Personal Comfort Systems (PCSs) in Offices: Efficient Utilization Threshold Based on Energy Consumption

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Abstract

Personal Comfort Systems (PCSs) have emerged as a solution to customize thermal conditions at individual workstations, potentially reducing overall energy consumption. This study investigates the optimal utilization of PCSs in office environments extending beyond their thermal comfort provision to delve into their overall energy performance, considering various HVAC systems, building insulation levels, and occupancy patterns. Building dynamic Energy Simulations (BES) were conducted for an open-plan office in London, utilizing heating desks. The evaluation method involves comparing scenarios with and without PCSs across various indices, including energy cost and Primary Energy consumption. Results highlight the year-round adaptability of PCSs, offering insights into their efficacy, efficiency, and potential impacts in both new and existing buildings. The absolute savings vary between non-insulated and highly insulated buildings and the study suggests integrating PCSs into building design for optimized energy efficiency and cost-effectiveness.

1. Introduction

Addressing the well-being and comfort of individuals has emerged as a central concern for researchers. The assessment of the thermal environment holds particular significance, given its substantial impact on both the comfort of occupants and the energy efficiency of the building (Veselý & Zeiler, 2014). Thermal comfort is the most influential Indoor Environmental Quality (IEQ) factor in space perception and the predominant one regarding energy consumption (Bluyssen, 2020). Ensuring thermal comfort holds utmost significance in work environments, playing a dual role in enhancing personal well-being and boosting productivity (Antoniadou & Papadopoulos, 2017; Kim et al., 2019) while also being a primary contributor to overall dissatisfaction within a space (Frontczak et al., 2012).

In this context, numerous researchers have developed models and systems designed to meet individual needs, such as Personal Comfort Systems (PCSs). PCSs are defined as systems that heat and cool individuals without affecting the environments of surrounding occupants (Arens et al., 2006). Unlike traditional HVAC systems that condition the entire building volume, PCSs focus solely on creating a "personal" microclimate. Moreover, neutral sensation in a uniform environment reaches the rating of “comfortable” but cannot reach the rating of ’very comfortable’, which can only be achieved in asymmetric or transient environment conditions (Arens et al., 2006), often created by PCSs.

This targeted approach allows for the customization of thermal conditions at individual workstations, enabling the primary HVAC system to operate within a broader setpoint range and leading to a significant reduction in overall energy consumption (Kalaimani et al., 2020; Toftum, 2010). This is based on the premise that individuals will primarily occupy the individually conditioned workstations, with limited time spent in other areas within the building (Zhao et al., 2014).

Given the insights above, the question arises: how many PCSs can be used simultaneously in a less conditioned environment while maintaining energy convenience?

This study aims to test a new methodology for defining the threshold for PCS usage in terms of energy efficiency within an office setting. Specifically, the research aims to identify when these systems

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can be efficiently applied in conjunction with various types of primary HVAC systems, taking into account the number of occupants and the building insulation quality in which they are utilized.

2. Method

The study aims to investigate how many PCSs can be used simultaneously in an office maintained at a less conditioned level to achieve both energy and cost gains. In this initial phase, Building dynamic Energy Simulations (BES) of an open-plan office during the heating period are employed. The office is situated in the city of London and utilizes heating desks, which have already proven efficient in recreating thermal comfort conditions in previous studies (Rugani et al., 2023). Although this is an initial exploratory phase of the methodology for assessing the overall impact of PCSs on energy consumption, the approach is general and can be adapted to any other type of PCS, for both heating and cooling.

2.1 BES Model

EnergyPlus was employed to investigate the PCS impacts. A three-floor standard landscape office building type was chosen, having a 27.6 x 28.0 m plan dimension (770 m^2) and 9 m height (3 m per floor). The building is north-south oriented and the window area ratio is 1/8 of the floor area, equally distributed on the four sides. Fig. 1 shows the architectural plan of the typical building floor.
The building simulation model was conceived according to the simplified definition developed in previous studies, named FREDS (Picco & Marengo, 2019). The building is conceived as a simplified geometric shape, with glazed areas equivalent to the sum of the individual glazed surfaces on each wall. For this geometric simplification, Fig. 1 does not include the windows drawn in the typical floor plan. The building was divided into three thermal zones, one for each floor.

