Scenario-based sensitivity analysis of energy dynamic behavior in residential buildings with radiant floors

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***Abstract* — This paper addresses the problem of thermal energy efficiency in domestic buildings. As opposed to classic optimal approach, a sensitivity analysis and comparison have been performed to evaluate both comfort and consumption of different heating scheduling, corresponding to different user-oriented scenarios, which allows to derive basic operating rules. Also continuous and discontinuous heating strategies are compared. The various scenarios are evaluated for different building thermal properties and different climatic conditions, under a classic mixed PID and hysteresis control scheme. The case study here considered is a house heated through a radiant floor system. A new index of assessment of user's comfort is also proposed. This paper explores the importance of heating scheme in terms of comfort and energy saving and highlights the importance of the decision maker point of view when deciding the most appropriate heating strategy. An optimal control strategy is also implemented (model-based predictive control) for comparison.**

Keywords—floor radiant heating system; PI control; control strategy; building energy efficiency.

I. INTRODUCTION

Buildings account for over a third of global energy consumption. In European countries, more than 60% of this energy is used in space heating. For the coming years, the EU committed to reduce energy consumption by 20% by improving energy efficiency. In this sense, one of the actions promoted is the energy certification of buildings by an energy label or building class [1].

Italy is among the top-five European countries with highest residential electricity use per capita [2]. Usually heating energy is non-efficiently exploited, given the lack of knowledge on optimizing heating phenomena and on thermal storage.

Floor heating has grown up significantly in Europe in the last decades. Most of previous studies focused on heat transfer formulation problem. Despite its demonstrated advantages as comfortable and energy saving system, [3] floor radiant systems are difficult to be controlled [4]. The adequacy of the controllers is assessed based on room temperature fluctuation from a desired value (comfort value). Temperature control is performed through flow rate control, according to two strategies: i) usage of on-off valves; ii) usage of mixing valves to regulate inlet water temperature. There is little previous research on the performance of controllers in floor radiant heating systems. Yang compared the performance of PID and a fuzzy-PID to control the radiant floor heating systems, concluding that the control based on the indoor air temperature reduces fluctuations compared with control based on floor surface temperature [3]. In their work, Joe et al. explored the performance of MPC with respect to a traditional one under different schemes of a radiant floor cooling system [5]. An energy saving up to 10 % was achieved with MPC compared to the conventional PI control. According to these authors, the potential of MPC for radiant floor system has not been fully explored due to: i) deficiencies in the prediction model; ii) lack of model validation with experimental data. The performance of a combination of traditional on/off control with a fuzzy-based control was compared with a conventional one by Kang et al. [6]. The results obtained proved the ability of a fuzzy logic-based advanced on-off controller to compensate solar energy and avoid internal overheating. Tahersima et al. proposed a two level hierarchical control strategy for a under-floor heating system with a geothermal heat pump: PI controllers to maintain individual temperature set points and MPC to maximize heat pump performance by adjusting water supply temperature [7]. These authors introduced the use of MPC to shift heat demand of the building from peak energy price hours to off-peak periods, by adjusting temperature set point. This combination of controllers was used to minimize power consumption considering energy price.

The importance of an adequate planning of heating hours has been previously highlighted and it has been a matter of discussion. Some authors considered that intermittent strategies save energy without impairing the comfort level [8]. The benefits of an intermittent heating strategy of a radiant floor system to utilize effectively the heat storage of the building mass has been previously investigated [9]. The authors compared the performance of a predictive control applied to an intermittent heating strategy, in order to improve the temperature regulation and consequently the energy efficiency. Similarly, [10] studied the relationship between the intermittent strategy and the heat storage capacity of a heating floor. According to [11] to bring forward heating period makes for a better indoor thermal comfort (especially at night), but without taking into account heating energy consumption. [12] concluded that in high insulated buildings, if used for a long period of time, intermittent heating strategy is more effective than continuous strategy and 18% of energy can be saved. However, [13], after the comparison of a boiler operation for continuous and intermittent heating strategies, concluded that for a high insulated building, it is necessary to operate 14h per day intermittently in order to obtain the same comfort level offered by continuous heating. According to [3] the role of intermittent operation needs to be further investigated.

The indoor temperature of a heated zone is a feasible indicator of user comfort. Traditionally it has been evaluated by scattering measurements which indicate how far the indoor temperature from the desired one is. The lower the value of the dispersion, the more constant indoor temperature and a higher comfort level of users. However, these measures do not take into account the energy expenditure required to maintain the desired temperature.

As a summary, the literature review shows three main research lines on radiant floor systems optimization: i) heat transfer problem formulation; ii) controller performance innovation; iii) heating scheme analysis based on energy consumption or comfort level.

