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Abstract: People mostly spend their time inside buildings, so great part of the energy consumed is used for assuring users' comfort by means of HVAC systems or illumination. Therefore, it is important to take into account users' comfort when dealing with energy management. Both objectives, energy efficiency and comfort, are opposed, thus a multiobjective approach is needed. In this paper,
a set-points optimizer is proposed. Concretely, it has been designed to be used within the CIESOL, a solar energy research centre located in the South East of Spain. Thanks to multiobjective optimization techniques, this system will provide optimal temperature and illuminance set-points which will ensure both users' thermal and visual comfort, subject to some energy efficiency criteria.
These set-points will make possible not only to reach significant energy savings - the results are estimated to be between 7 to 19 % - but also to create a proper
environment for users. This will have an impact in their productivity and, even more importantly, in their health.

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***Cover Letter**

Q. G. Wang
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Dear Editor,

Please find enclosed the paper entitled '*Multiobjective control architecture to estimate optimal set-points for users' comfort and energy saving in buildings*' and authored by María Martell, Francisco Rodríguez, María del Mar Castilla and Manuel Berenguel. It has been submitted to *ISA Transactions* journal to be considered for publication.

The goal of this work is to present the procedure for implementing a set-points optimizer for a solar energy research centre, the CIESOL building. To obtain the optimal set-points, two main objectives are considered: (i) users' comfort, which is defined by thermal and visual conditions and (ii) energy consumption. Moreover, this optimizer has been integrated into a multilevel hierarchical control system. The performance of the proposed architecture has been tested along different typical days from March to July and the obtained results are promising. More in detail, it is able to estimate appropriate temperature and illuminance set-points in order to guarantee users' comfort and, simultaneously, to increase energy savings between 7 to 19%.

We consider this paper as highly relevant in comfort control, energy efficiency and optimization fields. Furthermore, as the proposed architecture presented in this paper is versatile and flexible since it allows to easily obtain different results according to several users' criteria, locations, etc. by modifying the post-optimization processing stage and to add new objectives in a simple way, it can be extrapolated to any other building. Therefore, the results can be of interest for many researchers working on this field, so we kindly ask you to consider it for publication.

We confirm that neither the manuscript nor any parts of its content are currently under consideration or published in another journal.

We are looking forward to your response.

Yours sincerely,

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Multiobjective control architecture to estimate optimal set-points for users' comfort and energy saving in buildings

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Abstract

People mostly spend their time inside buildings, so great part of the energy consumed is used for assuring users' comfort by means of HVAC systems or illumination. Therefore, it is important to take into account users' comfort when dealing with energy management. Both objectives, energy efficiency and comfort, are opposed, thus a multiobjective approach is needed. In this paper, a set-points optimizer is proposed. Concretely, it has been designed to be used within the CIESOL, a solar energy research centre located in the South East of Spain. Thanks to multiobjective optimization techniques, this system will provide optimal temperature and illuminance set-points which will ensure both users' thermal and visual comfort, subject to some energy efficiency criteria. These set-points will make possible not only to reach significant energy savings - the results are estimated to be between 7 to 19 % - but also to create a proper environment for users. This will have an impact in their productivity and, even more importantly, in their health.

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***Highlights (for review)**

- This work presents the procedure for implementing a set-points optimizer for a solar energy research center, the CIESOL building.
- To obtain the optimal set-points, two main objectives are considered: (i) users' comfort, which is defined by thermal and visual conditions and (ii) energy consumption.
- The proposed optimizer has been integrated into a multilevel hierarchical control system.
- The performance of the proposed architecture has been tested along different typical days from March to July.
- The proposed set-points optimizer is able to estimate appropriate temperature and illuminance set-points in order to guarantee users' comfort and, simultaneously, to increase energy savings between 7 to 19%.

Multiobjective control architecture to estimate optimal set-points for users' comfort and energy saving in buildings

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Abstract

People mostly spend their time inside buildings, so great part of the energy consumed is used for assuring users' comfort by means of HVAC systems or illumination. Therefore, it is important to take into account users' comfort when dealing with energy management. Both objectives, energy efficiency and comfort, are opposed, thus a multiobjective approach is needed. In this paper, a set-points optimizer is proposed. Concretely, it has been designed to be used within the CIESOL, a solar energy research centre located in the South East of Spain. Thanks to multiobjective optimization techniques, this system will provide optimal temperature and illuminance set-points which will ensure both users' thermal and visual comfort, subject to some energy efficiency criteria. These set-points will make possible not only to reach significant energy savings - the results are estimated to be between 7 to 19 % - but also to create a proper environment for users. This will have an impact in their productivity and, even more importantly, in their health.

