Analysis of energy efficiency measures on envelope and control systems: case study for an existing building

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Abstract

The buildings dating back to the Italian economic boom of the 60s and 70s are the biggest part of the national building heritage. In general they have an envelope with very poor thermal insulation and a central heating system with high energy consumption, sometimes due to the lack of a proper control system, obsolete components and a not balance pipe network. This group of buildings is one of the first targets to be addressed through building renovation and improving plant.

Energy retrofitting actions is the main direction not only to provide a reduction in CO_2 emissions and money saving but also to achieve thermal comfort for a large number of families.

In order to reach both these objectives, a pipe balancing and proper control systems must accompany every kind of envelope upgrading.

This paper deals with the interaction between the envelope refurbishment and the optimization of the plant control system in a typical 60s-70s Italian residential multi-floor building served by a central heating system, focusing on a single flat.

After a proper calibration of the model, based on experimental measurements of the internal temperature and operating conditions of the heating plant, the dynamic simulation assessed through EnergyPlus was used to analyze the efficiency of different control systems to improve the energy performances: use of climatic curve control, zone control with ambient thermostat or thermostatic valves, and different proportional bands.

Simulation results indicate high energy savings.

1. Introduction

The use of building automation control systems to improve energy efficiency of heating systems and thermal comfort inside buildings has become an increasingly important over the years. In many buildings from the 60s and 70s, the water in the pipe network is usually set to 75-80 °C; consequently, the radiators were "sized" with these temperature values. Renovation works made in single apartments over the years, and different thermal loads for rooms with different solar exposition, resulted in discomfort conditions and high energy consumption. To optimize the control systems of these extremely energy-intensive, different systems of thermoregulation were compared. In the process of choice of systems related to energy conservation, it is essential to support energy-efficient design decisions with the help of dynamic analysis. This type of analysis can justify the choice of such interventions.

The dynamic energy simulation is a time-dependent simulation, which allows us to estimate the actual thermodynamic behavior of the apartment. The effect of the outdoor climate conditions and of the occupants' behavior, both measured hour by hour, add complexity to the problem and make it possible to predict building performance.

2. Description of the case study

2.1 The building envelope

The apartment under study is part of a linear building located in the extreme northern suburbs of Bologna, part of the pole settlement P.E.E.P. of Corticella, dated 60/70, served by a central thermal plant and a district heating network.
The opaque walls are of three different types: bearing structure of reinforce concrete, internal and external masonry walls, and precast concrete panels on the façades characterized by ribbon windows. These are singe glazed, with non-thermal break aluminum frame.

Fig. 1 – External view of the building (north façade)

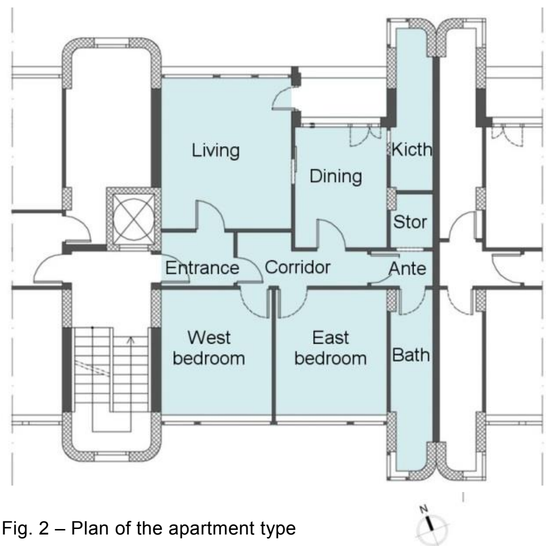

Fig. 2 – Plan of the apartment type

All data, such as the geometry and the components of building envelope, were known; otherwise, thermal properties of different building structures, in the absence of original data, were calculated according to actual technical standards: UNI/TS 11300-1, UNI 10351 and UNI 10355.

2.2 The heating plant

The terminal units of the heating plant are convective heaters (Fig. 3). Due to the impossibility to know the effective thermal power output, each terminal was sized according to the calculation procedure required by UNI EN ISO 12831.

Fig. 3 – View of an installed heater

The heaters are units with low thermal inertia, which can quickly satisfy changes in thermal needs of the room, working predominantly by natural convective heat transfer.
Terminal units were considered to be fed with a rated average water temperature of 70°C and sized according to a thermal gradient of 50°C.

