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Evaluación del impacto de las variables de entrada en la estimación de la carga térmica en espacios de oficinas mediante modelos validados

Evaluating the impact of input variables on thermal load estimation in office spaces using validated models

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Resumen-- **El diseño y optimización de las medidas de eficiencia energética en los edificios, suelen basarse en modelos de simulación, los cuales deben ser validados con medidas experimentales para garantizar una representación fiable del comportamiento real del edificio. Uno de los principales retos en este proceso es minimizar las incertidumbres asociadas a la introducción de las variables de entrada, ya que cualquier desviación puede generar discrepancias significativas con respecto al caso de diseño. El objetivo principal de este estudio es cuantificar el impacto producido por la variación de las variables de entrada sobre las cargas de calefacción y refrigeración del modelo de una oficina. Para ello, se ha desarrollado una metodología de simulación dinámica validada, implementada en varias fases: monitorización del despacho y de las condiciones de contorno; modelización dinámica de la oficina; validación del modelo de simulación con los datos experimentales; y estudio de sensibilidad a través de un análisis paramétrico y de influencia. Como resultado de la implementación de esta metodología, se han identificado las variables más influyentes en tres series anuales de la demanda térmica. En este caso de estudio, se concluye que la exactitud en la definición de las temperaturas de consigna estacionales, los archivos climáticos y las tasas de infiltración son cruciales para obtener estimaciones fiables de la demanda térmica de la oficina. Por el contrario, la variabilidad en los horarios de ocupación y los perfiles de temperatura del suelo tiene un menor impacto, permitiendo menor exactitud en la definición de sus valores de entrada sin comprometer la fiabilidad de los resultados finales.**

Palabras clave— modelos validados; performance-gap; variables influyentes; incertidumbres; análisis de sensibilidad.

Abstract— **The design and optimisation of energy efficiency measures in buildings are often based on simulation models, which must be validated with experimental measurements to ensure a reliable representation of the building's actual behaviour. One of the main challenges in this process is minimizing uncertainties associated with input variables, as any deviation can lead to significant discrepancies from the design case. The main objective of this study is to quantify the impact of input variable variations on the heating and cooling loads of an office model. For this purpose, a validated dynamic simulation methodology has been developed and implemented in several phases: monitoring of the office space and boundary conditions; dynamic modelling of the office; validation of the simulation model using experimental data; and sensitivity study through parametric and influence analysis. As a result of this methodology, the most influential variables affecting three annual series of thermal demand have been identified. In this case study, it is concluded that accurate definition of seasonal set-point temperatures, climate files, and infiltration rates are crucial for obtaining accurate thermal demand estimates. Conversely, variations in occupancy schedules and ground temperature profiles have a lower impact, allowing for less accuracy in their input definition without compromising the reliability of the results.**

Index Terms— validated models; performance-gap; influential variables; uncertainties; sensitivity analysis.

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I. INTRODUCTION

Many factors can lead to discrepancies between a building's actual energy performance and its initial design expectations (Zhihang et al., 2024). These include inaccuracies in design parameters, lack of knowledge, limited use of helpful tools, inefficient design or lack of post-construction verification (Patrick et al., 2019). The availability of analysis tools based on validated theoretical models plays a crucial role in optimizing building energy designs, assessing the effectiveness of various efficiency strategies in new constructions, and evaluating retrofitting actions (Soutullo et al., 2018). Furthermore, these tools have significant potential in the development of building energy regulations, as well as in certification and labelling procedures aimed at improving energy efficiency.

However, the reliability of theoretical results depends on the accuracy of the input data and adherence to design specifications. Significant discrepancies can arise between simulated energy performance and actual building behaviour (Tian et al., 2018), leading to inaccurate estimations of energy demand. Such inaccuracies can result in inadequate sizing of both passive design strategies and energy systems (Ascione et al., 2022).

