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Article

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Can buildings be more intelligent than users?- The role of intelligent supervision concept integrated into building predictive control

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Abstract

This study addresses a new generation of adaptable intelligent control systems for energy management. The proposed approach consists of a high-level predictive control system based on advanced simulation and optimization algorithms which interact with conventional machine-level controllers of HVAC systems, e.g., PID, in order to define optimized set points considering current and forecasted operation conditions, minimizing a predefined objective cost function, e.g., energy consumption, subjected to maintain predefined levels of comfort. The flexibility of the proposed architecture and the development of reliable surrogate models based on robust machine learning techniques are key features to combine green building requirements while granting or even improving occupant comfort. A first version of the proposed system was developed, and preliminary results emphasize its role in the path of transition to intelligent green buildings as a part of new buildings or, more important, as a retrofit of current buildings, with almost no changes on infrastructures, but promoting them to a smart building level.

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Keywords: Energy efficiency; Green buildings; Intelligent supervision; Supervised predictive control

1. Introduction

Recently, High-Tec companies have found that to maintain in a top-rank attractive company, to have a bright vivid future and to keep on their business life with more interest, or at least with a stable rate, especially in the battle of free market against other giant companies, they should be smart and use intelligent systems. The best examples of smart companies are Apple, Google, Microsoft and Amazon which makes an outstanding breakthrough in their recent product and services in order to provide more comfort and facilities for their customers. Wide repertoires of Google's artificial intelligence have been disclosed just recently [1–4].

Energy efficiency and circular economy are two of the most discussed topical issues all over the world. In this scenery, energy efficiency raises as a cost-effective way to reduce GHG emissions and improve energy supply

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Nomenclature

D	Discomfort objective function
E	Cost of Energy consumption
PPD	Further nomenclature continues down the page inside the text box
CT	Comfort Target
TE	Tariffs on Energy source
n_Y	Normalization vector for Energy Consumption
EC	Energy Consumed at each time-step
OFF	Occupants Forecast Filter
PF	Penalty Function
N_E	The number of energy sources available
N_a	Total number of time-steps considered for the forecast window

security by reducing primary energy consumption and decreasing energy imports [5]. Although energy efficiency levels have improved over the last years, there is a significant unexploited energy efficiency potential, namely in the building sector [6]. Indeed, buildings offer great potential for energy saving opportunities since their performance level is frequently far below current efficiency potentials [7]. In the United States of America, this sector accounts for more than 40% of national energy consumption [8]. In Europe, buildings are responsible for around 36% of CO₂ emissions [9] representing an increasingly important sector for energy efficiency measures implementation [10]. Only 2% of construction projects are new constructions and over 86% of investments in this sector go into existing buildings. Therefore, the greatest opportunity for overall reduction in primary energy use is by increasing the energy efficiency of existing service buildings [11]. Energy reduction efforts for existing buildings are numerous and include more energy efficient technologies for heating, cooling and ventilation systems, use of high-efficiency lighting and equipment, smart glazing, use of renewables, among other alternatives [8]. However, smart control systems are often neglected namely due to the apparent difficulty of integration in existing buildings [12].

It is obvious that one of the important pillars of better performance and higher efficiency in a thermal system is heat transfer enhancement [13–17]. In this way, building controls design becomes challenging when predictions of weather, occupancy, renewable energy availability, and energy price are used for feedback control. In addition, green buildings are expected to maintain occupants comfort while minimizing energy consumption, being robust to intermittency in the renewable energy provision and responsive to signals from the smart grid [18–20]. Achieving all these features in a systematic and cost-effective way is a significant challenge. Until the 2000s the main solutions for the building retrofitting were limited to using devices, application of systems with an alternative energy source in buildings, considering occupant behavior and operation of building systems [21–23]. Treado and Yan Chen [24] estimated the energy saving potential of improvements in building and control system operation, including the relative impact of recommissioning and hardware upgrades, based on a subjective assessment of the level of energy efficient design and the energy usage of the building relative to similar buildings. They also introduced a simulation platform composed of basic modular HVAC components, including conduit, damper/valve, fan/pump, flow merge, heating coil, cooling coil, and zone [25].

In this study, the goal regarding surrogate modeling lies in the development of accurate models of the building thermal response to the endogenous and exogenous disturbances to enable the integration of an optimization process which is part of the supervisory predictive control strategy.