Keywords: Thermal and visual comfort; efficient energy use; bioclimatic building; set-points optimizer; Pareto front; trade-off solution

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1. Introduction

Nowadays, buildings, both public and residential ones, are major energy consumers. In fact, last information provided by Eurostat reveals that buildings consume up to 38% of energy [1]. Furthermore, people spend the most part of their lives inside them. For this reason, assuring users' comfort has become a key aspect in energy management field.

Indeed, there are two main approaches in literature. On the one hand, those focusing on optimizing building components or characteristics supporting architectural design stage [2, 3]. Unfortunately, this approach does not provide a solution for existing buildings. On the other hand, approaches consisting of actively modifying building behaviour through automatic control strategies, which involve calculating optimal control signals or set-points, according to certain objectives. In addition, this strategy can be potentially implemented both in existing and newly-constructed buildings, as was proven in [4].

Within this framework, most research efforts focus on ensuring users' comfort as well as efficient energy management by controlling HVAC (Heating, Ventilation and Air Conditioning) or illumination systems. Regarding comfort objective, it is widely defined by thermal sensation, visual comfort and indoor air quality. Reaching comfort usually means controlling those aspects, as proposed in [5, 6, 7, 8, 9]. Additionally to energy management and comfort objectives, any can be taken into account, such as productivity [10]. Unfortunately, former objectives are opposed, i.e. it is not possible to set an operation point that optimizes them individually. Thus, a multi-objective optimization approach is needed to obtain a trade-off solution between users' comfort and energy consumption, so that both objectives are satisfied without putting at risk users' welfare.

Hence, this paper presents the procedure for implementing a set-points optimizer for a solar energy research centre, the CIESOL. To obtain the optimal set-points, two main objectives are considered: (i) users' comfort, which is defined by thermal and visual conditions and (ii) energy consumption. Moreover, this optimizer will be integrated into a multilevel hierarchical control system, described in [11].

This paper is organised as follows. In section 2, a description of the facilities where the study has been conducted is presented. In Section 3, multiobjective optimization concept is briefly defined as well as the cost functions and multi-objective algorithm proposed for this research. In Section 4, the optimization architecture is described. In Section 5, the results of two-days trial, concerning summer and winter operating modes, are shown and discussed. Lastly, in Section 6, main conclusions and future works are summarised.

2. System description

The CIESOL (http://www.ciesol.es) is a research centre on solar energy located inside the campus of University of Almería, in the South East of Spain. It is one of the five buildings which are part of the project ARFRISOL, a singular strategic project of the Spanish R&D plan 2004-2011 financed by EU-ERDF funds and the Spanish Ministry of Science and Innovation.

Furthermore, this centre was built under some bioclimatic criteria, such as specific insulation depending on the orientation or HVAC systems based on solar energy. The building itself has a total surface of 1071.91 m^2 distributed in two floors. Moreover, every room is monitored by a network of sensors, whose data is stored through an acquisition system, and controlled by means of some actuators, i.e HVAC systems, automated windows or shading devices. Data related to meteorological conditions, such as solar radiation, temperature or humidity, is collected and stored as well.

To evaluate the performance of the optimizer proposed in this paper, all the data were gathered in a selected room in CIESOL, henceforth called L6. This room, with a total surface of 76.8 m^3 (4.96 $m \times 5.53$ $m \times 2.8$ m), is in the first floor of the building and faces north, delimited by two similar laboratories, situated to the east and west of it, respectively. It has an only window located at north wall which takes up 4.49 m^2 (2.15 $m \times 2.09$ m). L6 is fully equipped with sensors and actuators which make possible an effective comfort control. According to the objectives set, main actuators are a FCU (Fan-Coil Unit) for thermal comfort control and adjustable lights and automated blinds for visual comfort control. The typical occupation of L6 is 4 people with their computers.