To bridge the gap between simulated and real performance data obtained through monitoring campaigns, experimentally validated models are essential. These accurate models help quantify deviations caused by uncertainties in input data, enabling the identification of each variable's influence on the building's thermal loads (Soutullo et al., 2019). Incorporating uncertainty analysis into these models enhances the accuracy of energy consumption estimates, ultimately generating more reliable models for optimizing energy-efficient strategies.

Uncertainties in theoretical building models can arise from different reasons (Wit & Augenbroe, 2002). On one hand, they may stem from modelling assumptions, such as adjustments to occupancy profiles or geometric simplifications of the building. The use of unreliable databases can also contribute to large discrepancies, particularly in relation to climatological data and the properties of construction materials. On the other hand, simplifications in modelling certain physical phenomena, such as ground temperature or infiltration rates, must be carefully addressed. Additionally, numerical resolution methods employed in simulation software introduce potential sources of error, though this uncertainty tends to be lower in commercial programs. Poor adjustment of input variables and physical phenomena can significantly impact simulation results (Porcar et al., 2018). Reducing these uncertainties enhances the accuracy of building energy consumption estimates, leading to more reliable models that allows optimizing energy-efficient strategies (Yu et al., 2022).

In this context, a theoretical analysis methodology has been developed and experimentally validated. This methodology quantifies deviations caused by uncertainties in boundary condition data, identifying the influence of each studied variable on building thermal loads. This research is framed within the Spanish Project In-Situ Plan-BEPAMAS (In-Situ Plan-BEPAMAS, 2020). The present study details the full development process of this methodology, outlining the key challenges in creating an accurate model for estimating the thermal demands of an office building.

II. LITERATURE REVIEW

This paper presents a theoretical analysis methodology for estimating the heating and cooling loads of an office room located in Almería (southern Spain). The thermal loads generated are used to assess the impact of different input variables on the energy performance of the office.

The methodology implemented in this research involves the development of an experimentally validated dynamic simulation environment, which quantifies the office's energy performance under different input and boundary conditions. The implementation process has been carried out in several phases:

- ***Monitoring***: development of monitoring campaigns in the office under study, as well as in the whole building.
- ***Dynamic modelling of the office***: development of a dynamic simulation model for the office room under free-floating conditions, using the experimental data as input.
- ***Model Validation***: a comparative analysis between simulated and experimental data series for indoor office temperatures.
- ***Sensitivity study***: running simulation batteries to conduct a parametric analysis of the office model.
- ***Influence study***: quantification of the variability obtained in the office's thermal loads within the range of analysis of the influential variables.

Fig. 1 shows the operational scheme used to develop the simulation methodology, which has been validated with experimental data.

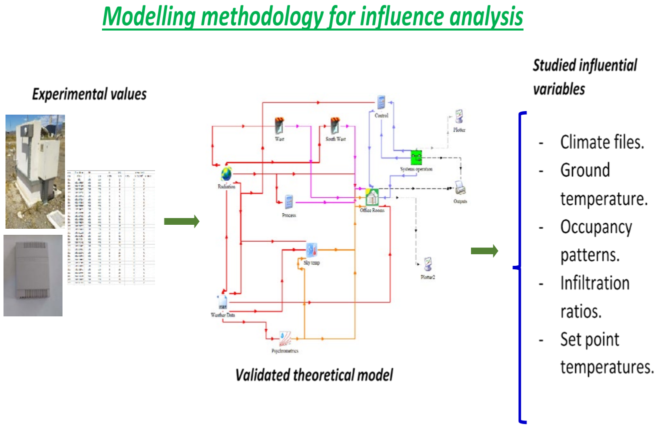

Fig. 1. Methodology of the theoretical office modelling for the influence analysis of the studied variables

III. CASE OF STUDY

The influence analysis of input variables on thermal loads has been carried out in an office room placed in an office building at the CIEMAT facilities in the Plataforma Solar de Almería (PSA), located in the Tabernas desert in Almería (Olmedo et al., 2016).

Fig. 2. South main façade of the PSA office building. The studied office room is in the southeast corner, marked with a yellow circle.