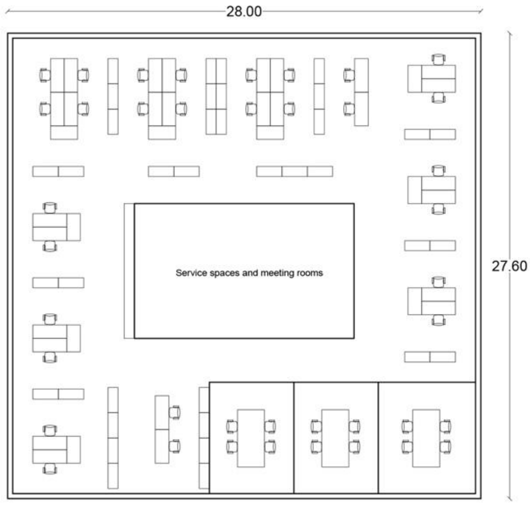

Fig. 1 – Architectural plan of a typical floor of the simulated building (measures in meters)

Two distinct building constructions were applied, one representing a typical heavyweight hollow brick, non-insulated structure, and the other exemplifying the same structure, but with insulation to meet nearly zero energy building (nZEB) standards (European Parliament, 2024) (Table 1).

Table 1 – Design features of the selected building

	nZEB config.	**Common config.**
Walls transmittance	0.256 W/m^{2}K	1.019 W/m^{2}K
Ground floor transmittance	0.26 W/m^{2}K	1.236 W/m^{2}K
Roof transmittance	0.224 W/m^{2}K	1.745 W/m^{2}K
Windows transmittance	1.323 W/m^{2}K	2.718 W/m^{2}K
Windows SHGC	0.416	0.737

The Office was simulated in London, which has a rainy climate in which temperatures remain fairly low throughout the year. TMY (Typical Meteorological year) weather files suitable for use with BES programs were chosen and downloaded from the Meteonorm database, statistically based on 19-year observations (2000-2019). Fig. 2 shows the output temperature trends of the climatic file.

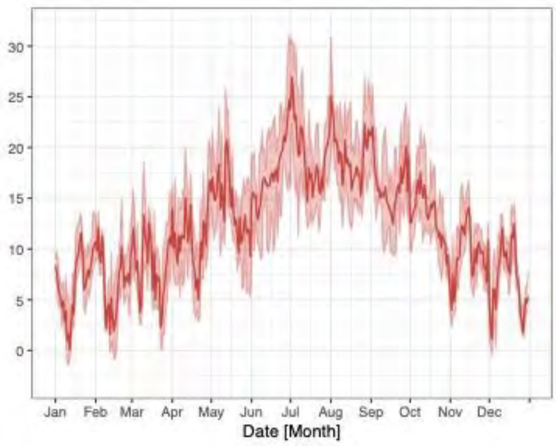

Fig. 2 – Annual evolution of daily temperatures in the TMY from Meteonorm. The solid lines represent the daily averages, while the opaque colored areas indicate the hourly minimum and maximum values observed throughout the day

Two distinct operational conditions of the building were simulated: one with PCSs (less conditioned state, 17 °C) and one without (regular setpoint, 21 °C). Specifically, the selected PCS for heating is a warming desk with 40W of power input. The desk has two distinct electric heating surfaces: a narrower one on top that heats upward and is concentrated towards the user (working primarily by conduction), and a larger one underneath that heats downward (working primarily by radiation).

The study utilized internal loads data from the FREDS database, adjusting people's time schedules to align with the analysis objectives. The office layout, based on a FREDS "people index" of 18.8 m^2/person, accommodated 40 people per floor in the case study.

The simulation considered four office occupancy scenarios: 25 %, 50 %, 75 %, and 100 % capacity. The purpose of the people loads configuration is to conduct a sensitivity analysis of PCS's benefit, considering the simultaneous presence load of individuals in offices and the electrical load generated by PCSs. The EnergyPlus simulations consider the heat load produced by the occupants and the corresponding activation of personal systems, depending on the specific combination of scenarios. In practice, the number of activated PCSs depends on the number of people present in each scenario, each of whom has their own PCS.