2. Methodology: intelligent supervision

The results regarding the development of the optimization process as a part of the supervisory predictive control will follow five major steps which are depicted in Fig. 1. First, a computational model of the building case-study is developed for simulating the building energy dynamics. This task comprises the building design process, including its architecture, location, occupation, equipment, lighting, materials selection, HVAC system design, as well as activity, lighting, equipment, occupation, and HVAC system scheduling. The building dynamic simulation of the

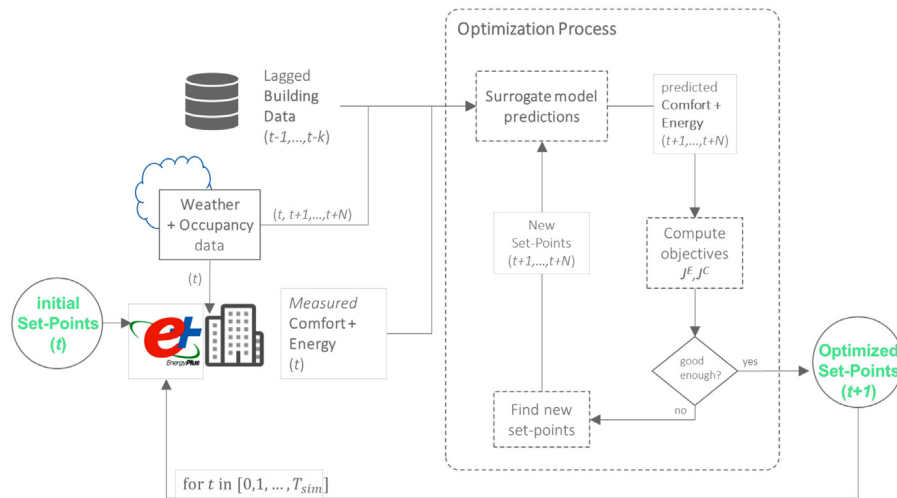


Fig. 1. Flowchart of the optimization process in the supervisory predictive control strategy.

Table 1. Inputs/Outputs description and exogenous variables related to the zone of the building.

Group	Description	Units	Lags [G1]	Lags [G2]
u_t	Heating Temperature Set-point	°C	$[t - 0, \dots, t - 2]$	$[t - 0, \dots, t - 4]$
u_t	Cooling Temperature Set-point	°C	$[t - 0, \dots, t - 2]$	$[t - 0, \dots, t - 4]$
x_t	Outdoor Air Drybulb Temperature	°C	$[t - 0, \dots, t - 2]$	$[t - 0, \dots, t - 4]$
x_t	Horizontal Infrared Radiation Rate per Area	W/m ²	$[t - 0, \dots, t - 2]$	$[t - 0, \dots, t - 4]$
x_t	Outdoor Air Relative Humidity	[%]	$[t - 0, \dots, t - 2]$	$[t - 0, \dots, t - 4]$
x_t	Zone People Occupant Count (POC)	[-]	$[t - 0, \dots, t - 2]$	$[t - 0, \dots, t - 4]$
y_t	VRF Heat Pump Cooling Electricity Demand	[kW h]	$[t - 1, t - 2]$	$[t - 1, t - 4]$
y_t	VRF Heat Pump Heating Electricity Demand	[kW h]	$[t - 1, t - 2]$	$[t - 1, t - 4]$
y_t	Zone Thermal Comfort Fanger Model PPD	[%]	$[t - 1, t - 2]$	$[t - 1, t - 4]$
y_t	Zone Air Temperature	°C	$[t - 1, t - 2]$	$[t - 1, t - 4]$

selected case study was carried out using DesignBuilder software. Second, a database is created for implementing any data-driven modeling strategy. The thermal behavior of the building under study populates the database by simulating three conventional HVAC control strategies using EnergyPlusTM. It may be said that the latter acts as the physics-based model. As a sub-product of this task, the resulting energy performance assessment is later used as references controlling strategies on the benchmarking of the proposed controlling method. Third, surrogate models, imitating the physics-based simulator, are implemented and validated in this step. The surrogate modeling result based on the machine learning methods will be presented. Fourth, the optimization of the HVAC set points during EnergyPlus simulations is fine-tuned in this step. The parameters required for the optimization formulation are determined and the preliminary results of the optimization process assessed. In surrogate modeling, optimal data distribution is not known up front and populating an optimization domain represents a computational investment. During this task, re-sampling is carried out on the optimization domain.