A. *Location and description of the building*

The building under study is a single-story structure with a longitudinal axis, with the main façades facing South and North. It has a floor area of 1114 m². The South façade houses most of the offices and features a longitudinal shading element running the entire length of the façade. In addition, there is a pergola on the roof, designed with a double slope to install thermal solar collectors and radio-convective panels for night cooling.

The office room under study is in the Southwest corner of the building, covering a floor area of 16.8 m² (see Figure 2). It has a double-glazed window on the South façade, while the entrance door is situated on the opposite façade, providing access to the central corridor of the building. Some of the building's installations and wiring are located above the office spaces, separated from the rooms by a technical space.

Building construction details have been obtained from the building´s technical documentation. Table 1 shows the thermal transfer coefficients for constructive walls of the building envelope.

B. *Climatology*

The climate in the Tabernas Desert is characterized by hot, dry summers and cold, dry winters (Soutullo et al., 2017), with average annual temperatures and relative humidity values of 18°C and 54%, respectively, along with low annual rainfall. The annual accumulated global solar irradiation is 1908 kWh/m² (Sánchez et al., 2020). The climate classification of this region is zone C3 according to the Spanish Technical Building Code (CTE, 2006) and zone BWk according to the Köppen-Geiger climate classification (Kottek et al., 2006).

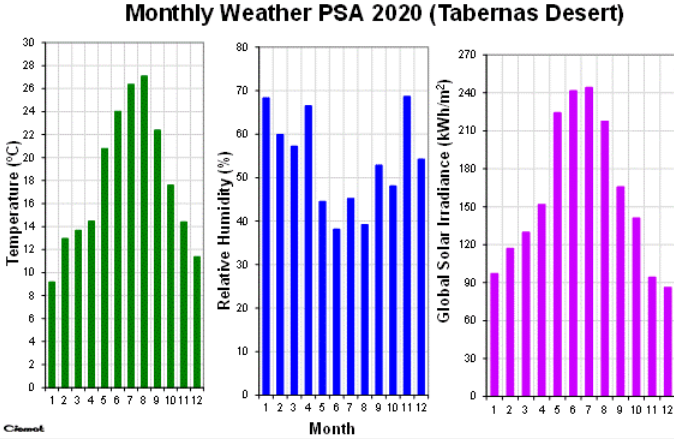

Fig. 3. Monthly values of air temperature (green), relative humidity (blue) and global solar irradiance (purple) measured at the CIEMAT facilities located in PSA (Tabernas, Almería) in 2020.

TABLE I
OVERALL THERMAL TRANSFER COEFFICIENTS FOR THE CONSTRUCTION WALLS OF THE BUILDING ENVELOPE

Construction Parameter	Heat Transfer Coefficients U (W/m²K)
Roof	0.62
Exterior wall	0.53
Partition wall	2.27
Ground floor	0.69
Ceiling	2.27
Glazing	3.21
Frame	4.00

Figure 3 shows the monthly variation in air temperature (green bars), relative humidity (blue bars), and globally accumulated solar irradiation (purple bars) throughout 2020 at the CIEMAT facilities in the PSA, located in the Tabernas Desert. Summer presents the highest values for temperature and global solar irradiation, with average maximum temperatures around 32°C and monthly accumulated values of approximately 234 kWh/m². This period is also the driest, with average minimum relative humidity reaching around 21%. In contrast, winter records the lowest average temperature and global accumulated solar irradiation values, with averages of 6.5°C and 100 kWh/m², respectively. This season is the wettest, with maximum average relative humidity reaching 78%.

IV. DEVELOPMENT OF AN ASSESSMENT METHODOLOGY

The quantification of the influence of input variables has been carried out by implementing an experimentally validated simulation methodology. The development of this simulation environment enables the generation of reliable results that accurately represent the office´s energy performance throughout its lifecycle.