Therefore, the activation of PCSs is contingent on two distinct factors: temperature conditions and the presence of individuals. Thanks to the "Energy Management System" of EnergyPlus, it was feasible to correlate the activation of PCSs with the indoor air temperature attained by the case study in the simulated location. The code utilized in EnergyPlus is as follows:

```
EnergyManagementSystem:Program,
  DESK,
  IF T1 >= 21,
  SET Desk_PT_power = 0,
  ELSEIF (T1<21) && (DayOfWeek>=2) && (DayOfWeek <=6) && (Hour >= 9) && (Hour <=19),
  SET Desk_PT_power = [XXX],
  ELSE,
  SET Desk_PT_power = 0,
  ENDIF;
```

The simulation encompassed different occupancy levels, and in the less conditioned scenario, during the heating phase, PCSs activated as the room temperature dropped below 21 °C. Additionally, the main heating system was triggered when the temperature fell below 17 °C during working hours.

2.2 Energy/Economic Impact Evaluation

The study compares the different conditions created by the scenarios with and without PCSs examining primary energy consumption and energy costs. An ideal heating system was modeled in EnergyPlus to obtain the energy requirements of the building envelope. Various heating scenarios for heating were then identified, and the energy consumed by the heating systems was calculated based on the yields of each specific case. This helped evaluate how PCSs interact with various heating scenarios, providing insights for optimizing energy efficiency and sustainability in different operational conditions. Table 2 shows the three simulated combination scenarios for heating.

Table 2 – Building main heating scenarios

Scena.	Generator	Source	Terminal
H_1	Condensing boiler	Natural gas	Radiant pan.
H_2	HP (air-air)	Electricity	Internal unit
H_3	HP (air-water)	Electricity	Fan coil

The analytical framework unfolded through a comprehensive process encompassing various stages. Firstly, EnergyPlus was employed to assess the heating envelope needs. Subsequently, an exploration of systems efficiencies informed the determination of energy source needs. This was followed by the incorporation of Primary Energy conversion factors for gas and electricity, contributing to the Primary Energy analysis. The subsequent steps involved the integration of energy cost conversion factors for detailed financial analysis in euros [€]. Therefore, the calculation process unfolded as follows:

- EnergyPlus -> Heating envelope needs (Q_H) [kWh]
- Systems Efficiencies (distribution, production, regulation, and emission) -> energy source consumption ($Q_{s,H}$) [kWh]
  - Primary Energy conversion factor (gas, electricity) -> Primary energy analysis ($Q_{p,H}$) [kWh]
  - Energy cost conversion factor -> Financial analysis [€]

In each scenario, the cumulative electricity consumption of the PCSs was added, calculated based on their actual usage throughout the year, as an effect of the previously explained EnergyPlus EMS.
The Energy costs for England were set at 0.27 £/kWh for electricity (Nimble Fins, 2023) and 0.07 £/kWh for natural gas (Nimble Fins, 2023). To standardize the results, all prices with foreign currency were converted to Euros (€) using the exchange rates applicable in October 2023 (resulting in 0.31 €/kWh for electricity and 0.08 €/kWh for natural gas). Since the costs are subject to rapid variations, simulations were conducted by applying variation factors of ± 20 % to evaluate the impact of potential changes over the years.
The primary energy factor is 1.50 for electricity and 1.13 for natural gas (UK Department for Energy Security and Net Zero, 2023).

2.3 Scenarios Summary

The earlier detailed scenarios are described here to provide a comprehensive overview of the conducted study. Fig. 3 shows a schematic plot of the 49 combinations, which can be summarized as:

- 2 operational setups of PCSs
- 1 location
- 2 stratigraphy configurations
- 4 occupancy patterns
- 3 HVAC configurations

