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Thermal and Lighting Control System with Energy Saving and Users Comfort Features

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Abstract — **Building automation systems (BAS) provide automatic control of indoor environments conditions. Their primary goal is to realize significant energy savings, to reduce costs and to increase users comfort. In this paper improvements of the control system of a Building and Home Automation system previously presented by the author are presented. The system integrates energy-consuming sources for heat and light power supply, such as heat pumps and artificial lights with green energy-supplying sources like natural radiation and natural illuminance. In particular, in the present work, control solutions as a new thermal control policy, an anti-glare logic, and a logic for accounting of the solar radiation are introduced. This controller works satisfactory reducing the need for energy-consuming sources and it reaches good control performances and energy efficiency by making the best of the advantages of intelligence building.**

I. INTRODUCTION

The key driver of the building automation market is the promise of increased user comfort at reduced operation cost. To this end, building automation systems make use of optimized control schemes for heating, air-conditioning systems, lighting, and shading. Energy and environmental sustainability is a major global trend for the 21st century. In recent years the European Union has actively promoted political campaigns toward energy efficiency and renewable energy [1]. The fact that a non-negligible source of pollution is represented by the emissions from our homes and offices has motivated the present research work. Hence the idea to model and implement a Home/Building Automation system [2] to control rolling shutters, heat pump and lighting system finalized to users comfort and energy saving, maximizing the exploitation of solar energy [3]. In the present state of the work, the interest has been focused on satisfying thermal and lighting user's comfort, without considering the air quality comfort aspect [4], the main reason being the absence of an Air Handling Unit (AHU) in the considered Building Automation System (BAS). The presence of coupling effects between the thermal and illuminance systems adds difficulties to the controller design especially because the actuators control outputs often result in contrasting requests. A supervision and control system based on a thermal and lighting interconnected modeling of the environment has been developed by the authors (see Figure 1). Several enhancements are introduced in the control solution like new thermal control policy, the anti-glare logic, the solar radiation presence logic and other functional features. The pursued goal is to obtain, by an intelligent management of heat pump, lights and shutters actuators, maximum energy saving while assuring reasonable users comfort.

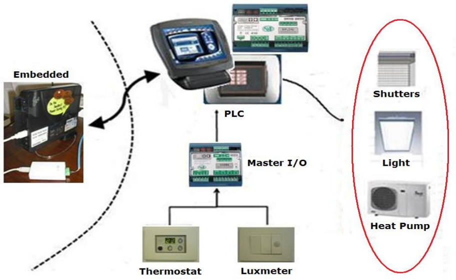

Fig. 1: The energy saving control architecture

The paper is organized as follows. Section II describes the mathematical thermal and light model of an office/house room. Section III presents the control policy while in Section IV exemplification examples of the proposed control solution are given. Section V illustrates the achieved results for the considered Building Automation System (BAS); conclusions and future perspectives for system enhancement are reported in section VI.

II. MATHEMATICAL MODEL

The environment taken into account in the present study is an office building; the typical office room considered in the model has a rectangular plant and consists of 6 walls (4 vertical, and 2 floors) and two windows. Both the thermodynamical and lighting behavior of the environment has been considered and separately modeled (see [7]).

A. Thermal Model

The following equations describe the thermal dynamic behavior of a room [8] which make use of the energy balance equation of the air inside the building area. Equation (1) accounts for the total thermal accumulation; the main contributions that has been considered consist on the internal heat sources Q_{INT} (due to people, lamps, and other apparatuses), auxiliary sources Q_{HP}, thermal conduction and convection exchanges through walls Q_W, thermal conduction convection and radiation exchanges through windows $Q_{GL\text{-}S}$, $Q_{GL\text{-}S\text{-}I}$ and finally the fluid dynamic exchanges with the outside environment Q_{VENT}.