A. *Experimental setup*

This building is monitored using high-quality indoor and outdoor measurement devices, with data recorded continuously by a data acquisition system. The experimental setup is integrated in different representative rooms of the building, with detailed characteristics provided in the reference (Olmedo et al., 2016). The recorded measurements include, among other variables: climatic data, air temperature, relative humidity, CO_2 concentration, electricity consumption, air velocity, ground

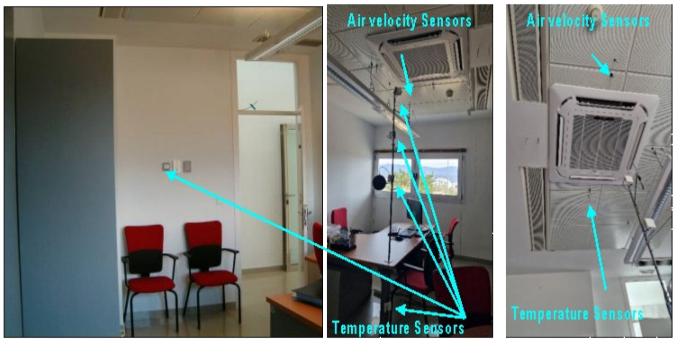

Fig. 4. Experimental setup installed inside the office room

temperature and surface temperatures. Figure 4 shows the distribution of the sensors installed inside the office room.

The monitoring campaigns have resulted in the generation of experimental datasets of climatic variables, boundary conditions, and indoor values measured within the office room, which were then used as inputs for the theoretical models of the office.

B. Dynamic modelling of the office room

The dynamic evaluation of the office´s energy performance was carried out using the dynamic simulation program TRNSYS (TRNSYS, s.f.). This software models the office room as a complex coupled system, mathematically solved with short time steps. Its flexibility and modularity allow for an in-depth analysis of energy performance by exhaustively defining the values selected for the input variables. This detailed characterization enables the simulated trends to align closely with the real situation, though it is essential to use real values from the building book and monitoring campaigns.

The TRNSYS dynamic model was created by coupling different ‘types’, using climate data measured at the Plataforma Solar de Almería as the climate file (Figure 5). The office room was modelled as a thermal zone, in contact with both the corridor and an adjacent office, with both areas considered adiabatic. The ceiling was modelled as a thermal zone adjacent to the upper part, with internal loads characterized by the type of equipment installed. Three external façades were defined: one facing South (including the window), one facing West, and a small wall to the North just before the access door. The terrain was modelled as a boundary condition, introducing as input the experimental values measured at a depth of 50 cm (Lapuente et al., 2023). Infiltration ratios were defined as a function of external wind, obtained from different experimental campaigns conducted with N_2O trace gas in the office (Jiménez et al., 2021). Occupancy patterns were derived from CO_2 measurements taken inside the office room and total electricity consumption values (Díaz-Hernández et al., 2021). Walls, materials and shading elements were modelled according to the dimensions and characteristics defined in the building book. Finally, internal load values were defined based on the experimental measurements.

The office room base case consists of an open cycle model developed under transient regime until the model converges. The input variables for this case are based on the real dimensions and characteristics of the room, as well as data from the monitoring campaigns. In the initial analysis, the office was evaluated under free-floating conditions, meaning the set point temperatures were turned off. These initial conditions are detailed in Table 2.

C. Model Validation

The office model validation was carried out under free-floating conditions, with the office unoccupied, to minimize the influence of system usage profiles, as different scientific experiments were being carried out inside the office during this period. Throughout 2022, the building underwent several improvements and maintenance works that impacted the operation of some thermal conditioning systems. Given these factors, two validation periods were selected:

- ***Winter***: early days of January 2020.
- ***Summer***: August 2020.

The model´s validity was assessed by comparing the data series generated by simulations with the experimental measurements. The initial comparison confirmed that the indoor temperature difference between both data series had an average value of less than 1.5°C. Subsequently, the CV(RMSE) values were under 30%, in line with the ASHRAE 14 guidelines (ASHRAE, 2014).

D. Sensitivity analysis

The model sensitivity to inputs’ variations was evaluated by a parametric study, adjusting the design values of the influencing variables. In this study, these variables include: climate files, average ground temperature values and frequency, infiltration ranges, occupancy patterns, and seasonal set point temperatures. The reference case was defined by the base model values for the office, setting seasonal set point temperatures of 21°C for winter and 26°C for summer, with a variability range of ± 2°C.