3. Actual situation: modelling and calibration

3.1 Energy Modeling

The dynamic simulations were performed through 'EnergyPlus' (version 8.1) software (energy calculation) and the corresponding 'Legacy OpenStudio' SketchUp plug-in (geometrical input data, see Fig. 4).
After the construction of the model, the comparison between simulation data and experimental measurements allowed us to calibrate the building-plant system.

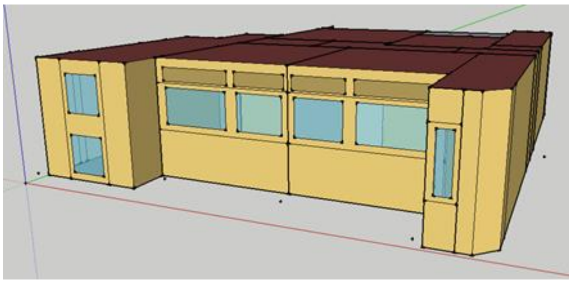

Fig. 4 – 3D model of the apartment

Afterword, simulations were performed to evaluate the energy consumption of the plant in the actual configuration, and compare it with the technical solutions proposed to improve the efficiency of control systems.

3.2 Calibration of the model

The calibration of the model was not easy to achieve due to the uncertainty of some features of the building envelope and the heating system. Due to the inability to carry out direct measurements of energy consumption, calibration was performed based only on temperatures, moving by successive approximations.
A campaign of measurements was conducted, monitoring the following parameters for each room:

- indoor air temperature at the center of the room, at an height of 1,20 m;
- temperature of the air coming out from the terminal unit.

Furthermore, we asked people living in the flat to record their time staying in the various rooms and the aeration duration intervals.
Data analysis suggested reducing the rated terminal units power outputs compared to those calculated according UNI EN ISO 12831 of more than 40%, bringing to values reported in Tab. 1.
A qualitative trend matching of measured and calculated internal temperatures, and their punctual deviations within 1°C when plant is on, were deemed satisfactory for the purpose of the present study (see Fig. 5).

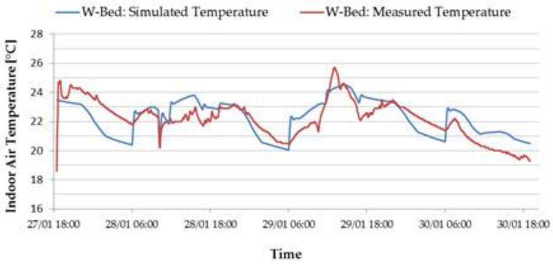

Fig. 5 – Comparison between measured and simulated indoor air temperature in west bedroom

Table 1 – Size of terminal units

Room	P,unit	M'	M',ratio
	[W]	[kg/s]	[%]
Dining	655	0,011565	11,2
Kitchen	983	0,023480	22,8
Living	1056	0,025430	24,6
West bedroom	655	0,011565	11,2
East bedroom	655	0,011565	11,2
Bathroom	819	0,019570	19,0
Ante-bathroom	0	0,00000	0,0
Storage room	0	0,00000	0,0
Corridor	0	0,00000	0,0
Entrance	0	0,00000	0,0

4. Control system

In order to understand how to model a more properly controlled system for radiators with thermostatic valves, it is worth analysing these two basic components, for which EnergyPlus does not have explicit objects for modelling.

4.1 Plant terminal units performances

4.1.1 Product standard

In plant design, radiator and convector performance is regulated by a specific product standard (UNI EN 442). They are rated in terms of heat output to room air $P_{,w/a}$ at standard condition ($\Delta t_{,w/a,std}$ = 50°C) with an exponent 'n' to correct their thermal performances, if different to standard conditions:

$P_{,w/a} = P_{,w/a,std} (\Delta t_{,w/a} / \Delta t_{,w/a,std})^n$ (1)

From the point of view of the terminal unit, the energy balance reduces to well-known equation:

$P_{,w} = M'_{,w}\, cp_{,w}\, \Delta t_{,w}$ (2)

with the two powers $P_{,w/a}$ and $P_{,w}$ obviously equal in a steady state condition.

After setting their design values and keeping the supply temperature $t_{,w,in}$ constant it is possible to solve the system equations (1) and (2) and express the percentage of terminal heat output in terms of percentage of water mass flow rate (both referred to their design values, as graphed in Fig. 6.