It is also important to note that the HVAC system is centralized and distributes cold/hot water to FCU of each room in the building. Therefore, there are two operating modes: (i) summer mode, from May to September, and (ii) winter mode, from October to April.

3. Multiobjective optimization framework

Regarding optimization problems, more than one objective is often considered. However, it is hardly-ever possible to minimize (or maximize) objectives simultaneously, as they are in conflict. Thus, a multiobjective optimization approach is needed.

A multiobjective optimization problem is defined as a search for a decision vector, x, which satisfies certain constrains and optimize a vector of objective functions, as shown in (1). Nevertheless, as this kind of problem is characterized by having two or more competing objectives, the solution will not be unique, but a set of efficient or non-dominated solutions, known as Pareto front [12]. Among them, the trade-off solution which fits best to the problem according to decision maker's criterion is selected.

$$\begin{aligned} J = \quad & \min_{x \in \Omega}(J_1(x), J_2(x), ..., J_n(x)) \\ s.t \quad & g_i(x) \leq 0, \;\; i = 1, 2, ..., m \\ & h_j(x) = 0, \;\; j = 1, 2, ..., p \end{aligned} \tag{1}$$

In this paper, two objectives are taken into account: (i) maximize thermal and visual comfort, and (ii) minimize energy consumption. Hence, a cost function which encompasses both objectives has been defined. In addition, the system proposed should be able to complete two tasks: (i) to calculate a set of non-dominated solutions, which achieves both goals, and (ii) to select the best trade-off solution among them following some decision maker's criteria.

3.1. Evaluation of human comfort

The aim of the system is to maximize users' comfort. Instead, a cost function which evaluates users' discomfort level is proposed, thus a minimization problem is faced. Moreover, it is necessary to include two comfort objectives in one cost function. As shown in (2), users' discomfort, J_1, is defined as the weighted sum of each set-point deviation from its ideal value. Absolute value is used so that positive deviation in one term do not reverse a negative deviation in the other.

$$J_1 = \omega_1 \left| \frac{x_1 - x_1^*}{x_1^*} \right| + \omega_2 \left| \frac{x_2 - x_2^*}{x_2^*} \right| \tag{2}$$

where x_i is the decision variable, which represents temperature (i=1) and illumination (i=2) set-points, x_i^* is the comfort ideal value for set-points and ω_i is a weighting factor, whose value determines the relative importance of each comfort element. By default, both comfort terms are equally important; consequently, the same value is assumed for them:

- **Thermal comfort**. An ideal temperature is needed to evaluate the cost function proposed previously. PMV index, defined by [13], is a seven-point thermal sensation scale between ±3, where 0 represent a neutral thermal sensation. PMV is function of six environmental and users dependent variables: air relative humidity, air velocity, mean radiant temperature, air temperature, clothing insulation and metabolic rate. The ideal temperature corresponds to that which makes PMV index equal to zero within a given set of environmental conditions and, therefore, changes depending on them.

- **Visual comfort** Among main parameters which determine visual comfort, illuminance is selected to estimate it, since it is easy to measure and its comfort range has been widely studied. Ideal illuminance is set in 500 lux, as standards suggest for typical office tasks [14]. Notice that in other applications of artificial lighting control, like indoor crop growth, other objectives may arise, for instance how to distribute the energy radiated in each photo-period [15].

3.2. Evaluation of energy consumption

Main actuators are FCU for thermal comfort control and adjustable lights for visual comfort control. Automated blinds' energy consumption is negligible compared to them. Thus, J_2, in (3), is an estimation of the economic cost, depending on the price of energy, p_{kWh}, and defined by the sum of the energy consumed by FCU unit (E_1) and adjustable lights (E_2).

$$J_2 = p_{kWh}\big(E_1(x) + E_2(x)\big) \tag{3}$$

where p_{kWh} is updated according to energy prices along the day and $E_1(x)$ and $E_2(x)$ are estimated through models. In particular, a temperature model of L6 based on first principles is used for FCU energy consumption. On the other hand, an Artificial Neural Network (ANN) black-box illuminance model of L6 has been used to estimate adjustable lights energy consumption. For more information, see [16] and [17], respectively.