This paper aims at studying systematically the operation and the heating strategy of a domestic floor radiant heating system of a residential house, based on energy saving and comfort requirements of occupants. In other words, the question at its basis is: given a house, a climatic condition and a request of thermal comfort in special hours of the day, how should we distribute the heating hours during the day to optimize energy saving without giving up comfort level? Is it the same in every day? What if we improve the energy class?

The most suitable heating profile should be the one that balance the energy consumed and the comfort of the users. In particular, the following test case scenario is adopted: i) different building energy classes, corresponding to different insulation levels; ii) diverse heating strategies and length of heating period.

The added value brought in this work is both the overall methodology, based on a sensitivity analysis, for the assessment of the effectiveness of heating strategies, as well as the mathematical model, parametrized in terms of energy thermal properties and climatic conditions, that could be easily generalized and used in different conditions. Two different approaches have been studied to regulate the heating system which are (i) a combination a classical PID and hysteresis control scheme and (ii) an advanced control technique Model Predictive Control (MPC).

In our study, a new methodology of evaluation of the performance of heating strategies of heating floor systems is proposed. This evaluation is conducted in terms of energy and comfort. As an innovation, a new index of user comfort evaluation is proposed, beyond the commonly used value of indoor temperature fluctuation.

II. Description Of The Case Study

The residential zone considered in this paper is rectangular shape, size 5.2×3.5 m, longer façade south-oriented and located in the city of Milano. The floor height is 2.7 m and the inner volume 48.92 m^3. Located on the corner, South and East façades are exposed to outdoor, whereas West and North façades correspond to boundary walls. Two windows of 2 m^2 and 2.5 m^2 are located in South and West façades, respectively.

To determine the level of insulation of buildings two criteria were selected: a) building age; b) energy efficiency label. In Italy, the Law 10/1991 was the first standard on limiting the heat transfer coefficients (U values) of the envelope elements. Later, the Legislative Decree 192/05 added more restrictive energy performance requirements in consonance with the European Union goals [1].The construction period is determinant for the definition of the level of thermal insulation, and consequently on heat losses in buildings. In this study, we consider two building ages that represent two stages of the national legislation on energy conservation in buildings: i) posterior to 2006, under the Legislative Decree 192/05; ii) from 1991 to 2005, from Law 10/1991 to the Legislative Decree 192/2005. Building before 2005 was characterized with a low level of insulation (building label C) whereas building posterior to 2005 corresponds to a letter A with a higher level of insulation (label A).

TABLE I summarizes envelope thermal properties of the two prototypes. Column 2 includes the level of thermal insulation of each period considered. Columns 3, 4 and 5 show the coefficient of heat transmittance of each element of the envelope. Buildings posterior to 2006 are characterized with more restrictive heat transfer coefficient values than those established by the Legislative Decree 192/2005, in order to reach the maximum qualification. Column 6 contains the corresponding energy label.

The building enclosure materials and layers were designed according to [14] and [15], which offers a set of national building typologies representing the residential building stock at European level, focusing on building parameters related to the energy consumption.

TABLE I. Typological Features Of The Prototypes Proposed

Building Age	**Level of Insulation**	**Building envelope Heat Transfer U-Value [Wm²/K]**			**Energy Label**
		Walls	***Roof***	***Windows***	
From 2006 in advance	High	0.265	0.22	1.82	A
From 1991 to 2005	Low	0.59	0.60	3.40	C

A. Heating System

Heating system corresponds to a hydronic radiant panel. The panel consists of 12 mm diameter and 2 mm thickness polyethylene tubes embedded in a highly conductive screed. The system runs on hot water heating the building by circulating inside the pipelines. Operating temperatures range from 20°C to 45°C, while nominal operating temperature is around 30°C. The panel is controlled through a valve which can be closed when no heat is required blocking the circulation of water in the pipelines. Temperature set-point of the heating system is 21°C: when 21.5 °C is reached valves are closed and they are re-opened if the room temperature falls under 20.5°C.

The house is located in Milano, Italy, whose climate is characterized by wet and cold winters and moderate summers. Two winter days are considered: day 1 (10th January) and day 2 (10th February). Fig. 1 shows a typical temperature profile of days studied.