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$$m_a \cdot c_a \cdot \frac{\partial T_a}{\partial \tau} = Q_{IS} + Q_{HP} + Q_W + Q_{GL\_S} + Q_{GL\_S\_I} + Q_{VENT} \qquad (1)$$

$$Q_W = \sum_{k=1}^{6} A_k \cdot h_{O_k} \cdot (T_{W_k} - T_a) \qquad (2)$$

$$Q_{GL\_S} = \sum_{j=1}^{2} A_{gl_j} \cdot h_{Ogl_j} \cdot \left[(1-SAF_j) \cdot (T_{gl_j} - T_a) + SAF_j \cdot (T_{gl\_s_j} - T_a)\right] \qquad (3)$$

$$Q_{GL\_S\_I} = \sum_{j=1}^{2} A_{gl_j} \cdot \left[(1-SAF_j) \cdot F_{G\_gl_j} + SAF_j \cdot F_{G\_gl\_s_j}\right] \cdot I_{V_j} \qquad (4)$$

$$Q_{VENT} = \sum_{j=1}^{2} \rho_a \cdot c_a \cdot N_j \cdot V_j \cdot (T_e - T_a) \qquad (5)$$

The above equations take into account the indoor wall and glass temperatures which in turn are modeled with a dynamic multi-layers model [8] here not reported for brevity. The windows contribution to the room thermal dynamic has three components: conduction, convection and irradiation. Equation (3) accounts for the first two while equation (4) considers only the irradiation contribution. In both equations (3) and (4) windows contribution has been differentiated into two sections: the first section refers to the lower part of the glass window and considers the contribution of sole glass, while the second section accounts for the contribution of the glass coupled with the rolling shutter. In Table I the thermal model parameters are summarized.

TABLE I
QUANTITY FOR THERMAL MODEL

Symbol	Quantity	SI
Q_{IS}	heat supplied by internal (people, lamps, engine) sources	*Watt*
Q_{HP}	heat supplied by heat pump sources	*Watt*
A_k	kth wall area	m^2
h_{O_K}	kth adduction coefficient	$W/[m^2 \cdot K]$
h_{Ogl_j}	mth glass adduction coefficient	$W/[m^2 \cdot K]$
$F_{G\_gl_j}$, $F_{G\_gl\_s_j}$	Solar gain coefficient (Glass, Shutter)	
N_j	N° of times air is exchanged through the window opening (Parameter)	
ρ_a	Air density	Kg/m^3
c_a	Air heat capacity	$J/[Kg \cdot K]$
V_j	Air incoming volume (fixed value)	m^3
T_{W_k}	kth internal temperature of wall	*K*
T_{gl_j}	jth internal temperature of glass	*K*
$T_{gl\_s_j}$	jth internal temperature of glass combined with shutters	*K*
T_a	Room temperature	*K*
A_{gl_j}	jth glasses area	m^2
SAF_j	jth shutters actuation factor	*%*
I_{V_j}	jth solar thermal radiation	W/m^2

B. Lighting Model

Modeling the lighting inside the room, the illumination inside the environment can be classified into two categories: artificial lighting and natural illumination. For the development of the mathematical model additional hypothesis on light radiation and lighting sources have been considered. In particular, light radiation is assumed to be uniform in order to apply the superposition principle [9] while, for light sources the following assumptions holds:

- artificial sources: approximated to point light sources;
- natural sources: considered as extended light sources.