Finally, the supervisory predictive control is implemented as a control strategy of the building case study. Since this implementation is simulation-based, the EnergyPlusTM will play the role of the building. Moreover, the module developed in this study for the co-simulation process in order to connect EnergyPlusTM and PythonTM environment in real time. This major purpose is to address and discuss the energy performance of the building, considering the proposed control strategy and compare it against conventional HVAC scheduling methods through PMV and PPD indexes [26].

The goal of the optimization process is to find the most suitable set-points for time step $t + 1$ given: (A): the building conditions of the time-step t , namely the measured energy demand and comfort, and the occupancy and weather data. (B): the building past thermal behavior of time-steps from $t - k$ to $t - 1$, namely the lagged variables required by each of the surrogate models presented and summarized in Table 1, where k is the maximum required

lag. (C): the forecasted disturbances for the time-steps from $t + 1$ to $t + N$, namely the occupation and weather variables, where N is the size of the forecast window.

2.1. Objective function development

The core of this research is to formulate multi-objective optimization problem inherent to the supervisory predictive control problem, adapting to the case of energy consumption, Eq. (1), and discomfort minimization, Eq. (2).

$$E = \frac{1}{N_E + N_a} \sum_{j=1}^{N_E} \sum_{i=1}^{N_a} (TE \times EC) n_Y \quad (1)$$

$$D = PF + OFF \times (PPD - CT) \quad (2)$$

3. Result and discussion

All data used in this work is provided by a computational model of the building under investigation. Therefore, a model is developed, describing the architecture, type construction, location conditions, HVAC systems, equipment, zone utilization types and occupancy profiles. In this study, the surrogate model is responsible for predicting the building states for a forecast horizon and presents the approach to the problem of minimizing energy consumption of a building and its energy-related costs, while maximizing the comfort conditions within a range accepted to take into account the occupants opinion. The case-study, Fig. 2, is a low-rise office building, located in Oliveira de Azeméis, in Portugal, with 300 m above sea level, fully exposed and there are no direct obstacles on its surroundings, has only one floor which is above ground, having two conditioned zones, and comprising a total area of 207.76 m². Both zones are air-conditioned leaving no unconditioned area. Weather data is provided by LNEG (Laboratório Nacional de Energia e Geologia).

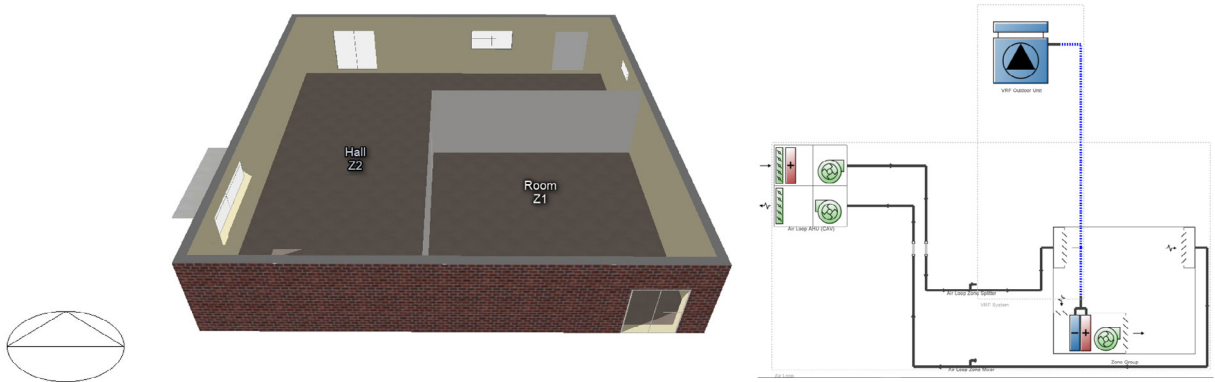


Fig. 2. (Left): Office building reference case-study, (Right): Detailed HVAC system of case-study.