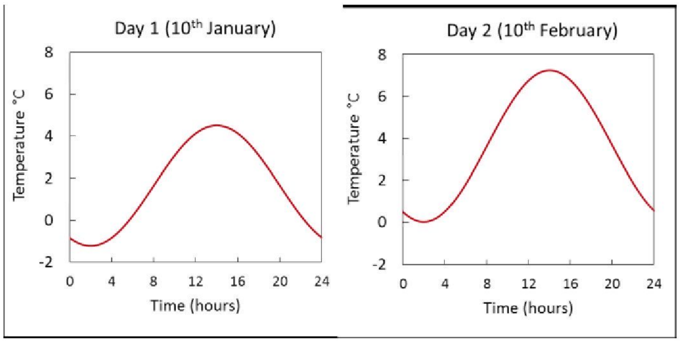

Fig. 1. Outside temperature profiles of two winter days

B. Controller

Commonly, the residential thermal controller is the hysteresis one (e.g. thermostat) where the system switches between two modes: (i) full capacity, i.e. totally open the valve, and (ii) totally close the valve, when the zone temperature reaches a boundary as sketched in Fig. 2. As working in extreme modes would cause problems in tracking set-point, zone temperature overshooting and undershooting and energy consumption, a combination of PID (acting on a mixing valve) and hysteresis (acting on an ON/OFF valve) controllers is here adopted. The actuator will be then governed by (i) hysteresis controller as high level controller for monitoring valve status and (ii) PID controller to regulate the valve opening when it is open to adapt the inlet temperature. PID parameters are tuned following a classic Ziegler – Nichols method.

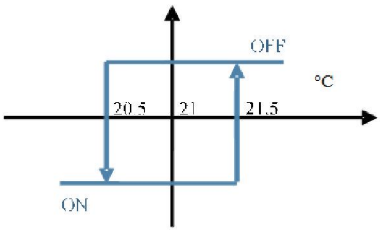

Fig. 2. Hysteresis controller

To complete the analysis and evaluation, an optimal approach based on Model Predictive Control (MPC) technique has been also tested in this paper: the obtained results from both controllers will be suitably compared. The MPC technique is based on the receding horizon control framework where a control optimization problem is formulated over a given finite horizon at every time instant. Then, only the first control action is actually applied to the system. The cost function contains two different opposite terms: temperature set-point tracking term and energy consumption term. Each of them is associated to a weight coefficient which determines how important each term is in the considered optimization problem. Namely, a high weight for temperature tracking and a low weight for the energy consumption are used during occupied hours, which means that the main purpose during this period is to satisfy the user comfort. On the contrary, an opposite setting of weights is chosen outside of the occupation hours, which means that we care only about the cost saving. Both controllers, i.e., PID with hysteresis and MPC ones, are operated with 3 minutes of sampling time. The horizon of MPC is set to 40 samples which equals to 2-hour prediction and control horizons. The MPC controller developed in this paper is built under the assumptions of perfect predictions and modeling.

C. Control Period and Heating Strategy

The study of heating strategy of a residential house allows to meet the thermal requirements without comprising the occupant comfort and heating system energy consumption. Regulating the floor radiant heating system is necessary both for reasons of energy saving and occupant's comfort [11]. The number of operating hours of a heating system has effect on the fluctuation of the indoor temperature, the amount of heat losses and ultimately in the energy consumption of the system. According to [9], two important variables must be determined in predictive control strategy for heating: daily heating operation time and distribution of heating hours throughout the day. In our study, a range of operating hours from 7 to 12 is considered for two reasons: 1) the users do not know the appropriate number of hours to heat the house to achieve the desired comfort at lower energy consumption; 2) willfully the system works less hours than necessary, for example for economic reasons.

III. Experimental Scenario

A. Description

The following scenarios have been setup and investigated:

- 2 simulation days: 10th January and 10th February
- 2 building envelope conditions: class A and class C
- Internal gains: 5 W/m^2 [16]
- 6 controlled period length: 7 hours, 8 hours, 9 hours, 10 hours, 11 hours, and 12 hours
- 5 heating strategies: 3 of them are continuous, and 2 of them are discontinuous.

Occupancy has a considerable impact on overall internal gains and consequently on heating demand and energy consumption. However, in this paper a fixed value derived from the normative method is considered assuming that the role of occupancy is not the matter of discussion of the paper. Also, adding as a new variable the occupancy role would potentially increase the number of simulation combinations and distract the analysis of the results from the aim of the paper.

The heating strategy has effect on the heat storage and dynamic heat exchange processes of building envelope. Considerable energy saving can be achieved by selecting the proper operation regime of the heating system [17].

In the case of continuous heating schemes, the house is heated when occupied, assuring a comfortable indoor temperature during occupied hours. A standard occupancy schedule of the house is considered: the inhabitants wake up in the morning, then they leave the house for working and come back in the afternoon. In continuous strategies, the time of starting heating has been matter of discussion [8] [11]. In our study, the following are considered:

- BASE: heating hours match the occupancy periods.
- EARLY: the heating system is switched on in advance a 10% of the operation time before the house is occupied.
- POSTPONED: the heating system starts a 10% of time in delay with respect to the occupancy.