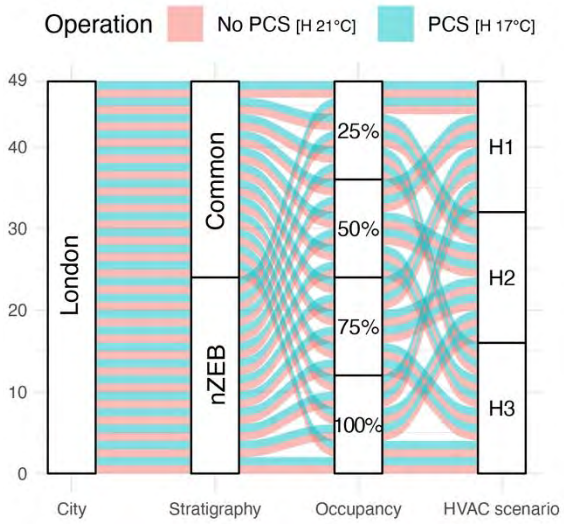

Fig. 3 – Schematic summary of the combinations (49) with which the simulations were performed

3. Results

The EnergyPlus EMS script facilitated the simulation of the practical utilization of PCSs. Fig. 4 shows the usage hours of PCSs, drawing also a comparison between non-insulated (common) and insulated (nZEB) buildings.

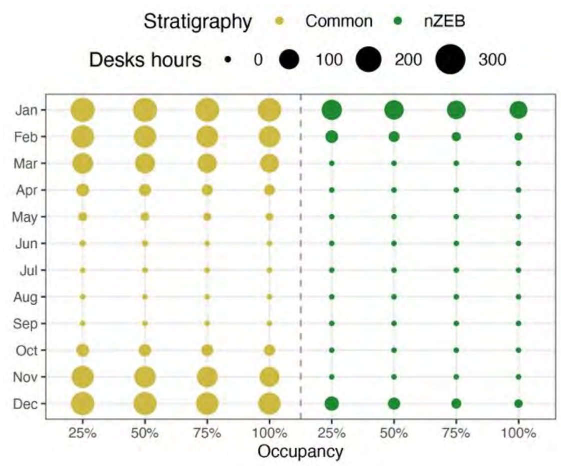

Fig. 4 – Usage hours of the heated desks, divided by months, based on the occupational profile, for the common non-insulated and the nZEB insulated building