Two thermal zones have been defined, a smaller one, identified as ROOM with 65.83 m² area having six people, and a larger one, the HALL with 141.93 m² total area accommodating fourteen people. All occupants are working in a seated position and, as a result, the metabolic activity can be approximated to 70 W/m² (i.e. 1.2 met) according to ASHRAE and is considered constant throughout the year. Clothing isolation is set to be dependable of the Season, being 1 and 0.5 clo for the heating and cooling season respectively. The density of occupation follows the Portuguese directive for offices, which is 10 m²/person. There are also five exterior windows of double glazing type having an air gap of 10 mm. The opaque thermal characterization of the office, and for each wall the fenestration characteristics are presented in Tables 2 and 3 respectively. The HVAC system includes a VRF (Variable-Refrigerant-Flow) system and an air-loop system responsible for zone ventilation and air renewal as depicted in Fig. 2 (Right). The coefficient of performance of the VRF outdoor unit is 3.3 and 3.6 for cooling and for heating, respectively. Moreover, HVAC turns ON every time the temperature dual-band set-point, defined for each zone, is not met. The dual temperature

Table 2. Opaque envelope solutions' characteristics.

Architectural element	Reflectance	U-factor [W/m ² K]
Exterior wall	0.3	0.372
Ground floor	0.4	0.253
Flat roof	0.15	0.250

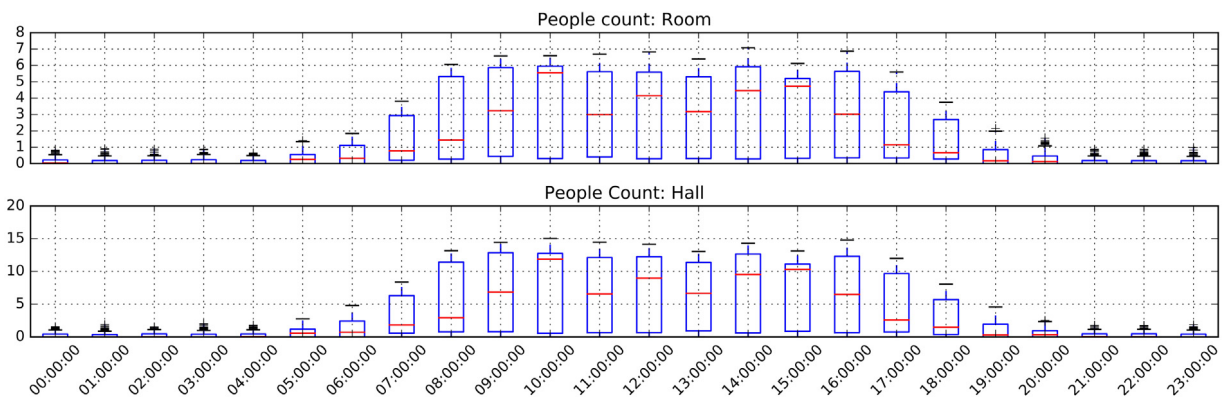
Table 3. Fenestration characteristics.

Cardinal direction	Total area [m ²]	SHGC ^a	U-factor [W/m ² K]	Shade control
All	16.59	0.713	2.786	
North	6.86	0.713	2.786	No
South	3.28	0.713	2.786	Yes
East	2.06	0.713	2.786	No
West	4.38	0.713	2.786	Yes

^aSolar Heat Gain Coefficient.

thresholds are the same for each zone, being 20 °C and 25 °C for heating and cooling, respectively. The setback temperatures defined were 12 °C for minimum allowed temperature and 28 °C as a maximum.

In fact, the proposed management strategy based on a supervisory predictive controller is expected to supervise the temperature set-points and optimize each zone's dual temperature set-points for every simulated hour. The hourly distributions of people occupant count for each zone can be depicted from Fig. 3.

**Fig. 3.** Hourly distribution of occupants count per acclimatized zone.

In Fig. 4, the distribution plots of the output variables are presented. The most frequent value of heating and cooling power for both HALL and ROOM is aggregated in lower values and lower PPD has a higher frequency. This implies a good achievement for the employed methodology in which at the same time could minimize the thermal dissatisfaction and heating/cooling power required for keeping conditioned spaces (HALL and ROOM) in a thermal comfort zone. This result shows the important role of intelligent supervision for predictive control and constructing a smart building with an ability to keep its occupants in thermal comfort and consume a low level of energy as well.