In discontinuous strategies, heating hours are spread over the day. These strategies have been proved to be effective to guarantee indoor thermal comfort whereas reduce energy consumption, compared to continuous heating [18]. Two discontinuous schemes are considered:

- AVERAGE: hours are grouped into 3 or 4 periods over the day.
- INTERMITTENT: heating hours are not grouped and are intermittently distributed over the day.

Fig. 3 summarizes the five heating strategies studied. Considering the operation duration from 7h to 12h, each of the above mentioned schemes is formulated for each case. Simulation conditions considered is 1 day after reaching equilibrium.

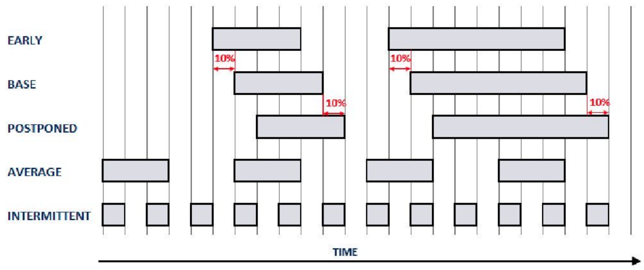

Fig. 3. Heating strategies proposed

B. Metrics

i) Total energy consumption: The energy consumption is computed as the difference between energy at pipe inlet and outlet, which supposed to warm up the room without any losses:

$$Q = w\ C_p\ (T_e - T_{out}) \tag{1}$$

where w is the water mass flow in kg/s, C_p is the specific of hot water in J/kgK, and T_e and T_{out} are, respectively, the inlet and outlet temperature in °C.

ii) User comfort. There are many indexes to assess the thermal comfort in indoor environments. Traditional approaches to evaluate thermal comfort are based on the thermal feeling from occupants, such as the Fanger method. On the other hand, there are many ways to estimate efficiency of heating systems, mainly based on the relation between the energy used and the output obtained (thermal energy).

The index here proposed is the *Index of Satisfaction* of users (IS), calculated as follows:

$$IS = M_s\ /\ Heat_{min} \tag{2}$$

where $Heat_{min}$ corresponds to the total operating time in minutes, and M_s represents the minutes at which:

$$|T(t) - 21| \leq 0.25 \tag{3}$$

where *21*°C the indoor comfort temperature and $T(t)$ the temperature of the zone also in °C. This index measures for how long the temperature of the zone is within a comfort level and allow to compare the efficiency (in terms of comfort level) of different heating strategies.

C. Calculation of upper and lower bounds

In addition to experimental scenarios, a set of 1,800 simulations are run for each length of heating period. Heating hours are randomly distributed into two periods: 5 a.m. to 9 a.m. and 3 p.m. to 12 p.m. The aim of these simulations is to obtain the upper and lower bounds for any possible continuous heating strategy.

Fig. 4 summarizes the case studies design scheme based on 4 categories to obtain the final 120 scenarios.

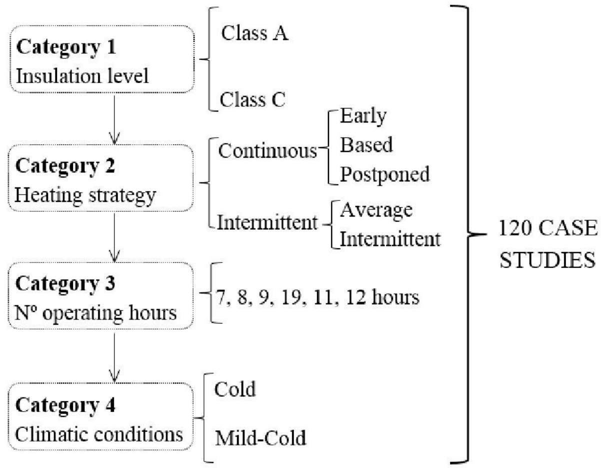

Fig. 4. The considered case studies

IV. Simulation Results

Simulations were performed with the software MatLabR2015b® to analyze the heating system performance under the different scenarios. In this section, the main simulation results of the scenarios afore mentioned are discussed.

A. High Insulated Building

Table II shows the amount of energy consumed and the Index of Satisfaction obtained for the less energy consuming strategy. In addition, the indoor temperature fluctuation is expressed in terms of RMSE from the value of 21°C. The results of the rest of strategies are shown in terms of % with respect the former.