Given the room/lights and room/window dimensions the above assumptions can be considered reasonably valid and the following equation governs the light variations in the environment (see [10]). Table II summarize its parameters.

$$E_a(P) = \sum_{j=1}^{2} \left[\left| C_{c_j} \cdot E_{(ND\_gl)_j} + C_{r_j} \cdot E_{(NR\_gl)_j} \right| + \frac{\tau_j \cdot V_j \cdot A_{gl_j} \cdot \sigma_{weighted}}{sum_{AREA} \cdot (1-\sigma_{weighted})} E_{NAT\_gl_j} \right] + \frac{I_L \frac{Lumen}{1000} \cos(\gamma)^3}{d^2} + \frac{Lumen \cdot \eta \cdot M \cdot P}{Sum_{AREA} \cdot (1-\sigma_{weighted})} \qquad (6)$$

TABLE II
QUANTITY FOR LIGHT MODEL

Symbol	Quantity	SI
Ea(P)	environment illumination at the point of interest P(x,y,z)	Lux
$E_{N\_D\_glj}$	natural diffuse illumination on windows	Lux
$E_{N\_R\_glj}$	natural reflection illumination on glass	Lux
E_{NAT_glj}	natural direct illumination on glass	Lux
C_{mc}/C_{mr}	environmental influence of natural diffuse/reflections illumination at the point of interest P(x,y,z)	
I_L	artificial light source	cd/klm
Lumen	luminous flux	lm
γ	incidence angle of the light radiation in relation to the point of interest P(x,y,z)	°
d	Distance between point of interest and light source	*m*
$\sigma_{weighted}$	reflection coefficient of the walls	
sum_{AREA}	total area of the reflective walls	m^2
η	efficiency of artificial light source	
M	is the environmental maintenance factor	

III. CONTROL SYSTEM

The developed control system is based on the interconnection of PID controllers adopting architectural scheme solutions typical of industrial processes such as cascade, override, and higher-level logic interconnections [11]. These controllers consent having excellent results using techniques commonly used in industrial process control [12]: in particular, the "Valve Position Control" and "Override", in order to maximize an objective function that must evaluate energy saving and comfort. The thermal control system and lighting have similar requirements, and have been designed according to the same criteria of engineering. The control scheme previously developed has been modified in the thermal control policy and enhanced by the introduction of new control features like an anti-glare logic, a solar radiation presence logic as it will be described in the present paragraph. This new characteristic allows to obtain enhanced control performances and add more functionalities. Two different control policies are considered: *Energy Saving* control mode and *Comfort* mode.

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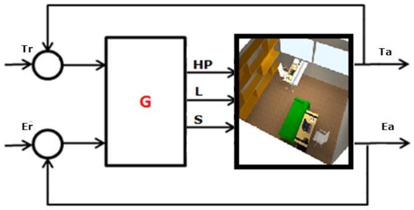


Fig. 2: The energy saving control system. Temperature Set Point (Tr), Illuminance Set Point (Er), Room Temperature (Ta), Room Illuminance (Ea), Heat Pump (HP), Lighting (L) and Shutter (S) control efforts.

When the (*Energy*) *Saving* mode is selected the only specification is the reduction of energy consumption while optimization functions that takes into account constrains derived by the preservation of the user comfort are considered in the *Comfort* mode. The regulation of the rolling shutters requires handling possible conflicting requirements of interconnected thermal and lighting controllers. Depending on the desired user policy (*Energy Saving* or *Comfort*) the rolling shutters control logic has to adapt. The *Personal Comfort Logic* (PCL) module described in the sequel is in charge of the choice of the control signal that best fits to the current state of the system.

Lighting control is realized adopting two PIDs in cascade configuration; an override selector is inserted which manipulates the rolling shutters control signal. The regulator EC0101-PID (see Figure 5) is properly tuned for lights control (dimmer control effort). In order to minimize the dimmer control effort a second controller MPC0101-PID is placed in cascade configuration. Since the main interest is to minimize the use of artificial light through the exploitation of natural light, its set point value is set to zero. A third TEC0104-PID is finally introduced with the aim to control the rolling shutter while not exceeding the illumination threshold. The MPC0101-PID and TEC0104-PID is coupled by an override configured in low-pass mode. Since it is important to keep limited the dimmer control effort, a much faster dynamic has been imposed to MPC0101-PID with respect to TEC0104-PID dynamic.