4. Conclusion

The energy saving prospects in the case study of an office building characterized by a contemporary construction and HVAC system highlights the importance of having robust and intelligent supervisory systems even after an investment on the retrofit of the architecture and systems. Thus, to avoid a cumulative investment of retrofitting solutions, one could prioritize the retrofit to an adaptable and supervisory control first, improving the energy

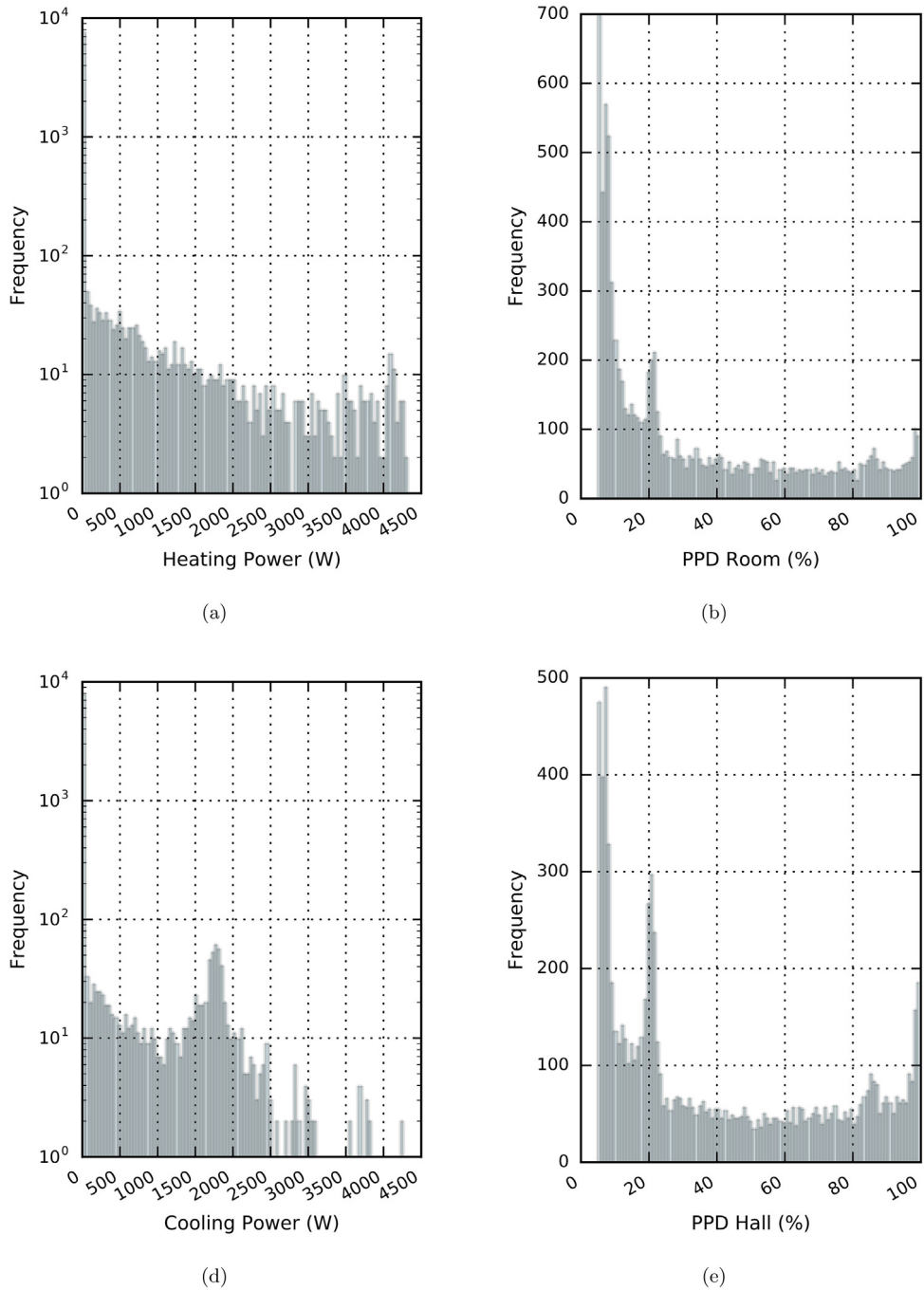


Fig. 4. Distributions of output variables.

efficiency directly while assessing the retrofit of the architecture and systems. Since the supervisory predictive control is independent of the HVAC system, it could adapt to a new building framework that retrofit was due. By employing advanced machine learning algorithms and robust surrogate-driven models, it is possible to deliver a supervisory predictive model for most of the problems encountered.

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