The early strategy is the less energy consuming. In terms of comfort (evaluated by the Index of Satisfaction previously defined), the intermittent strategy is the most comfortable option. This is also confirmed by the value of RMSE. From the comparison made it can be said that the increase of satisfaction associated with the increase of energy invested depends on the strategy followed and the length of the operation period. It can be observed that an increase of the energy invested in certain strategies can be very efficient in terms of comfort. For example, for a building heated 7 hours, an increase of just 10% of the energy and the change to an intermittent strategy leads to a comfort 47% higher compared with the less energy consuming strategy.

In all the cases, lower room temperature fluctuation is obtained with the intermittent strategy which also corresponds with the higher value of IS. Considerable reduction of temperature fluctuation is obtained in the case of continuous heating strategies (average and intermittent) with respect to no-continuous strategies, at the expense of high energy consumption. The results confirm a reduction of indoor temperature fluctuation when heating longer periods for all the strategies.

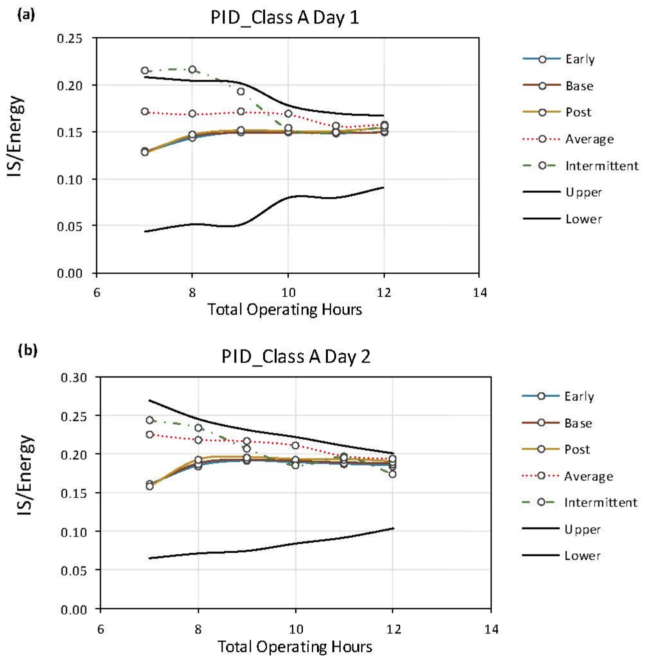

Fig. 5. Index IS/Energy of a high insulated building under a) cold climatic conditions; b) mild-cold climatic conditions.

TABLE II. RESULTS OBTAINED FOR A HIGH INSULTED BUILDING ON 10TH JANUARY

	Operating Hours					
	7	8	9	10	11	12
Strategy	***Energy [kWh]***					
Early	**5.97**	**6.18**	**6.27**	**6.29**	**6.33**	**6.40**
Base	0.31%	0.09%	-0.09%	0.23%	0.16%	0.42%
Postponed	0.88%	0.51%	-0.07%	0.66%	0.46%	3.05%
Average	10.88%	8.16%	9.64%	9.04%	10.48%	7.86%
Intermittent	23.79%	21.73%	24.38%	20.34%	28.68%	28.21%
	Index of Satisfaction					
Early	**0.77**	**0.89**	**0.94**	**0.94**	**0.94**	**0.96**
Base	0.00%	2.11%	0.00%	0.53%	0.97%	0.86%
Postponed	-0.21%	2.75%	1.15%	1.57%	1.91%	6.09%
Average	47.22%	27.46%	25.55%	23.49%	16.47%	13.95%
Intermittent	106.48%	83.10%	60.36%	23.94%	29.09%	33.60%
	RMSE					
Early	1.97	1.61	1.49	1.43	1.37	1.15
Base	-4.00%	-1.67%	-1.23%	-1.62%	-1.83%	-2.45%
Postponed	-6.91%	-3.25%	-2.74%	-3.58%	-4.29%	-21.27%
Average	-47.60%	-44.37%	-53.18%	-52.41%	-50.80%	-48.60%
Intermittent	-69.61%	-69.65%	-69.18%	-65.16%	-74.38%	-76.77%

Fig. 5 shows the impact of heating strategies on the relation IS/Energy in the case of a high insulated building, under a) cold climatic conditions (day 1); b) mild-cold climatic conditions (day 2). The energy consumption is expressed in kWh, while IS is a dimensionless quantity. Black lines represent upper and lower bounds obtained for continuous strategies. Fig. 6 represents the effect of heating strategy on the relation ΔIS/ΔEnergy under different climatic conditions. Early strategy is assumed as base line.