The thermal control system uses the same logic scheme, consisting of three interconnected PID controllers in the same way as previously described. In this scheme the TC0102-PID controls the thermostat for the activation of the heat pump, while the TEC00103-PID and MPC0102 PID are respectively the temperature limiter and the controller for the optimization of the heat pump control effort. Both control systems act on the rolling shutter to adjust the room illuminance and the room temperature. Thus, it is necessary to identify a logic that manages the possibly contrasting shutters requirements coming from the thermal and lighting controllers. At this purpose, the coupling of the thermal and lighting control outputs are handled by a *Personal Comfort Logic* (PCL) module as depicted in Figure 4. The internal logic of this module determines the policy of the selection for the input signals depending on the actual system configuration.

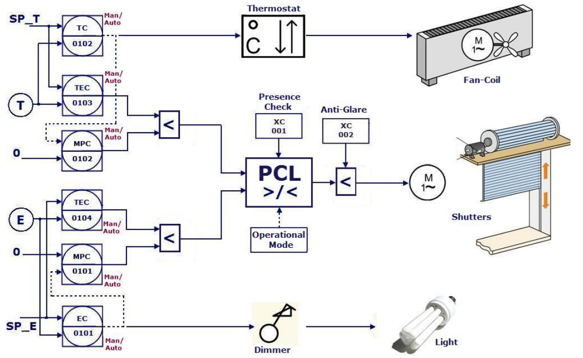


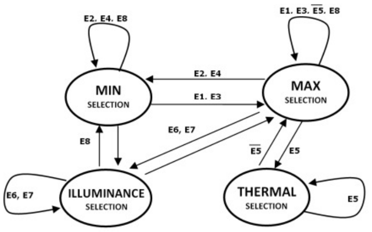
Fig. 3: Control scheme

TABLE IV

FUNCTIONAL BLOCKS DESCRIPTION

Symbol	Description
EC|0101	*PID, lighting control*
TC|0102	*PID, thermal control*
TEC|0103	*PID, thermal limitation*
MPC|0102	*PID, motor position control*
TEC|0105	*PID, lighting limitation*
MPC|0101	*PID, dimmer position control*
MODE	*Logic, control mode*
XC|001	*Logic, presence radiation*
XC|002	*Logic, no excessive brightness*

Each of the four states of the PCL automaton represents the implemented control policy: coupled control action and override configured in low(high)-pass mode in the *Min* (*Max*) state or assigned priority to thermal (lighting) controllers in the other two states, respectively. Events are combinations of the selected pairing of *Heating/Cooling* and *Saving/Comfort* modes which takes into consideration possible temperature and lighting thresholds. When the system is in *Saving (Energy)* mode the object is to reduce power consumption. In this case the requested control efforts are mostly achieved by the actions of the shutters thus reducing the use of the heat pump. On the contrary, when in *Comfort* mode, the system assigns higher priority to the lighting control aiming at achieving the desired set point by means of the natural illumination. In order to meet user possible personal comfort preferences, such as for example limitation of the shutter position within assigned range limits, specific management constraints are implemented. The inclusion of this feature increases the degree of user interaction with the system. It's important to note that if the shutter can't meet the required control effort due to the imposed limits, the heat pump will be activated. The coupling automaton contains a condition "XC001–Direct solar radiation Presence Check" that evaluates the presence (conduction factor plus convection factor plus irradiation factor not equal zero) of direct solar radiation on the glass wall, i.e. if the solar radiation is present, the logic for signal selection works normally. While, if the direct solar radiation is not present, the logic selects the rolling shutter control signal computed by the lighting control system.