3.3. Multiobjective optimization algorithm for comfort and energy management problem

Multiobjective optimization process must provide relevant information to decision maker, i.e a diverse and accurate Pareto front, to take final decisions. Due to non-linearities and difficulties of derivability of models and cost functions, evolutionary algorithms have received considerable attention in energy management field. Specially, NSGA-II (Non-dominated Sorting Genetic Algorithm) and MOPSO (MultiObjective Particle Swarm Optimization) are the most used algorithms in building performance design [18]. In this case, MOPSO performance was better, therefore this algorithm is integrated into the optimization scheme. MOPSO algorithm is inspired by behaviour and dynamics of a bird flock, where each particle is characterized by its position, velocity and previous performance and moves around the search space arbitrarily, updating according to its own and best particles' characteristics. Some particles are non-dominated solutions and, thus, part of the Pareto front [19].

4. Optimization architecture

In this paper, the optimization architecture proposed and implemented is based on a hierarchical control architecture defined in [11] for CIESOL building, including some modifications in the upper layer, see figure 1.

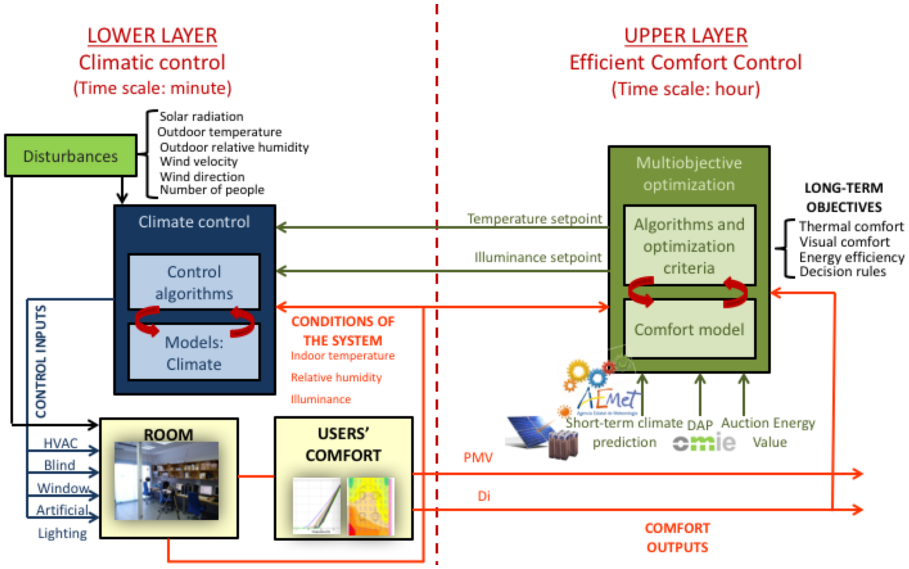

Figure 1: Hierarchical control architecture proposed for CIESOL building.

Briefly, the hierarchical control architecture proposed consists on two layers. The upper layer calculates optimal set-points during the day, so that both energy efficiency and users' comfort objectives are achieved. One set-point is communicated to the lower layer per hour. In turn, the lower layer is composed by the control loops which allows to reach the set-points established by the upper layer through the use of the main actuators. A description of some of these control loops can be found in [16].

By default, a time scale of one hour is chosen for three main reasons. Firstly, temperature steady-state model of L6 can be used assuming little error. Secondly, predictions are more accurate an hour ahead than a whole day ahead. Finally, energy price predictions in Spain are also published hourly.

More concretely, upper layer is started at 8 a.m each working day to calculate a set-point for a preconditioning of the room. All set-points are maintained during an hour. The system restarts the optimization process once an hour to calculate a new set-point according to updated values of the main variables (energy price, indoor and outdoor conditions, etc.). To do that, it is necessary to have at disposal predictions or real-time values of these variables. Concretely, energy price predictions have been obtained from [20], indoor conditions of L6 are assumed constant and equal to the last available values provided by the network of sensors from CIESOL building, and finally, outdoor conditions predictions are hourly provided by the Spanish Meteorological Agency.