The parametric study is carried out by modifying the input conditions of the design case model and obtaining the resulting annual thermal loads for office. This analysis is performed by coupling the dynamic simulation program TRNSYS with the parameterization software GenOpt (GenOpt, s.f.), executing

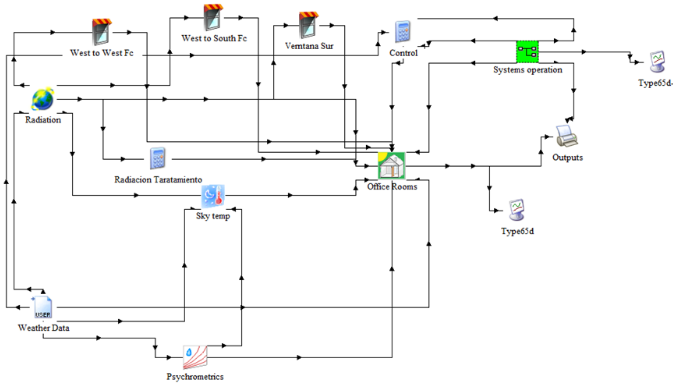

Fig. 5. Theoretical model of the office room developed through the coupling TRNSYS types

TABLE II
INITIAL VALUES SELECTED FOR THE BASE CASE OF THE OFFICE MODEL

Input parameters and inlet variables	Initial values for the office model
Climatology	Data measured throughout 2020
Volume	Book of the building
Walls	Book of the building
Shadings	Book of the building
Terrain temperature	Hourly measurements at 50cm depth in 2020
Infiltration ratios	Wind-dependent function derived from experimental tests
Number of people	1 person
Occupancy patterns	Patterns obtained from experimental measurements in 2020
Set point temperatures	Off

TABLE III
DEFINED ANALYSIS RANGE FOR THE STUDIED INFLUENTIAL VARIABLES

Climate file (Winter-summer)	Ground Temperature	Infiltration	Occupancy	Set point Temp
CTE	50cm hourly	0.1	8-16 h	19°C - 27°C
Energy Plus	50cm monthly	0.2	9-17 h	19°C - 28°C
10-year Experimental	50cm seasonal	0.3	9-12 h / 14-18 h	18°C - 27°C
	100cm hourly	0.4	9-12 h / 15-19 h	20°C - 27°C
	100cm monthly	0.5	8-12 h / 14-17 h	20°C - 26°C
	100cm seasonal	0.6	8-12 h / 15-18 h	21°C - 25°C
	Tª air hourly	0.7		22°C - 24°C
Set point temperatures	Off			

series of simulations as one influencing variable is modified. The design building model, defined in TRNSYS, represents a room used as an office with internal loads. The parameterization model modifies the influencing variables within the ranges shown in Table 3. The selected cost functions are the annual thermal loads for heating, cooling and the total series.

V. RESULTS

After running the simulation batteries required at parametric study, a sensitivity analysis was performed for the three annual series evaluated: heating, cooling and total. This analysis estimates the influence of each variable by comparing the deviations between the annual thermal load series and the design case. The following figures show the maximum and minimum deviations obtained for each of the studied variables: climate, ground temperature, infiltration, occupancy, and seasonal set point temperatures.