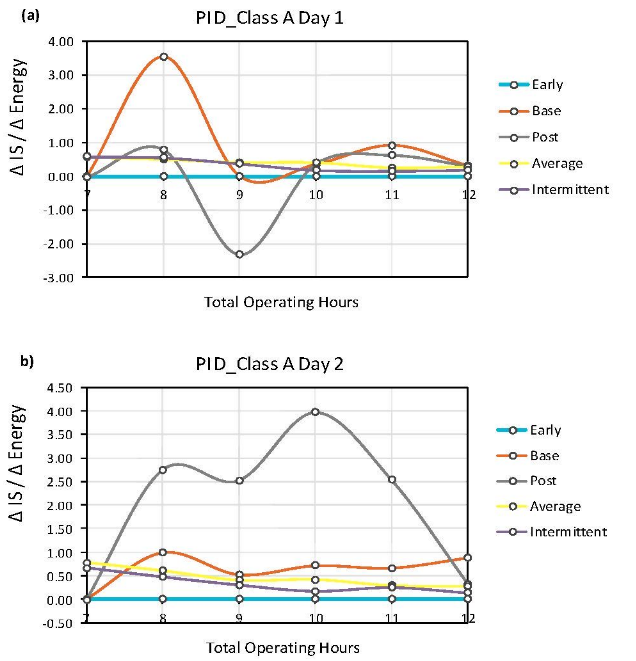

Fig. 6. Ratio ΔIS/ΔEnergy of a high insulated building under a) cold climatic conditions; b) mild-cold climatic conditions.

B. Low Insulated Building

Table III shows the results obtained for the less energy consuming strategy and the increase in % of the rest of strategies in a winter day. The temperature fluctuation with respect the comfort value is shown (RMSE) for the case of the less energy consuming strategy. The rest numbers are shown in % with respect the former.

As well as in the case of a high insulated building, the less energy consuming scheme is the early strategy. Early strategy is also associated with a lower satisfaction index (except for the case of 7 heating hours and postponed strategy, although the difference is almost negligible) and a higher indoor temperature fluctuation.

TABLE III. RESULTS OBTAINED FOR A LOW INSULTED BUILDING

ON 10TH JANUARY

	Operating hours					
	7	8	9	10	11	12
Strategy	*Energy [kWh]*					
Early	**8.82**	**9.40**	**9.62**	**9.73**	**9.83**	**10.00**
Base	0.84%	0.50%	0.16%	0.10%	0.21%	0.26%
Postponed	1.53%	0.67%	0.29%	0.38%	0.39%	2.81%
Average	14.29%	8.91%	9.49%	8.47%	7.78%	7.70%
Intermittent	22.72%	17.48%	17.36%	18.22%	20.04%	19.82%
	Index of Satisfaction					
Early	**0.63**	**0.66**	**0.74**	**0.78**	**0.80**	**0.83**
Base	0.00%	1.90%	2.24%	0.64%	1.13%	0.92%
Postponed	-0.43%	3.50%	2.06%	1.79%	2.16%	6.44%
Average	21.59%	20.95%	20.07%	15.32%	12.38%	10.46%
Intermittent	65.91%	78.10%	60.45%	50.00%	56.64%	59.67%
	RMSE					
Early	**3.28**	**2.50**	**2.26**	**2.12**	**2.01**	**1.72**
Base	-3.43%	-1.33%	-1.11%	-1.34%	-1.52%	-1.92%
Postponed	-6.68%	-2.80%	-2.09%	-2.87%	-3.45%	-18.50%
Average	-48.88%	-41.41%	-49.27%	-47.87%	-45.10%	-44.81%
Intermittent	-70.57%	-69.50%	-69.09%	-68.11%	-77.22%	-84.64%

From these results, it is observed that small increases in the energy invested in the heating system, result in a considerable increase of comfort level. For example, in the case of a building heated 9h, an increase lower than 17% in the energy invested results in a gain up to 60% in the index of satisfaction following the intermittent strategy instead of the early one.

Fig. 7 plots the ratio IS/Energy of a low insulated building in the case of a) cold day; b) mild-cold day. Intermittent strategy is more efficient in terms of ration comfort/energy. The ratio ΔIS/ΔEnergy under different climatic conditions is compared in Fig. 8 The results show that continuous strategies are more efficient if operating longer periods.

C. MPC controller results

Results obtained with the MPC controller are shown in Fig. 9 for a high insulated building (9a) and a low insulated building (9b). The results show stable trend of IS/Energy with respect to changing of operating hours in both class A and class C as well as high and low insulated buildings. In average, MPC provide 0.16 and 0.1 of IS/Energy of cold day cases of class A and class C which account for 14% improvement with respect to the performance of PID control.