The optimization process consists on two stages. First, a Pareto front is generated through a multiobjective optimization algorithm - MOPSO, in this case. Then, a post-optimization processing stage is needed so that a single solution is chosen from the set of trade-off solutions in the Pareto front, see figure 2. An algorithm selects one solution in compliance with decision maker's criteria. More in detail, these criteria consider: i) To discard these solutions which provide a temperature set-point with an associate PMV index out of thermal comfort range, that is, $[-0.5, 0.5]$; ii) Among the previously selected solutions, to choose this one able to reach the greatest visual comfort level, and iii) in case of conflict, the solution which guarantees the lowest energy consumption is selected. The system is shut down once the working day comes to an end, at 6 p.m, since the building is unoccupied thereafter.

5. Results and discussion

As noted, an optimization process is started each hour with updated parameters and values, therefore a new Pareto front is generated. For this reason, ten Pareto fronts are calculated along the day, from 8 a.m until 5 p.m, last set-point is maintained until 6 p.m.

The optimization system has been tested for typical days of months from March to July with promising results. These tests cover the two operating modes of CIESOL building: winter and summer. Two most remarkable tests

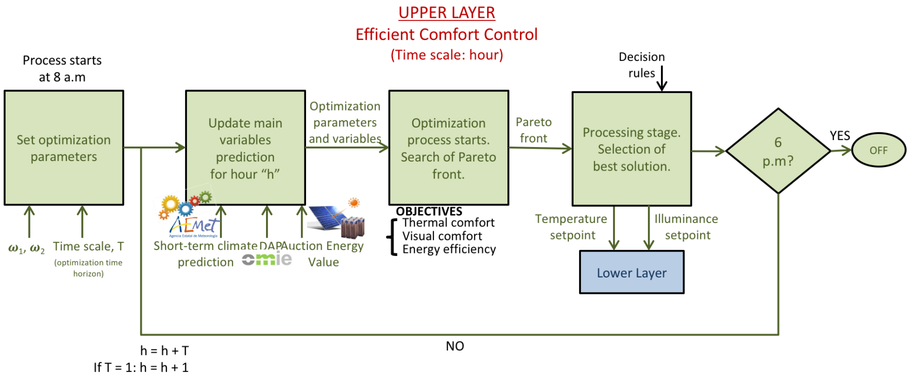

Figure 2: Functioning scheme for the upper layer.

are presented and discussed below; one for summer operating mode and one for winter operating mode of HVAC system. In general, different tests performed with the proposed optimization system are characterized by a computing time[1] between 3 and 6 minutes.

In figures 3 and 4, environmental conditions for the tests are shown for a better understanding of results. In figure 5, Pareto fronts are presented for a typical day in April. One Pareto front is generated per hour. A diamond represents the solution selected by post-optimization processing stage, therefore it is the one that fits best with decision maker's criteria. In figure 6, set-points selected from each Pareto front are gathered and presented. Dot lines mean comfort ideal temperature and illuminance (without taking energy efficiency into account). In figures 7 and 8, equivalent results are presented for a typical day of July.

In general, Pareto fronts are unique and depends on main parameters and variables of the optimization process. Thus, there are infinite Pareto fronts related to infinite possibilities for environmental conditions. Additionally, HVAC operating mode has a relevant impact on results.

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[1] Simulations are conducted in Intel® Core™i5-6500T CPU 2.5GHz RAM 8 GB, Windows 10x64 and Matlab 2017.

Winter operating mode. According to international standards, comfort ideal temperature (class C) and illuminance for offices are close to 24.5°C and 500 lux, respectively. When a solution approaches those values, discomfort level decreases. Simultaneously, an increment on energy cost function is recorded. Instead, optimal solution for energy consumption objective means proposed set-points equal to outdoor temperature and natural illuminance, getting a poor comfort condition for users. As seen above, optimization process does not necessarily find an optimal solution for comfort objective, due to restrictions of FCU and lighting system. These restrictions makes possible to calculate and subsequently choose a pair of coherent set-points, which lower layer can handle. Moreover, it has been reported an impact of occupation in energy consumption. A person is a heat-generator entity, thus more occupation implies less energy consumption, in contrast to summer operating mode where energy consumption increases.