In the heating series (Figure 6), it is observed that the most influential variable, in relation to the design case, is the adjustment of the seasonal set point temperatures. The variation of this variable registers the maximum deviation when the set points are set at 23°C in both summer and winter, increasing heating demands by 76%. On the other hand, the deviation is minimal when seasonal set points are set at 21°-25°C. The selection of the climate file results in deviations that either over-estimate (CTE) or under-estimate (Energy Plus and 10-year experimental file) the design case heating loads. The maximum deviation arises with the Energy Plus file, while the minimum occurs with the 10-year experimental file. Another influential variable is the adoption of infiltration ratios. When the values are less than or equal to 0.7 ren/h, the heating loads are underestimated by up to 40%, while exceeding this value leads to an overestimation of the loads by up to 17%. The maximum average deviation occurs with an infiltration rate of 0.1 ren/h, while the minimum deviation takes place with a rate of 0.8 ren/h. The selection of ground temperature and the frequency of its recording tends to over-estimate the design heating loads, reaching a maximum of around 15% when the air temperature series is used. In these cases, the maximum mean deviation is obtained, while the minimum deviation is observed for the temperature series measured at 50 cm. Finally, modifying the occupancy patterns results in an underestimation of the heating loads by about 2% in all scenarios.

The most influential variables of the cooling series are the seasonal set points (Figure 7). This variable causes the design cooling loads to be overestimated by more than 100% with annual set points of 23°C, and by around 100% with set points of 22°-24°C. Conversely, setting the set points to 19°-28°C underestimates the design loads by up to 60%. The maximum deviation occurs at 23°C, while the minimum deviation is observed at 20°-26°C. Another influential variable is the choice of climatic input data. Using the file provided by the Spanish normative CTE, the cooling loads are underestimated by up to 16%. In contrast, the selection of the Energy Plus or experimental files tend to overestimate the loads, with the maximum deviation occurring in the experimental series (up to 24%). Ground temperature values and their recording

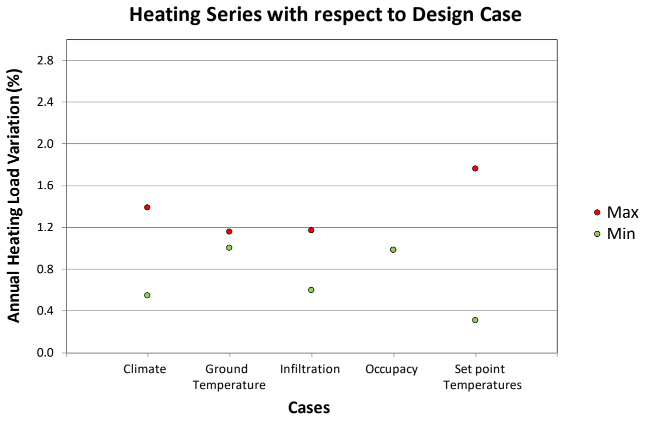

Fig. 6. Maximum and minimum deviations observed in the sensitivity analysis for the heating series, relative to the design case.

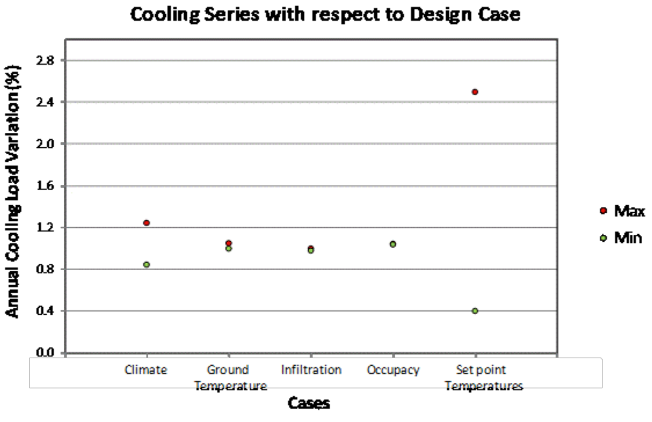

Fig. 7. Maximum and minimum deviations obtained in the sensitivity analysis for the cooling series compared to the design case.

