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Comfort and Economic Viability of Personal Ceiling Fans Assisted by Night Ventilation in a Renovated Office Building

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Abstract: An expected increase in the use of air conditioning by 2050 will significantly increase electricity demand and come at a cost to the environment. Implementing passive cooling strategies and focusing on personal environmental control systems (PECSs) could help to address this issue. While numerous studies have investigated the positive impact of PECSs on thermal comfort and energy savings, their overall economic benefit has been poorly addressed. We present an economic evaluation of personal fans for an office building in Germany. Building performance simulation was used to compare passive and active cooling concepts, and sensitivity analysis was performed for different climate scenarios. A cost-benefit analysis was carried out, including an assessment of investment and operating costs and the monetary value of relative performance. The transferability of comfort and productivity into costs is the novelty of this paper. The results showed that by supplementing night ventilation with personal fans, discomfort hours could be reduced by up to 50%. However, the initial investment of the fan is not compensated by savings in productivity losses compared to night ventilation alone. A reduction in the cost of the technology could help to economically offset the investment. The results contribute to the literature on the economic evaluation of a PECS by proposing a framework to motivate its implementation in buildings.

Keywords: personal environmental comfort system; cost-benefit analysis; energy efficiency; thermal comfort; passive cooling; night ventilation; productivity loss; sensitivity analysis; building simulation; building monitoring

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1. Introduction

The impact of climate change on energy use has raised concerns as the global contribution of buildings has reached 31% of total energy consumption [1]. The expected rise in the frequency of hot days caused within the context of global warming assures an upward trend in cooling demand in the future [2]. The increase of indoor temperatures outside the comfort range brings along a rising demand for building services, in which the growth of HVAC system energy use has been playing a significant role [3]. As a result, several initiatives yield to reduce the operational energy demand in buildings. The German national "Climate Action Plan" posits as one of its main objectives to reduce 80% of primary energy consumption by 2050. Alongside improvements in the thermal performance of buildings during the winter period and decarbonization of the cooling source, the need to minimize cooling loads requires a paradigm shift in the design of buildings to achieve this goal.

While decarbonization of heating and cooling systems impacts emissions, some authors advocate for climate-responsive designs as the first step for energy efficiency. Besides early-stage building design strategies, such as thermal insulation or orientation optimization, Lechner [4] described the importance of including passive or hybrid systems, such as night ventilation, in warm climates. Night ventilation can reduce initial cooling loads between 10% and 40%, with an average of 26% [5], and can increase occupants' acceptance of indoor conditions by reducing indoor temperatures [6]. However, the effectiveness of night ventilation presents some limitations for climate zones and varying building characteristics [7]. The need to include additional mitigation measures to achieve effective night ventilation has been investigated. He et al. [8] described the benefits and use of fans in non-residential buildings, as they can increase occupant satisfaction via increased air velocity while at the same time maintaining energy consumption at relatively low levels.

Along with passive cooling strategies, attention has been drawn to the use of personal environmental control systems (PECSs) to target the direct thermal environment of occupants by conditioning their personal space in contrast to the entire building [9]. These systems are an effective solution to provide acceptable comfort levels for occupants [10,11] along with improvements in energy performance [12,13]. While most PECS studies of PECSs have focused on assessing thermal comfort and energy savings, cost-effectiveness analyses have rarely been performed. A recent review paper [14] found that only 16% of the analyzed studies mentioned costs as an analysis dimension of PECSs. The lack of studies assessing the economic aspects of PECSs motivates the investigation of a comprehensive economic viability analysis and framework to evaluate the feasibility of PECSs for real building applications. It is, therefore, the objective of this paper.

1.1. Background

HVAC systems have been widely installed in non-residential buildings to maintain acceptable indoor environmental conditions. During hot summer months, air conditioning systems (ACSs) provide constant room temperatures and contribute to employee satisfaction within the indoor environment. However, ACSs can lead to building overcooling, which can be associated with dissatisfaction [15] and even health issues [16]. Additionally, the use of air conditioners is still not seen as an adaptation measure for thermal comfort, especially with centralized systems in multi-occupant spaces that do not provide personal control, often resulting in increased dissatisfaction rates.