4.1.2 EnergyPlus object method

The most suited EnergyPlus inbuilt plant components to represent radiators or convectors are the "baseboard" objects "ZoneHVAC: Baseboard: Convective: Water" (*conv-bb*) and "ZoneHVAC :Baseboard: RadiantConvective: Water" (*radconv-bb*) (EnergyPlus Engineering Reference). These two objects are simulated by the same algorithm with two small differences: first, in *radconv-bb* a quote of radiant heat exchange can be added to the convective one; second, the way the thermal performance at standard conditions of the unit is described. *Conv-bb* requires directly the UA value, rather than *radconv-bb* where input fields are the rated water mass flow rate $M'_{,w,std}$, the rated average water temperature $t_{,w,avg,std}$ and the rated thermal output $P_{,w,std}$ (EnergyPlus Input/Output Reference). Starting from these values, before performing the energetic simulation, assuming a rated inlet air temperature of 18°C ($t_{,a,in,std}$ = 18°C) and a rated air mass flow twice of the rated water mass flow rate ($M'_{,a,std} = 2\, M'_{,w,std}$), the code runs a basic calculation based on LMTD method to achieve the UA value even for *radconv-bb* component. Running the simulation, the code evaluates at each timestep the component performance through the NTU-e method, with the efficiency expressed by the characteristic equation of the counter-flow heat exchanger (EnergyPlus Engineering Reference), (ASHRAE HOF, 2009).

The resulting mass flow / heat output relationships are graphed in Fig. 6.

Two different approaches are shown, which lead to different performance assessments: product standard deals with radiators and convectors as plant terminal units, rather than EnergyPlus algorithm that models them as a generic counter-flow heat exchangers.

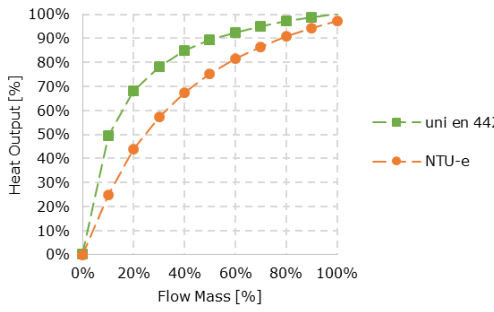

Fig. 6 – Terminal unit characteristic curves for radiator according to UNI EN 442 and NTU-e method

4.2 Valves performances

Thermostatic radiator valves (TRVs) are a control system consisting of a sequence of sensor -> regulator -> actuator.

4.2.1 Sensor and regulator

Sensor and regulator are both embodied in the valve head that performs as self-operated temperature proportional regulator. The sensing head moves the stem and the shutter proportionally (kp) to the air room temperature detected ($t_{,room}$) due to expansion or contraction of the sensing element itself, according to:

$U = b + kp\, e$ (3)

where the output 'U' is the stem travel (ST) or valve opening, 'b' is the bias, the proportional gain 'kp' can be expressed as the reverse of the proportional band PB (kp=1/PB), and the error 'e' is $\Delta t = t_{room} - t_{setpoint}$ (see Fig. 7) (AICARR, 2009), (Socal 2013).

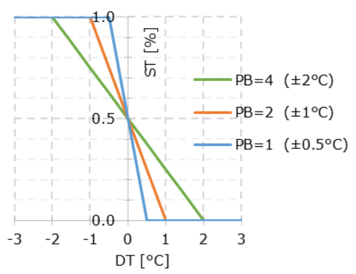

Fig. 7 – Signal control (stem travel ST for TRVs) for different working proportional bands PB

4.2.2 Actuator

The shutter is the actuator in the control chain: it acts on the water flow rate to be passed to the radiator, based on the signal control output and following its characteristic curve. There are four main types of valve characteristic curves (Miccio, 2012) (Scali, 2006): 1-Quick Opening (QO), 2-Linear (LIN), 3-Parabolic or Quadratic (PAR), and 4-Equal Percentage or Exponential (EQP), all suitable to perform control operations, except the quick opening (see Fig. 8 and Tab. 2).