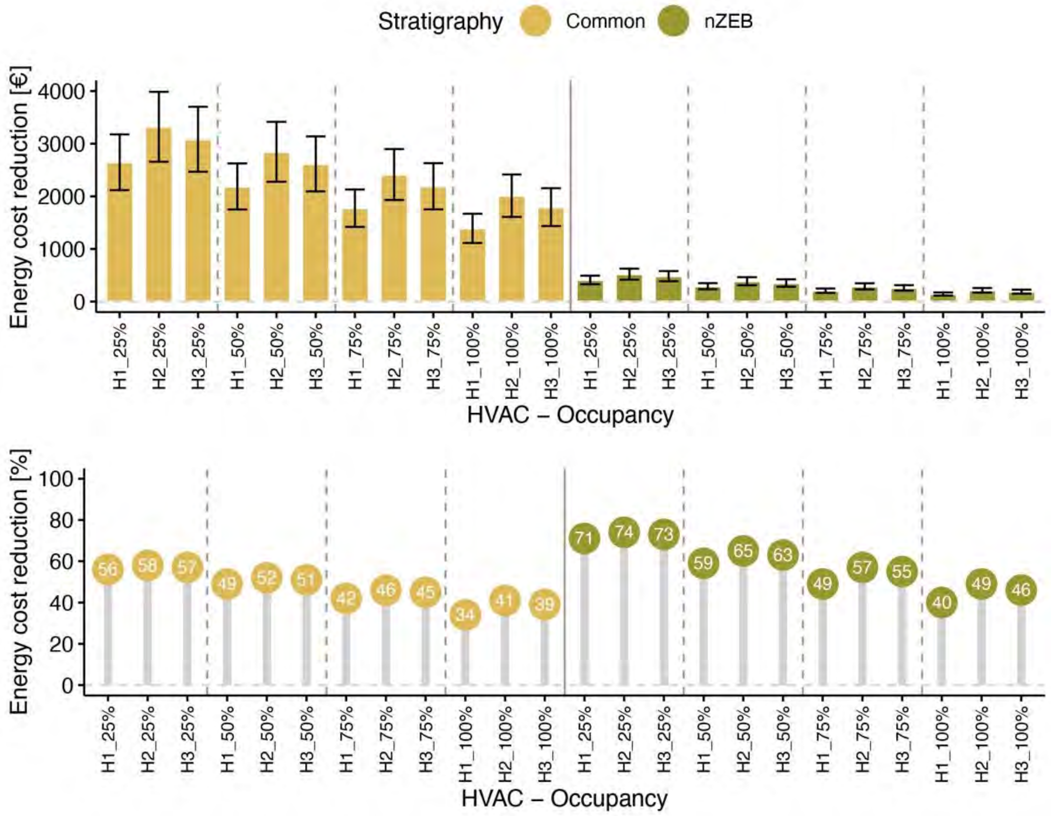

Fig. 5 – Absolute and percentage energy cost reduction according to the heating system scenario and the occupational profile, for the common non-insulated and the nZEB insulated buildings. The interval bars show the result in the case of a ± 20 % change in input energy cost

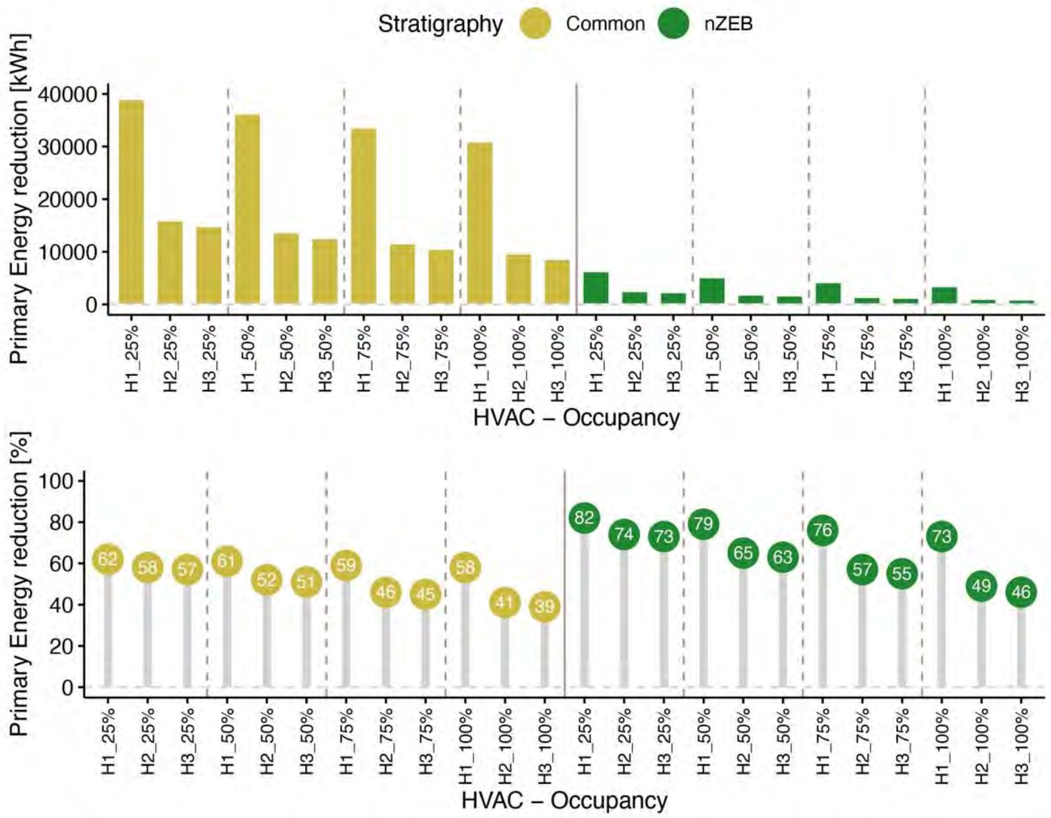

Fig. 6 – Absolute and percentage Primary Energy consumption reduction according to the heating system scenario and the occupational profile, for the common non-insulated and the nZEB insulated buildings

Usage hours peak around 240/260 in January and December in the non-insulated building, while they are lower in the nZEB (160 in January and 60 in December). The desk sees substantial use until April, with some hours in May, and resumes in October for the non-insulated building, while it has more limited use (from December to February) in the nZEB building. The results highlight the effectiveness of enabling year-round usage of PCSs, emphasizing the dynamic adaptability of PCS strategies to various building structures.