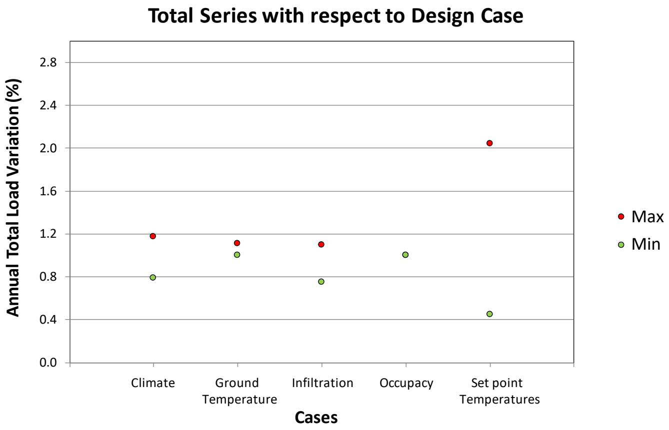

Fig. 8. Maximum and minimum deviations obtained in the sensitivity analysis for the total series, relative to the design case

frequency also play an influential role. When the adiabatic condition is set for the ground boundary, the cooling loads are overestimated by about 5%. However, the minimum deviation occurs with the monthly ground temperature series measured at 50 cm, showing almost no change in the loads. Occupancy patterns generally cause an increase of around 3-4% compared to the design value, across all assumptions. Finally, varying the infiltration ratios leads to a decrease of 1-2% in the design cooling loads.

The influence of the studied variables on the total loads of the design case follows this order, from highest to lowest: seasonal set points, infiltration ratios, climate files, ground temperatures, and occupancy patterns (Figure 8). Among these variables, seasonal set point temperatures stand out with significantly higher dispersions. For set points of 23°C, 22°-24°C, 18°-27°C, and 19°-28°C, the variations are particularly pronounced. The first two set points increase the annual loads by over 100% and 59%, respectively, while the latter two reduce the design loads by 55%. The election of infiltration ratios presents a notable shift around 0.7 and 0.8 ren/h. For values lower than 0.7, total loads decrease by as much as 25%, with 0.1 ren/h resulting in the maximum reduction. For values above 0.8 ren/h, total loads increase by up to 10%. The maximum deviation occurs at 0.1 ren/h, while the minimum deviation occurs at 0.8 ren/h. The selection of the climate file leads to underestimations of the annual loads with the Energy Plus file and overestimations with the CTE file, with a larger deviation in the first case. When using the 10-year experimental file, there is little change in the total load estimates compared to the design case. Changes in the ground temperature input file result in an overestimation of the total loads, with the maximum deviation occurring with the air temperature series (showing increases of around 10%) and the minimum deviation occurring with the monthly ground temperature series at 50 cm. Finally, changes in occupancy patterns have minimal impact on the total annual thermal loads, with average deviations of less than 0.2.

VI. CONCLUSIONS

The optimization of passive energy efficiency strategies in building design often relies on simulation tools. However, the results provided by these tools are not always entirely accurate. To bridge the gap between theoretical data obtained with simulation programs and real data collected through monitoring campaigns, experimentally validated models are used.

This research presents a theoretical analysis methodology developed from a simulation model of an office room, experimentally validated, which quantifies the deviations resulting from uncertainties in input data. The implementation of this methodology allows the identification of the influence of various variables on the office´s thermal loads. The influential variables studied include key input variables and boundary conditions commonly used in building simulation models: climate files, ground temperature, occupancy patterns, infiltration ratios and set point temperatures.

The energy deviations caused by differences in the input values of these variables have been quantified through a sensitivity analysis. The cost functions established as outputs in this study include heating, cooling and total thermal loads over a year. This analysis was conducted using a local parametric study, which involved running a series of simulations with modified input values to generate simulated annual thermal load series for the office. The evaluation of these series provides insight into the energy response of the office to variations in the input variables.

The influence analysis of the total annual thermal loads of the office identifies that the variables with the greatest impact are the set point temperatures, followed by the climate file and infiltration ratios. In contrast, the variability of occupancy patterns and ground temperature values has a lesser effect on the estimation of total annual thermal loads.

Quantifying the impact of uncertainties in input variables on thermal loads is invaluable when designing a new building or retrofitting an existing one, as it highlights which deviations may be critical in terms of energy savings. The use of experimentally validated theoretical methodologies is a highly effective tool in decision-making, offering reliable criteria to optimize the construction process.

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