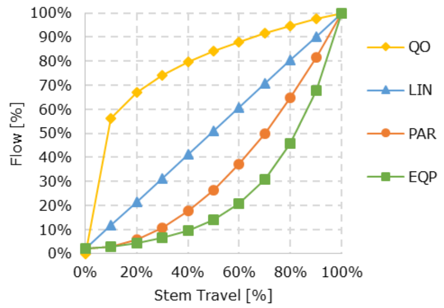

Fig. 8 – Valve characteristic curves, built wih R=50 and δ = 4

Table 2 –Four main types valve characteristic curves and their equations

Valve Type	Curve equation
Quick Opening (QO)	Flow = ST^(1/δ)
Linear (LIN)	Flow = ST + (1-ST)/R
Parabolic or Quadratic (PAR)	Flow = ST^2 + (1-ST^2)/R
Equal Percentage or Exponential (EQP)	Flow = R^(ST-1)
R = Valve rangeability = Kvs/Kvr (30-100 typical for TMVs)	

4.3 Terminal-Valve matching

With the hypothesis of a linear behavior of the thermal problem (i.e. fixed room air temperature value by means of a variation of the thermal power delivered by a terminal unit), we looked for a linear relationship between the process variable (room air temperature) and the parent variable (heat output from terminal unit) (Belimo, 2014). As shown in Fig. 9, an equal percentage valve characteristic better matches the standard product terminal unit characteristic, while a parabolic valve better matches the output terminal unit as implemented into EnergyPlus with baseboard objects.

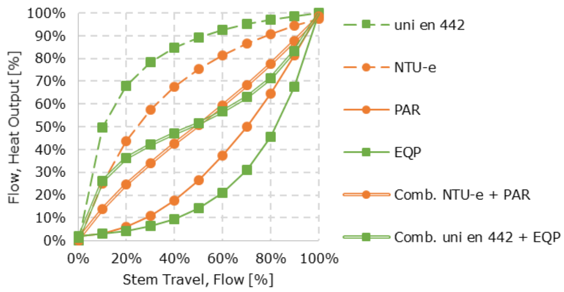

Fig. 9 – Terminal and valve characteristic curves combinations to obtain linear output

Some extra considerations are necessary. The proportional gain kp of the regulator (or similarly its proportional band PB) depends, in real casas, on the pressure drop Δp between upstream and downstream of the valve and can be evaluated with appropriate choice of the valve body and its pre-setting. Similarly, the effectiveness of flow control by the valve is subject to the condition that the pressure drop generated by the same valve never becomes marginal with respect to those realized on its branch, that is, its authority (a = $\Delta p_{,valve}$ / $\Delta p_{,branch}$) maintains high enough in every flow rate conditions (Russo, 2013), (Socal 2013). EnergyPlus code ignores the pressure drop for the evaluation of flow rates in various branches (pressure drop simulations are allowed to only correct pump consumption) (EnergyPlus Engineering Reference), therefore it is quite simple to introduce a TRV with unitary authority and any proportional band via EMS as explained below.

Beyond considerations about characteristics of real thermal plants and effective performances of commercially available thermostatic valves, in this paper we consider a TRV with constant intrinsic characteristic (small distortion at every flow rates) and operating with the desired proportional band (appropriate thermal inertia of the bulb sensor – wax, liquid or gas - and stem travel pre-setting).

4.4 Valves implementation

In EnergyPlus many control types are pre-defined, but nothing with the TRVs properties previously described. However, by using the *Energy*

Management System (EMS), almost any control system can be introduced combining into algorithms sensors, actuators, and other specifically defined parameters through a basic and simplified programming language (*EnergyPlus Runtime Language – Erl*) for which the same calculation engine serves also as a parser (EnergyPlus Application Guide for EMS).

In the control algorithm written for modeling the TRV's behavior (see Fig. 10) the 'T_Room_Air' is the sensor (*EMS:Sensor object*) detecting the 'Zone Mean Air Temperature' variable for the thermal zone, while the 'MFR' is the actuator (*EMS:Actuator object*) acting on the 'Mass Flow Rate Maximum Available Setpoint' control type on the inlet node for the baseboard. The program is then called by the manager (*EMS:ProgramCallingManager object*) at the 'InsideHVACSystemIterationLoop' calling point.

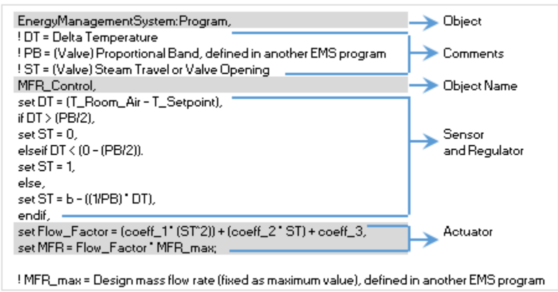

Fig. 10 – EMS Program modelling TRVs behavior, actuator parabolic characteristic curve written in standard form

4.5 Assessment of effectiveness of valve implementation algorithm

Simulations including specific EMS programs for TRVs, reveal the consistency of theoretical assumptions.