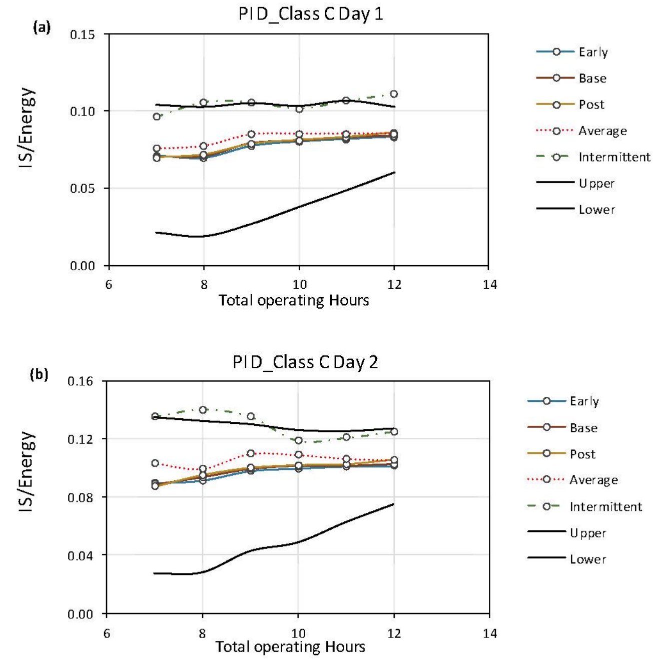

Fig. 7. Index IS/Energy of a low insulated building under a) cold climatic conditions; b) mild-cold climatic conditions.

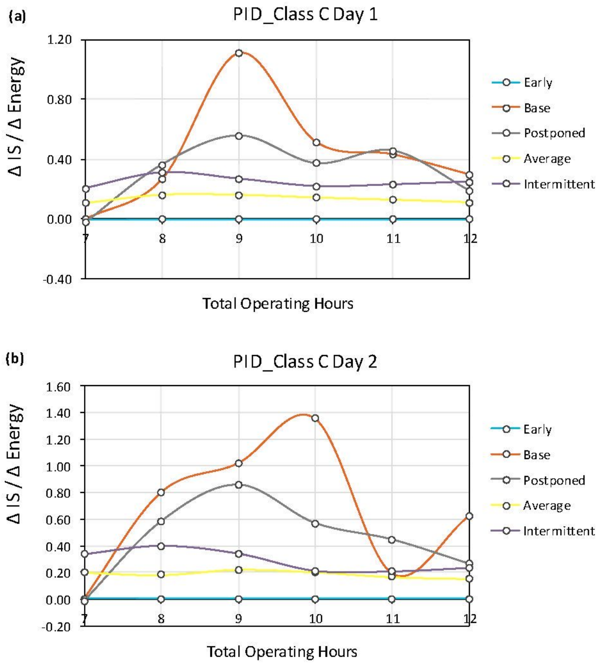

Fig. 8. Ratio ΔIS/ΔEnergy of a low insulated building under a) cold climatic conditions; b) mild-cold climatic conditions.

In particular, the differences in performances of PID and MPC are typical higher in short operating-hour (i.e., 7, 8 hours) than in medium and long operating-hour cases (i.e., 9, 10 hours and 11, 12 hours) that can be explained by the capability of reaching the set-point in short rise and settling times and low overshoot manner of MPC.

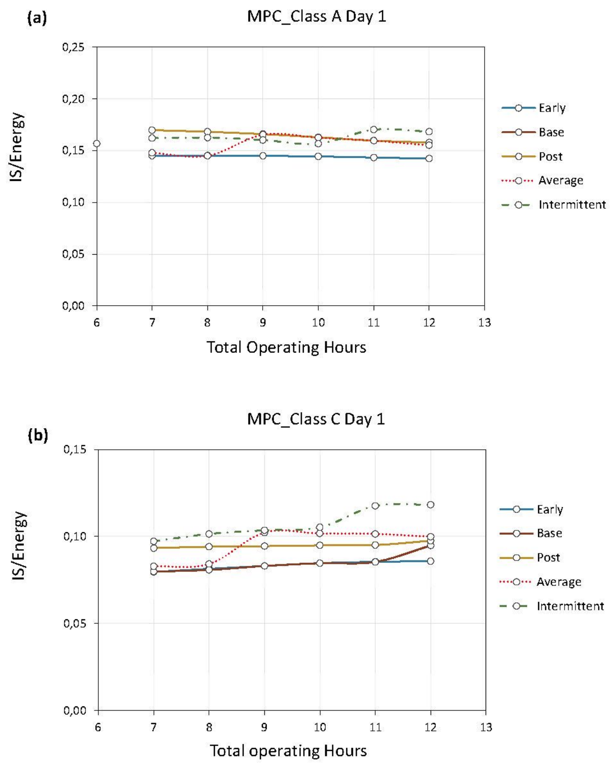

Fig. 9. Results obtained with the MPC controller for a high insulated building (a) and low insulated building (b) in a cold winter day.