Along with high installation and maintenance costs, ACSs bring along high energy usage during operation. The growth in ACSs' and electric fans' energy use is particularly significant, accounting for 20% of the total electricity used in buildings worldwide and 18% of the total increase in global emissions between 2016 and 2050 [17]. Additionally, occupant behavior plays a key role in energy consumption [18]. Nakaya et al. [19] found that passive occupant behaviors, such as opening windows and using fans, can reduce AC-use rates by up to 20% and decrease temperature setpoints at which ACSs are switched on for temperatures between 25 °C to 30 °C.

To reduce energy costs and be in line with sustainable development, low-energy strategies are alternatives to active cooling. By including night ventilation, particularly in buildings with a high mass and high thermal inertia, indoor temperatures can potentially be reduced and consequently allow a reduction of cooling loads during the daytime. Based on monitoring results of a building in a continental climate, Pfafferott et al. [20] concluded that night ventilation strategies could achieve acceptable indoor thermal conditions without increasing electricity demand. Kolokotroni et al. [21] pointed out that the difference in cooling loads between a building with night ventilation and a typical office building with air conditioning in the UK can reach up to 10 kWh/m^{2}a. Moldovan et al. [22] analyzed the cooling energy demand of an office building in a temperate continental climate, concluding that night ventilation allowed significant energy consumption savings, achieving a reduction of energy use up to 33% in the hottest months.

However, the effectiveness of night ventilation can vary according to certain parameters, mostly related to the type of construction, control strategies, and climatic conditions [5]. Landsman [23] compared the performance of night ventilation regarding indoor thermal conditions in three buildings in mild and hot/humid climates. He concluded that buildings with night ventilation in mild climates successfully kept the indoor operative temperature below the upper 80% acceptability comfort limit. In contrast, the thermal acceptability in the building in the hot and humid climate went above the upper 80% comfort limit on the hottest days of the year. To guarantee sufficient cooling, night ventilation can be optimized by coupling it with other energy-efficient techniques and supplementary systems. For instance, Landsman [23] recommends combining night ventilation with low-energy strategies, such as ceiling fans, to improve thermal comfort.

Fans can improve occupants' thermal comfort without using compressor-based cooling by effectively cooling human bodies via elevated airspeed [24,25]. Previous studies [26,27] showed that at indoor temperatures above 28 °C, occupants rated indoor conditions in a warm-humid environment as still acceptable when increasing air velocity was provided by ceiling fans. Zhang et al. [28] concluded that ceiling fans were normally operated at indoor temperatures above 28 °C in naturally ventilated buildings in hot-humid climates; Lipcznska et al. [29] found that thermal satisfaction in a warm environment was significantly higher with operating ceiling fans even in spaces of 26 °C when split air conditioners were provided. Additionally, fans can achieve cooling energy savings of up to 47% when using fans at elevated indoor temperatures [30].

Providing an acceptable indoor environment to increase thermal comfort and reduce energy savings can be achieved using PECSs. Zhang et al. [9] reviewed the performance of several types of PECSs and estimated potential HVAC energy savings greater than 30% as a relaxation of the comfortable indoor temperature range could reduce the total HVAC energy at a rate of 10% per degree Celsius. According to He et al. [10], personal fans can achieve higher energy efficiency than other personal cooling systems while addressing individual differences in perceived air quality and thermal comfort. Rissetto et al. [11] studied the performance of personal ceiling fans and concluded that they are a viable approach to reaching high satisfaction rates.

Increasing individual thermal satisfaction in the workplace has been related to productivity [31]. Lipcznska et al. [29] studied the performance of personal fans and found that increasing thermal satisfaction positively affected the reported work performance. This becomes of relative importance, as air conditioning costs account for about 1% of the labor cost in developed countries [32]. Seem and Braun [33] concluded that a potential 15% increase in the HVAC energy use produced by PECSs could be offset by a 0.08% increase in occupants' productivity associated with personal environmental control.

While most PECSs studies have focused on assessing thermal comfort and energy savings, cost-effectiveness analyses have rarely been performed. In a recent review [14], the authors concluded that only 30 studies in the literature included cost considerations in their analyses; most of them only considered one cost aspect. Table 1 shows a summary of the number of papers analyzing each cost aspect.

Table 1. Summary of cost aspects analyzed in publications about PECSs.