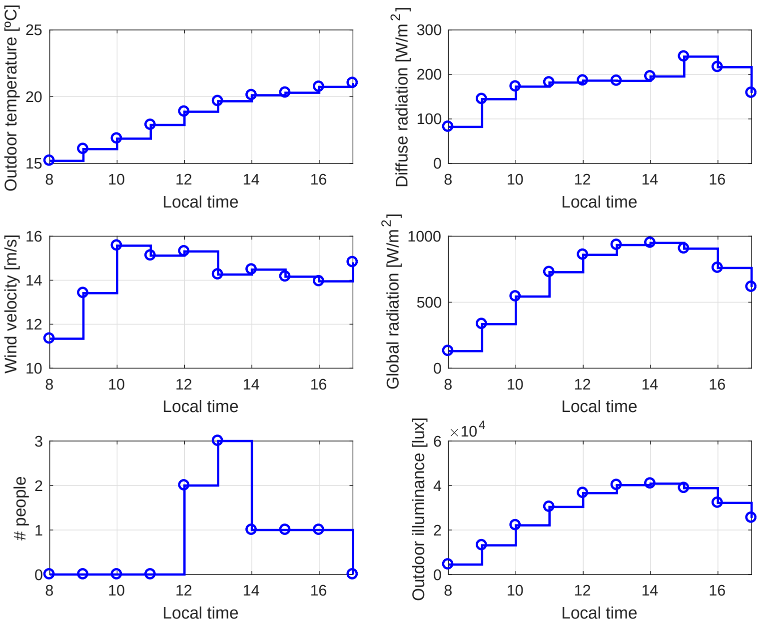

Figure 3: Environmental conditions for day 21/04/17.

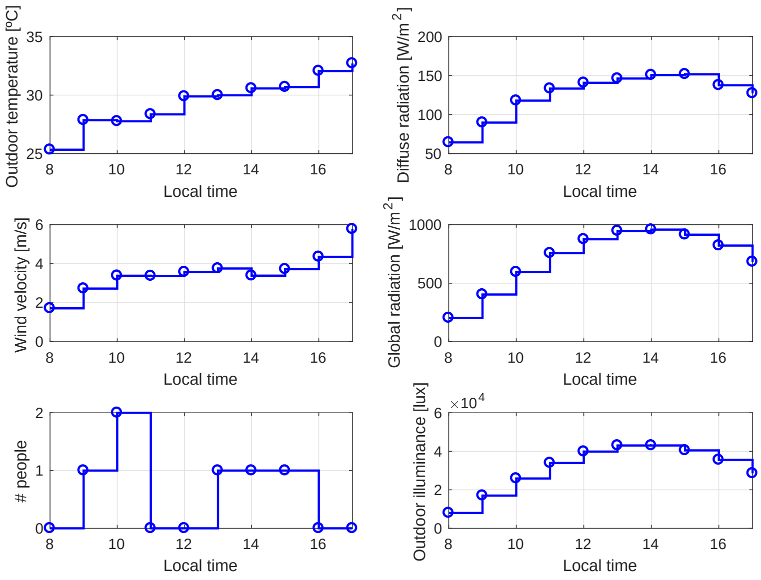

Figure 4: Environmental conditions for day 10/07/17.

Summer operating mode. According to international standards, comfort ideal temperature (class C) and illuminance are close to 26.7°C and 500 lux, respectively. Discomfort decreases when set-points approach those levels, as well as energy consumption increases. Opposite to winter operating mode, energy consumption increases at the same time that temperature set-point is reduced, since it is needed to cool down L6. In addition, it is easier to maintain high comfort level at lower costs at midday (12 a.m) than at any other time, as natural light contributes to perform better. In fact, some limitations in lighting system, included in light model, often impede from achieving optimal visual comfort. Thus, all proposed set-points can be reached, but a possibility of not getting a comfort ideal solution exists. Indeed, as seen in figure 5 and 7, the optimization process does not always propose a solution for $J_1 = 0$ (discomfort cost function).