E1	Comfort & Cooling
E2	Comfort & Heating
E3	Saving & Heating
E4	Saving & Cooling
E5	ATTE Alarm Temperature Threshold Exceeded
E6	AITE Alarm Illuminance Threshold Exceeded
E7	Presence Check (True)
E8	$\overline{E7} \wedge (E1 \vee E3)$
E9	$\overline{E7} \wedge (E2 \vee E4)$

Fig. 4: Personal Comfort Logic automaton

This is because the heat gain due to solar radiation is negligible. The logic takes account of two aspects, that is the presence of direct solar radiation on the glass wall and the composition of the thermal conduction/convection and the heat radiation contributions. When the sum of the two components are positive then it means that the heat flow comes from outside into the environment, otherwise, if the sum is negative, the heat flow has opposite direction. Combining these two components it is possible to obtain empirical information on the heat flow input due to solar radiation that intervenes in the coupling logic previously described and also completes the control policy for the management of the shutters. The logic "XC002–Anti-glare" evaluates from the starting position of the sun (azimuth and solar height, based on the latitude of the current location) the possibility to have glare into the environment. Then according to the sun's position the actuations to the rolling shutter are calculated, allowing the user to avoid direct glare. This value is inserted into the control by using an override selection logic.

IV. CONTROL SYSTEM SIMULATIONS PERFORMANCES

To evaluate the validity of the proposed model a room of *5 x 4 x 2,7* [m^3] with two windows on the wall at SW exposition is considered. In table III the main room characteristics are summarized (See [13] for more details on environment parameters). In this section the performances of the coupled thermal-illuminance control system are discussed. The two simulated scenarios refer to the winter and summer season paired with different control policies: *Saving* or *Comfort*.

TABLE III
ROOM PARAMETERS

Symbol	Quantity	SI
Lacation	Ancona - Italy	
Dimension	[5 x 4 x 2,7]	m
Wall - 1	Vert, [5 x 2,7], SW	m
Wall - 2	Vert, [4 x 2,7], NW	m
Wall - 3	Vert, [5 x 2,7], NE (Not Expose)	m
Wall - 4	Vert, [4 x 2,7], SE (Not Expose)	m
Wall - 5	Horiz, [5 x 4]	m
Wall - 6	Horiz, [5 x 4], (Not Expose)	m
Window - 1	Vert, [2; 1,25; 1], SW	m
Window - 2	Vert, [2; 1,25; 1], SW	m
Artif. Light	Flux 8900, pos. [2; 1,25; 1]	Lumen, m
Heat Pump	Pot.Max = 4, C.O.P = 2,8	Kw

First Scenario. Winter Season, February 2nd.

The imposed set points are: Temperature = 22° C, Lighting = 300 Lux; The imposed operative and logic system configuration is *Heating*, *Energy Saving and Comfort*.

In *Comfort* mode the fulfillment of the room illumination request has higher priority and in order to keep the desired level of illuminance the shutter are closed in the central part of the day and artificial light is used instead (Figures 5, 6 and 7). The *Energy Saving* mode gives its consensus to the full opening of the shutter as requested by the controller, entirely exploiting the thermal solar radiation and fulfilling the energy consumption optimization goal (Figures 8, 9, 10). It can be noted from figure 8 that during the central hours of the day (presence of solar radiation equal to one) in the room there is a high illuminance that can be of disturbance to the user. This can be prevented by the imposition of range limits to shutter actuation as described in the previous paragraph.

The consequence of this policy that aims to balance the energy saving and comfort of the user, is an increase of the energy consumption in that part of the day; nevertheless the overall control policy guarantees consumptions optimization. Despite the fact that in the chosen day the thermal radiation had low intensity, the energy consumption reduction while in the *Saving* mode can still be observed.