As expected, when a perturbing event happens, the smaller the proportional band, the closer to the setpoint the process variable is, but with higher fluctuations and a longer tail. Moreover, because of the only proportional nature of control, the process variable shows off a standing offset to the value required (Fig. 11).

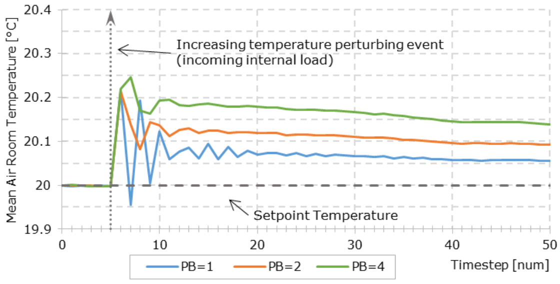

Fig. 11 – Room air temperature trend following a perturbing event with different values of proportional band for the regulator (parabolic characteristic curve applied for the actuator)

A parabolic characteristic applied to the actuator shows a more accurate process variable control, and this behavior is between the linear (higher) and equal percentage (lower) characteristic curves (Fig. 12).

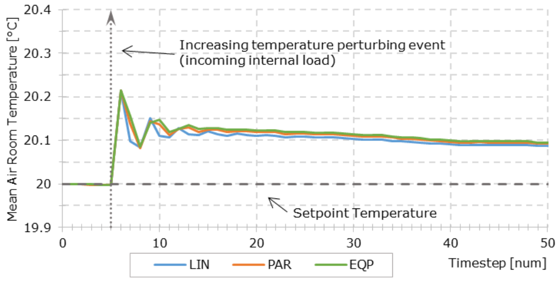

Fig. 12 – Room air temperature trend following a perturbing event with different curve types for the actuator (PB=2 for the regulator, characteristic curves built with R=50)

5. Simulations with different control systems

The final objective concerns the evaluation of energy efficiency and improved comfort conditions resulting from the installation of different kinds of thermoregulation systems, and from the reduction of energy dissipations through the windows.

Therefore, the project of upgrading the energy efficiency of the apartment was assessed by comparing six types of improvements.

All proposed actions are applicable to a single unit in a context of a building's central heating, where other boundary conditions (the opaque building envelope and the central heating plant) are kept fixed.

The following 6 cases were analyzed:

1-1_Current Condition: external climatic regulation only with temperature curve;

1-2_External climatic regulation and zone control (all TRVs act in the same way as the one in the living room, where the thermostat is placed);
1-3_External climatic regulation and thermostatic valves (every TRV acts independently from the other);
2-1_Replacement windows and external climatic regulation only with temperature curve;
2-2_Replacing windows, external climatic regulation and zone control;
2-3_Replacing windows, external climatic regulation and thermostatic valves (PB = 2).
Each simulation holds the following basic setting parameters:

- Winter heating period: 15 Oct-15 April
- Continues (not stepped) climatic regulation
- Internal loads as in Table 9 UNI/TS 11300-1
- Infiltration value, only for the exposed rooms (0,3 vol/h)
- Communicating zone air mixing (1 lt/s)
- Shading devices active 22:00 - 06:00
- PB = 2°C (only for x-2 and x-3)
- Setpoint temperature = 20°C (only for x-2 and x-3)

6. Analysis results

In Fig. 13, energy consumption is compared to the percentage of hours falling within the air temperature range during plant operation time for the whole heating season. The graphed data, related to the whole apartment, are calculated as averages of respective values of thermal zones. The hours outside the throttling range are distinguished between excess (red) and lesser (blue).