Energy and cost results are shown as differences between the standard conditioned state (21 °C) and the less conditioned state (17 °C) with PCSs. Every positive outcome signifies a benefit derived from the operational state with PCSs. Primary energy (Fig. 6) and costs (Fig. 5) are investigated.

The scenarios with condensing boilers show a greater absolute reduction in primary energy, with values of up to 40 MWh for the non-insulated building and 6 MWh for the nZEB. Meanwhile, other scenarios with heat pumps hover around 15 MWh and 2 MWh. The percentage reduction follows a consistent trend, approximately 40-60 % for the non-insulated building and 50-80 % for the nZEB.

Annual cost savings range from about 40 % to 60 % for the non-insulated building, with absolute values ranging from €1400 to €3300, while they range from 40 % to 75 % for the nZEB, equivalent to values between €250 and €550. In terms of costs, scenarios with heat pumps experience greater savings due to the higher cost of electricity.

4. Discussions

The use of heated desks as a PCS in the simulation of the case study office, coupled with a reduction in the office's winter setpoint, consistently yielded positive effects in London. Full scenarios, where everyone has their PCS turned on, were explored to establish thresholds, even though they don't align with the logic and objective of PCS usage.

In the worst-case scenario, where 40 people per floor have 40 W desks powered on, the minimum primary energy savings amount to 39 %, and the minimum cost savings to 34 %.

The advantage of PCSs depended on factors like occupancy rates, building insulation, and heating system configurations. The reduction in primary energy consumption demonstrated the environmental benefits of heated desks, especially in scenarios powered by natural gas. However, the influence of occupancy rates and building insulation on these reductions highlighted the need for a tailored approach to maximize environmental gains.

While the percentage savings are very high, the absolute savings between the non-insulated building and the nZEB building are vastly different. This study does not consider the installation cost of PCSs, which, if taken into account, would change the equation. From these initial results, it can be argued that PCSs would yield good results in retrofitting an existing system of a non-performing building, bringing both economic benefits and high thermal comfort, justifying the expenditure and return on the investment cost. The same might not apply to the installation of these PCSs in a newly constructed nZEB building whose system has already been designed. However, looking at it from a different perspective, if the PCSs had been designed alongside the building's system, allowing for downsizing of the main HVAC components to operate with lower thermal loads associated with reduced working setpoints, it would have led to cost and environmental impact reductions. In this scenario, the PCSs would have delivered advantages to the nZEB building in terms of personal comfort, control, as well as environmental and energy consumption.

5. Conclusions

In conclusion, the study delves into the intricate landscape of PCSs and their impacts on building energy dynamics. Utilizing a comprehensive evaluation framework that incorporates energy considerations, the study offers actionable insights for the effective deployment of PCSs in real-world scenarios. The approach is general and can be used to evaluate any type of PCS, not limited to the specific heating desk in this study.

The examination focused on a three-floor standard landscape office building, taking into account diverse building stratigraphy, occupancy patterns, and heating configurations.

Key findings include:

- The energy benefits and savings resulting from the use of a 40 W heated desk combined with less-conditioned operation of the main heating are consistently positive.
- In these scenarios, there are no usage thresholds; even if the entire office were to utilize a 40 W desk, disadvantageous situations would never arise.
- Great potential has emerged in the application of PCSs to complement the improvement of existing underperforming buildings.
- The study recommends conscious PCS use in highly insulated buildings and their integration into new building projects to optimize energy efficiency and costs.

Overall, the findings provide valuable insights for deploying PCSs as effective, adaptable, and sustainable solutions in various operational scenarios.

Future developments of this work will involve expanding the combinations of analysis, including the cooling season, other climatic locations, and various PCS power levels. This aims to create an informative usage map and more general thresholds to be considered during the economic and environmental assessment of the applicability of PCSs with different power inputs.

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