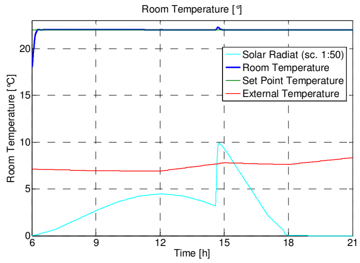


Fig. 5: Comfort, Room Temperature [°C]

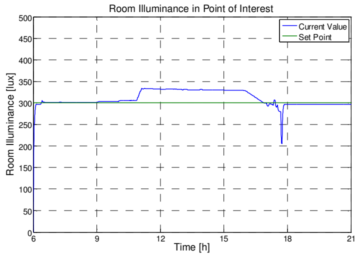


Fig. 6: Comfort, Room Illuminance [Lux]

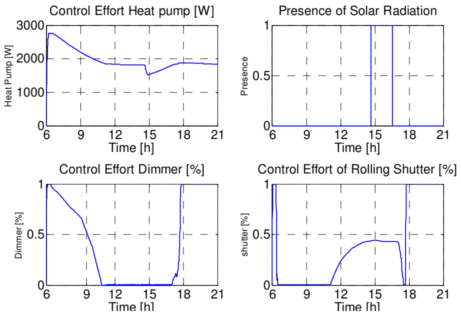


Fig. 7: Comfort, Control Effort

Second Scenario. Summer Season, July 19th.

The imposed set points are: Temperature = 23° C, Lighting = 300 Lux; The imposed system operative and logic configuration is *cooling*, *Energy Saving and Comfort*. In summer simulations and in energy savings mode, the influence of rolling shutters allows considerable energy savings (Figure 14, 15, 16). Keeping shutters totally closed could lead to an excessive reduction of visual comfort of the user, so that shutter limits were introduced. Correspondingly when simulating the winter season in comfort mode, the room luminance was regulated maximizing the exploitation of natural lighting (Figure 11, 12, 13).

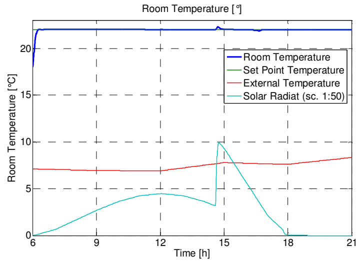


Fig. 8: Saving, Room Temperature [°C]

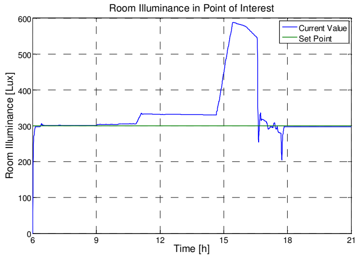


Fig. 9: Saving, Room Illuminance [Lux]

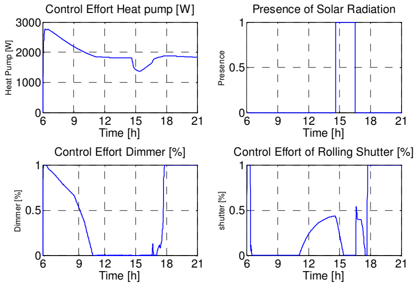


Fig. 10: Saving, Control Effort

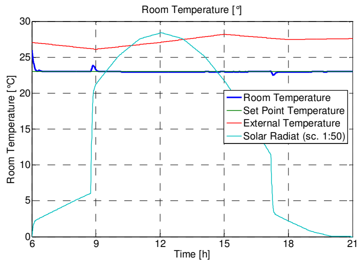


Fig. 11: Comfort, Room Temperature [°C]

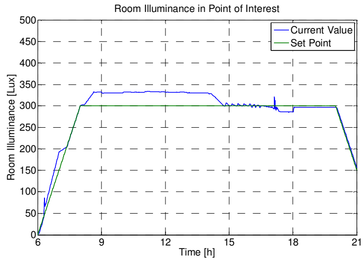


Fig. 12: Comfort, Room Illuminance [Lux]

