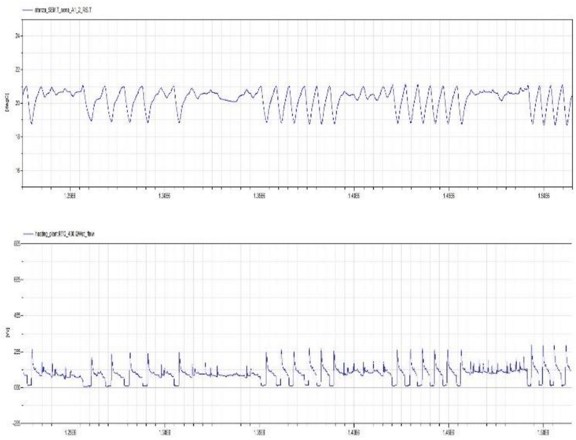

Figure 12. Plots of the indoor temperature in the controlled thermal zone of block A1 (a) and the power supplied by the boiler (b) during three days.

4 Conclusion

As the old building stock is responsible for a considerable amount of energy consumption, several levels of strategies must be set up, in order to reduce the overall energy need. Owners of a high number of buildings, such as public administrations, prefer to retrofit first the biggest buildings, so as to get considerable savings from each refurbished building. But the larger a retrofit action is, the longer the time needed to accomplish it is. Meanwhile, less demanding retrofit actions might be suggested for the remaining stock made of small buildings, because a high number of them is usually scattered over territories. This is the case of the many, even if small, community clinics usually found in regional territories. So, this paper showed the great reliability of the advanced simulation software program Dymola/Modelica, that allows to model even the non-standard control policies that are aimed at an enhanced regulation of existing sub-systems. In this case, the adoption of low cost retrofit of buildings for energy refurbishment, with particular focus on the improvement of their regulation system, is a very good and feasible option. When a huge number of buildings of the same kind are enhanced in this way, the overall savings is quite high.

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