Regarding final set-points, figures 6 and 8, which are finally sent to lower layer, there are two main conclusions. First, temperature set-points tend to be higher/lower than ideal comfort temperature in summer/winter. Depending

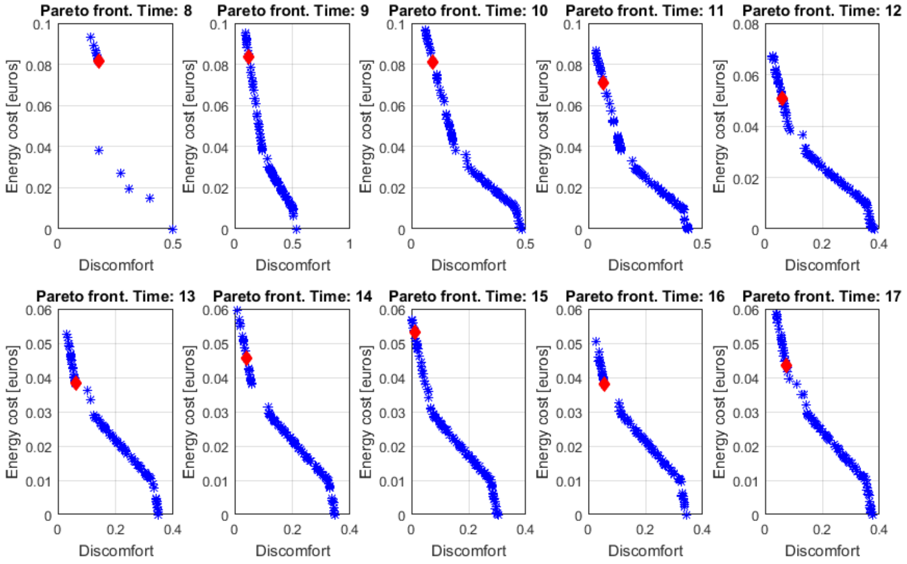

Figure 5: Pareto fronts for a typical day of April. Operating mode: winter.

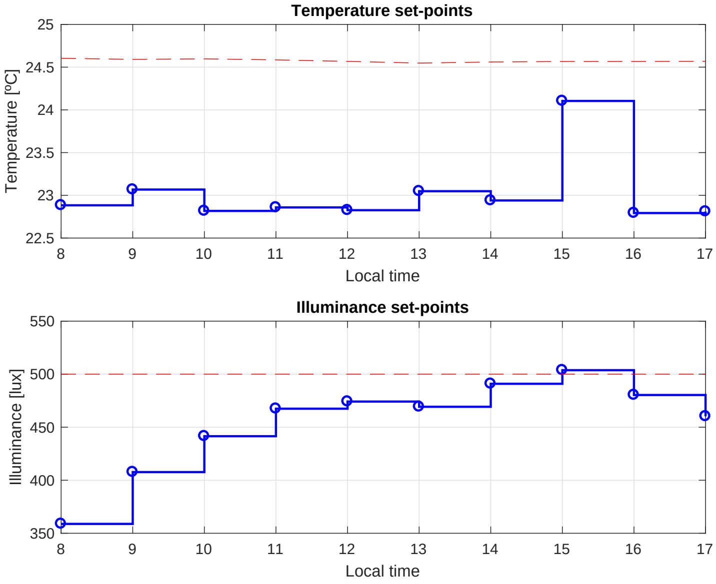

Figure 6: Set-points along a typical day of April. Operating mode: winter.

on post-optimization processing algorithm and decision maker's criteria, those values may vary. In this case, criterion chosen was temperature to be in a PMV region of ±0.5 assuring low energy consumption. Indeed, proposed temperatures set-points are close to PMV $= \pm 0.5$ for summer and winter, respectively. Secondly, due to lighting system limitations noted above, processing algorithm always selects an illuminance set-point associated to a higher visual comfort level, thus main energy savings comes from thermal comfort control.