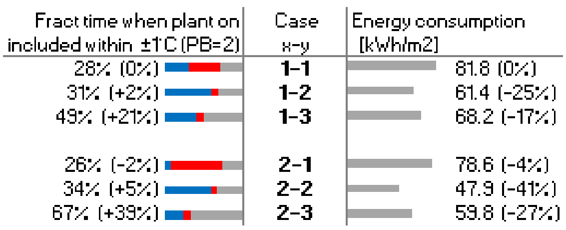

Fig. 13 – Comparison for the whole apartment of different control systems (y) applied to different envelope configurations (x), in terms of energy consumption and air temperature control

The distribution of the temperature values, reported in Tab. 3, shows that the thermostat for the whole apartment realizes an effective control only in the room in which it is placed (Living). TRV installation brings better comfort conditions in all the rooms because they take advantage of both endogenous and exogenous thermal gains, varying in time and space through the apartment. Despite these comfort conditions, throughout the whole apartment there are lower energy savings. Furthermore, if an energy saving measure is performed on the building envelope (replacing external windows), a more advanced control system has to be coupled with the original climatic regulation in order to a better thermal comfort and energy saving.
Figs 14 and 15 show, for all six cases, the mean air temperature trend of two rooms with different exposure and different use:

- east bedroom: south exposure and internal thermal loads mainly in night hours (23:00-07:00);
- living: north exposure, and internal thermal loads (higher than bedroom) mainly in the late afternoon and in the evening (17:00-23:00).

The TRVs always perform better than other control systems. The zone control system shows good behavior for the living room because of its position in that room. Notice how the variation of the mean air temperature levels with respect to the setpoint (20°C) presents little dependence on thermal gains while it mainly depends on the heating power of the terminal unit in the room.

7. Conclusion

This paper has investigated different heating control systems for a single unit, part of a building heated by means of a central plant water heating system. A deep investigation on terminal units and control systems allowed us to model them properly in a dynamic simulation tool (EnergyPlus), even by means of lines of code written for the purpose. A control system acting actively on each room (TRVs) proved to be the only one able to effectively combine an increase in comfort conditions with a reduction of heating energy consumptions.

Table 3 – Room air temperature distribution

	A	Fract time when plant on 1-1			1-2			1-3		
	[m2]	in PB=2 (±1°C)	over htg	under htg	in PB=2 (±1°C)	over htg	under htg	in PB=2 (±1°C)	over htg	under htg
Dining	12	**36%**	52%	12%	**47%**	9%	44%	**69%**	11%	20%
Kitchen	8.2	**30%**	35%	35%	**6%**	0%	94%	**54%**	1%	45%
Living	22	**38%**	56%	6%	**69%**	15%	16%	**71%**	15%	14%
West bedroom	15.4	**24%**	38%	38%	**20%**	14%	66%	**42%**	13%	45%
East bedroom	15.4	**23%**	35%	41%	**15%**	11%	74%	**39%**	13%	49%
Bathroom	8.2	**22%**	30%	48%	**7%**	2%	91%	**43%**	3%	54%
Ante-bathroom	2.5	**19%**	29%	52%	**15%**	4%	81%	**26%**	5%	70%
Storage room	1.7	**17%**	30%	53%	**14%**	2%	84%	**23%**	3%	73%
Corridor	6.2	**21%**	32%	47%	**14%**	11%	75%	**22%**	11%	66%
Entrance	4.5	**20%**	30%	50%	**15%**	13%	72%	**20%**	11%	69%
	0									
Flat	96.1	**28%**	41%	30%	**31%**	10%	59%	**49%**	11%	40%

	A	Fract time when plant on 2-1			2-2			2-3		
	[m2]	in PB=2 (±1°C)	over htg	under htg	in PB=2 (±1°C)	over htg	under htg	in PB=2 (±1°C)	over htg	under htg
Dining	12	**1%**	99%	0%	**57%**	10%	33%	**85%**	14%	1%
Kitchen	8.2	**44%**	48%	8%	**7%**	0%	93%	**70%**	1%	29%
Living	22	**1%**	99%	0%	**82%**	17%	1%	**80%**	20%	1%
West bedroom	15.4	**45%**	53%	2%	**15%**	6%	79%	**76%**	6%	18%
East bedroom	15.4	**40%**	51%	9%	**14%**	4%	82%	**66%**	6%	28%
Bathroom	8.2	**33%**	33%	33%	**5%**	0%	95%	**53%**	0%	47%
Ante-bathroom	2.5	**31%**	34%	35%	**14%**	1%	86%	**29%**	3%	68%
Storage room	1.7	**32%**	36%	32%	**12%**	1%	88%	**28%**	3%	69%
Corridor	6.2	**42%**	50%	8%	**13%**	8%	79%	**37%**	6%	58%
Entrance	4.5	**37%**	43%	19%	**15%**	10%	75%	**29%**	5%	66%
Flat	96.1	**26%**	66%	8%	**34%**	8%	59%	**67%**	9%	24%