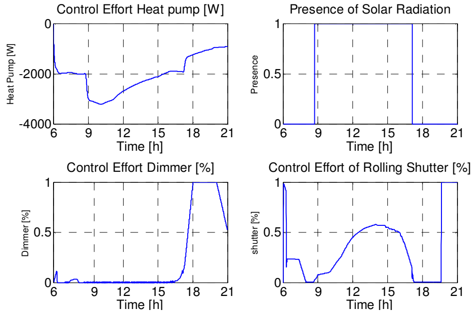


Fig. 13: Comfort, Control Effort

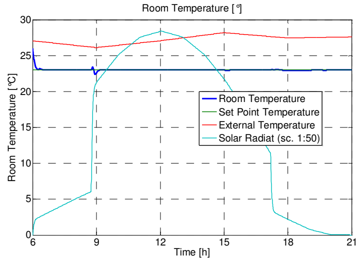


Fig. 14: Saving, Room Temperature [°C]

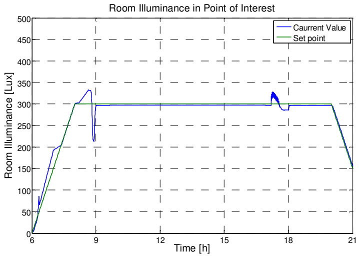


Fig. 15: Saving, Room Illuminance [Lux]

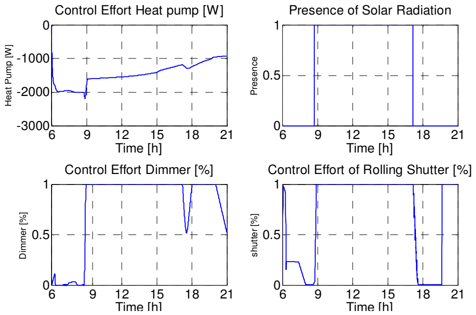


Fig. 16: Saving, Control Effort

TABLE V
SIMULATED SITUATION

Single Loop	Shutter Open/Close “worse situation”	1
	Shutter 50 % “average situation”	2
Coupled Loop	Saving Energy	3
	Comfort	4

V. FINAL RESULTS

In the previous section system performances in term of control index specification and granted comfort to the users were discussed. Now, in order to evaluate the ultimate system performances in term of energy saving and reduced emission of CO_2, suitable simulation tests have been performed. Performances of the single independent thermal and luminance controllers as well as of the final coupled controller have been evaluated. With the purpose to obtain daily average results, the simulations have been carried out over several days, considering several different atmospheric conditions. Table V summarizes the characteristics of the four evaluation tests that have been deemed significant for performance comparison. Histogram below (Figure 17) illustrates the test results that can be quantified in an average saving of about 23%. Graphic of Figure 16 shows the reduction of CO_2 emissions computed considering a linear relation between energy produced in KWh and CO_2 emissions as suggested by the International Energy Agency [14].

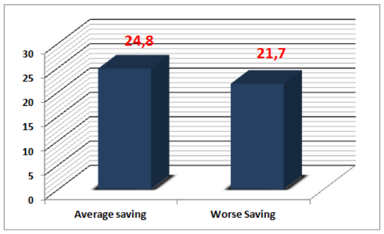


Fig. 17: Percentage saving in average and worse situations [%]

VI. CONCLUSION AND FUTURE WORKS

The aim of the present work is the enhancement of performances of a Building and Home Automation system that is reducing the operative cost while assuring a suitable comfort to the users. The system integrates in an interconnected control loop, techniques of natural heating and daylight penetration to minimize electric lighting as well as electric heating. Energy saving as well as thermal and lighting comfort of the users have been taken into account when designing the controller. In the present work, the air quality comfort aspects have not been considered but they will be included in its future developments.

The simulations performed on a dynamic model developed by the authors have shown satisfactory results in terms of control behavior and, above all, in terms of economic and environmental savings. An average saving of about 23% has been estimated though it is important to notice that these results are influenced by the values of thermal and light solar radiation that generally are highly variable both on the requested set point and on the simulation conditions (e.g. weather). Further validation of the system is expected from its implementation in a real context. This will be one of the main issues in the follow-up of the work, in order to fully test the control system on real data.

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