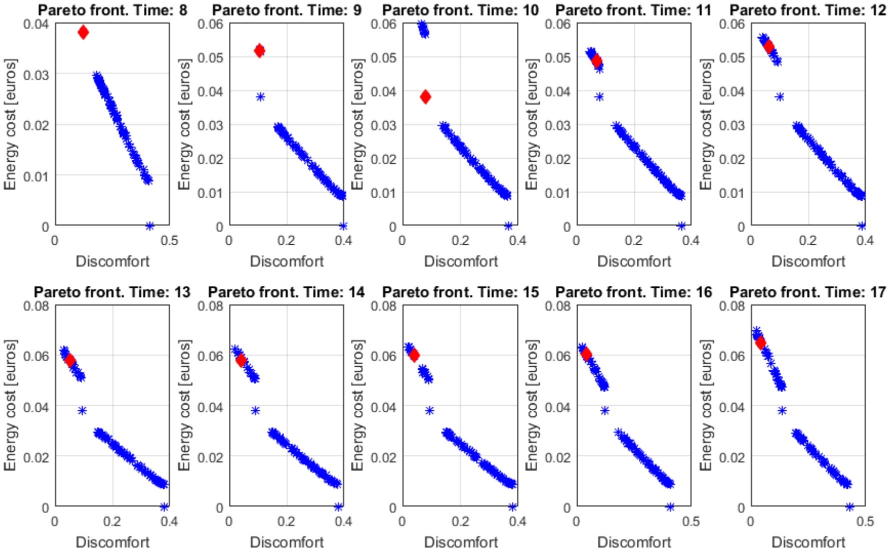

Figure 7: Pareto fronts for a typical day of July. Operating mode: summer.

Additionally, a relative energy cost reduction has been estimated. Main assumption is to consider that users always tend to an ideal comfort condition, which means they would choose a solution close to that one with highest energy consumption and lowest discomfort level from Pareto front. As noted in table 1, promising results for energy savings are presented. Although a deeper study which compares energy consumption for users' selected operating points and set-points proposed by the upper layer of the hierarchical control architecture is needed, these results suggest significant energy savings - between 7 to 19% on average -, mainly during spring and, therefore, autumn, when weather

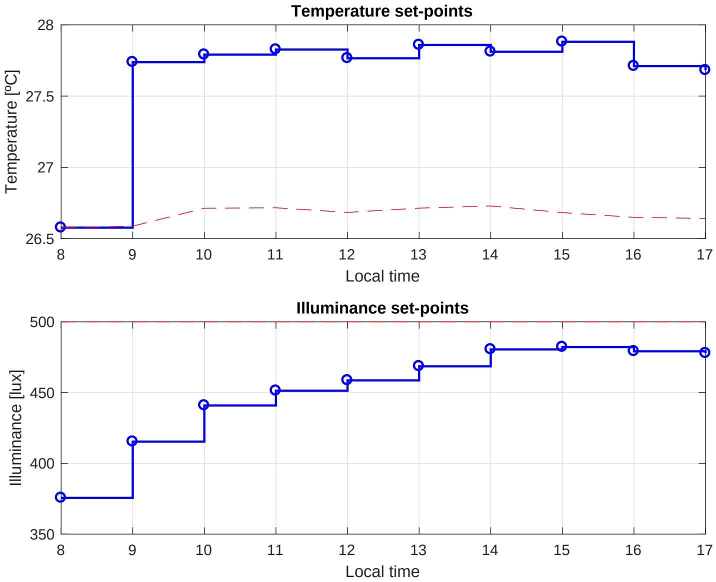

Figure 8: Set-points along a typical day of July. Operating mode: summer.

conditions are moderate.

6. Conclusions

In this paper, a set-points optimizer for the CIESOL building has been presented. Specifically, two main objectives have been considered: users' comfort (from thermal and visual points of view) and energy efficiency. Furthermore, this optimizer has been integrated into a multilevel hierarchical control system. The performance of the proposed architecture has been tested along different typical days from March to July and, as it was shown within the Results and discussion section, the obtained results are promising. More in detail, it is able to estimate appropriate temperature and illuminance set-points in order to guarantee users' comfort and, simultaneously, to increase energy savings between 7 to 19%. Additionally, it is necessary to emphasise that the optimization

Table 1: Relative energy cost reduction.

Time	**April**	**July**
8 a.m	12.2	0
9 a.m	12.6	0.5
10 a.m	15.8	36.1
11 a.m	17.6	5.5
12 a.m	24.6	4.8
1 p.m	27.5	6.2
2 p.m	23.7	7.3
3 p.m	6.4	5.6
4 p.m	24.3	4.4
5 p.m	25.7	6.8
Mean	19.0	7.7

architecture presented in this paper is versatile and flexible since it allows to easily obtain different results according to several users' criteria, locations, etc. by modifying the post-optimization processing stage. Moreover, it is possible to simply adapt the presented optimizer in order to include new objectives and to consider new actuators.

As future works, the multilevel hierarchical control system which includes the optimizer presented in this paper will be evaluated in L6 room of CIESOL building by means of real tests. In addition, indoor air quality will be added as an additional objective in order to evaluate users' comfort.

Acknowledgments

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