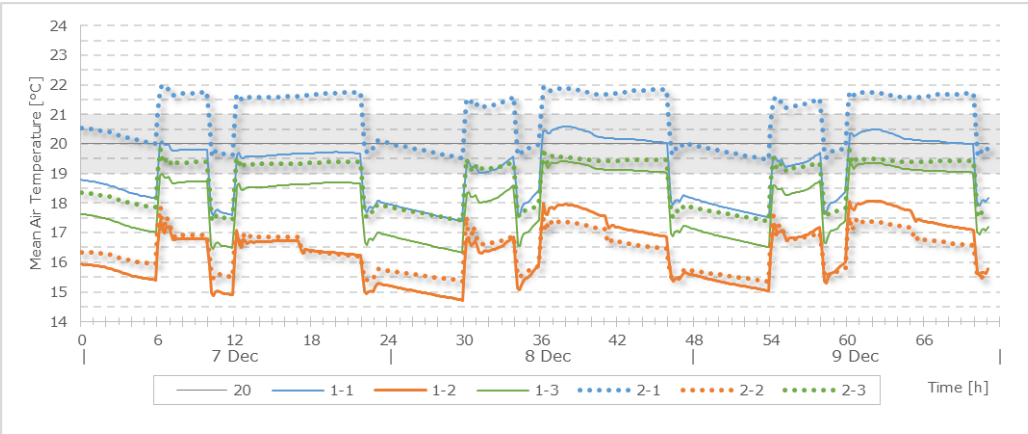

Fig. 14 – East bedroom: mean air temperature in three December days for various control systems and envelope configurations

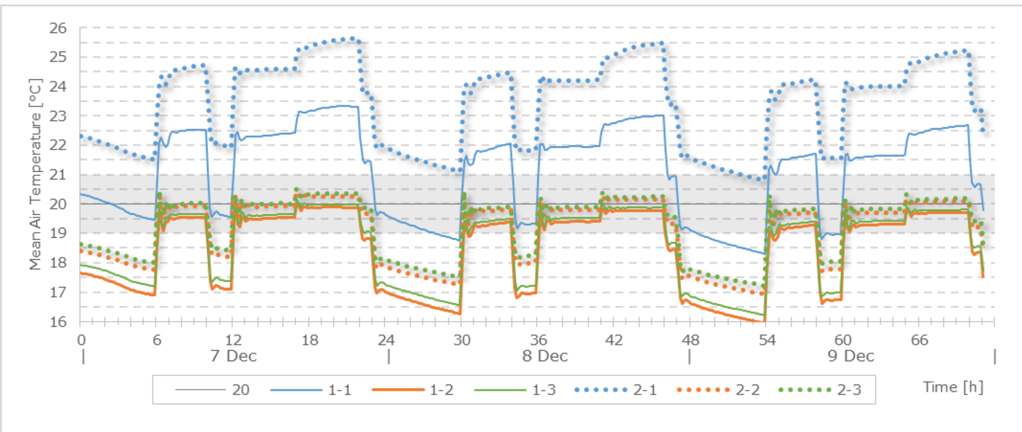

Fig. 15 – Living: mean air temperature in three December days for various control systems and envelope configurations

8. Nomenclature

Symbols

P	heat output power [W]
ΔT	temperature difference [°C]
M'	mass flow rate [kg/s]
cp	specific heat [J/kg-K]
LMTD	logarithmic mean temp. difference [°C]
NTU	number of transfer units [-]
e	effectiveness [-]
U	regulator output [-] or [%]
b	bias [-] or [%]
kp	proportional gain [1/°C]
e	error [°C]
PB	proportional band [°C]
t	temperature [°C]
ST	stem travel or valve opening [-] or [%]
R	valve rangeability = Kvs/Kvr (30-100 typical for TMVs) [-]
Kvs	mass flow rate through the valve fully open at standard conditions (ΔP=10 kPa) [m^3/s]
Kvr	minimum mass flow rate the valve can regulate at standard conditions (ΔP=10 kPa) [m^3/s]
ΔP	pressure difference [Pa]
a	valve authority

Subscripts/Superscripts

w	water
a	air
w/a	water to air
std	at standard conditions
in	inlet terminal unit section
out	outlet terminal unit section
avg	average in thermal unit
room	relative to the thermal zone
setpoint	required value
valve	relative to the valve
branch	relative to the branch whose flow rate is controlled by the valve

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