V. Discussion

A. High Insulated Building

The results from Table II show the most efficient strategy to invest energy in terms of comfort level and indoor temperature fluctuation. The results from Fig. 5 show that intermittent strategy is associated with higher comfort level. However, when increasing energy higher increase of comfort level is allowed by non-continuous strategies. Average strategy shows the most stable behavior in terms of increase of IS by Energy increase. As the heating period becomes longer, the ratio IS/Energy for continuous strategies tends to stabilize.

B. Low Insulated Building

Results from Fig. 7 demonstrate that in the case of a low insulated building, non-continuous strategies are more efficient, reducing the indoor temperature fluctuation. Heat loss velocity is increased in poor thermal insulated buildings and consequently spreading heating hours during the day contributes positively to maintain indoor temperature more stable. However, as can be seen in data from Table III, non- continuous strategies consume more energy.

C. General Discussion

The results from Table II and Table III highlight the benefits of the intermittent heating strategies under different insulation levels. From an energetic consumption point of view, the pre-heating has advantages over the rest, as less effort is required to the system to maintain the room temperature at the required temperature. However, from a comfort point of view, pre-heating is the strategy in which higher indoor temperature fluctuations occurs and is associated with higher rates of discomfort.

VI. Concluding Remarks

In this paper, a study of the efficiency of continuous and discontinuous heating strategies for a floor heating system controlled with a combination of PID control and hysteretic one is presented. The efficiency is calculated in terms of energy consumed compared to the comfort level reached.

As major contribution, a new assessment of user comfort is proposed, evaluating time under comfort range level regarding the total operation term. The methodology proposed enables to assess the efficient investment on energy in terms of comfort. The experimental scenarios address different insulation levels, depicted as building classes.

The results obtained are useful for the decision making of the heating strategy and number of hours in a building. For different building insulation levels and outdoor conditions, decision makers can observe the most efficient way to invest energy in the heating system in terms of raising indoor comfort. In addition, the results can help in the decision of energy retrofitting of existing buildings, indicating the potential energy saving.

This study highlights the role of the decision maker purpose when determining the most convenient heating strategy, as the decision can be made under comfort criteria, under energy saving criteria or following both criteria. Also, it also evidences the sensibility of the floor heating system to climatic outdoor conditions variations, the level of thermal insulation and the effect of the heating strategy. As a major contribution, the results of the study manifest the advantages of the intermittent heating strategies in terms of comfort, in contrast of the traditional continuous heating strategies. The results here discussed demonstrate that a higher user's comfort can be reached by selecting the most appropriate heating strategy. In other words, the energy is more efficiently used.

With this analysis, the following conclusions can be drawn:

- The efficiency of a strategy is affected by: a) building thermal insulation level; b) total number of operating hours (length of heating period); c) distribution of heating hours (heating strategy); d) outdoor climatic conditions.
- When unheated period is reduced, the energy is more efficiently used in keeping the indoor temperature under comfortable levels.
- Investing the same amount of energy, significant improvements in comfort can be achieved by selecting the correct heating strategy.

The modeling framework allows obtaining the most efficient heating scheme under different conditions:

- Building retrofit by improving the insulation level (from class C to class A), allow higher comfort level with less energy consumption, indicating the results the number of hours of heating.

- In winter, in poor insulated buildings (class C) an energy saving of more than 5% is possible by choosing a proper heating strategy whereas obtaining the same satisfaction index.
- When the energy investment in heating is limited (for economic reasons for example) the satisfaction level can be maximized by choosing the most effective heating strategy. For example, in a building class C that consumes less than 10kWh for heating, a 33% more satisfaction can be achieved following a postponed strategy compared with an early strategy.
- The efficiency of the energy invested in heating depends on the operation strategy and insulation level. For example, in the case of a low insulated building that operates for 8h following an average strategy, less than 10% more energy produces an increase of 20% of satisfaction than if a continuous strategy is followed.
- Optimal controllers can of course be used. However, strangely enough, the gain in comfort/efficiency is not that strong, thus proving that a suitable design of the heating panels along with a well-tuned traditional controllers and compensators can be a valid option.

Future directions include the analysis of the impact of various control schemes on the control performances under different user requirements and external conditions. The less energy consuming control schemes will be investigated and compared.

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