Cost Aspect Analyzed	Number of Studies Assessing that Aspects
Low initial costs of small PECSs [1]	4
Low running costs of small PECSs [1]	5
Reduced maintenance cost measured as reduction of labor costs	1
Increased initial costs for ventilation PECSs	7
Increased maintenance costs for ventilation PECSs	2
Increasing productivity on overall economics	6
Reduced energy costs	4
No change in energy costs	2

[1] Small devices like fans and foot warmers.

To fill this gap, the authors proposed a framework to holistically assess the costs related to the implementation of PECSs. Table 2 shows an adaptation of the proposed methodology, which consists of a comparison between a system with a PECS and an alternative "classic" system without a PECS, named a conventional system.

Table 2. Proposed framework for assessing the cost-effectiveness of a PECS solution combined with a conventional system. Adapted from [14].

Type of Solution	PECS + Conventional System	Conventional System without PECS
Direct installation costs (system itself)	X-times costs of PECSs (number of devices) + 1-time (reduced) costs of conventional system	1-time costs of conventional system
Indirect installation costs (ductwork, installations, etc.)	X-times costs of PECSs (number of devices) + Y-times (reduced) costs of conventional system	Y-times costs of conventional system (number of elements belonging to the system)
Maintenance costs	Costs of PECSs + (reduced) costs for conventional system	Cost of conventional system
Operation costs	Increased or decreased costs	Cost of conventional system
Energy costs	Savings in overall conditions + costs to drive PECS	Cost for conventional system
Productivity	Potentially increased productivity through PECS	

The existent tradeoff between implementing cooling strategies in buildings to provide high levels of satisfaction while reducing energy usage and costs is yet to be researched in depth. A detailed assessment in terms of economic viability may help establish the prominence of PECSs over conventional air conditioning methods.

1.2. Research Gap and Scientific Contribution

Despite the benefits of personal comfort systems in improving occupants' comfort levels and energy savings, the implementation of such devices in commercial buildings is still limited. The lack of a comprehensive assessment of the economic viability of PECSs motivates the investigation of PECS implementation in real building conditions. The present work is developed within the framework of a district office building renovation in Dillingen, Germany. To reduce energy consumption while improving the thermal comfort of the employees, night ventilation was implemented, and personal ceiling fans were installed individually at each workplace.

This paper aims to assess the effort and benefits of personal ceiling fans in terms of energy demand, cost, and thermal comfort compared to alternative active and passive cooling solutions. While thermal comfort levels provided using personal environmental control systems have been widely studied, this paper contributes to the research on PECS' economic viability. A comprehensive examination of thermal comfort and productivity transferred into costs, including monitoring data from an existing office building, constitutes the novelty of this paper.

2. Materials and Methods

Figure 1 presents the workflow of this study. To evaluate the economic viability of personal ceiling fans, the performance of the ceiling fans is compared to other cooling strategies in a simulation study, assessing different locations and climatic scenarios. The following cooling concepts were modeled (Table 3).

Table 3. Simulated cooling strategies.

Cooling Concept	Description
NoCooling	No night ventilation or air-conditioning. This concept represents the situation before the building renovation.
NV	Night ventilation.
NVandCF	Night ventilation (NV) and ceiling fans (CF). This concept represents the implemented solution in the building (after the renovation).
ACS	Air-conditioning system (decentralized, ideally modeled).

A base case study with the office building in Dillingen was used for the modeling and simulation of the cooling concepts and cost calculation. A building energy model was necessary to simulate the temperature distribution and the building cooling energy demand for all cooling concepts—except night ventilation and ceiling fan, from which monitoring and project data were available. The building model and boundary conditions are derived from the project data. Based on monitoring data, a behavioral model for fan usage was created. The building was calibrated and validated with monitoring data. The main outputs of the simulation were the indoor environmental conditions (indoor temperature) and energy consumption, namely from the air conditioning system and the ceiling fans. The energy consumption was used to calculate the electricity costs. Both comfort and productivity assessments were carried out using well-established models. Indoor temperatures and ceiling fan usage are inputs for the comfort models to obtain occupants' discomfort hours and productivity losses. Results from the productivity model were then translated into cost values. The different cooling strategies' investment, installation, operation, and maintenance costs were estimated based on building data and the available literature. The comprehensive economic assessment of the base case was then compared to other locations in Germany and future climatic scenarios to assess the potential of the personal cooling solution.

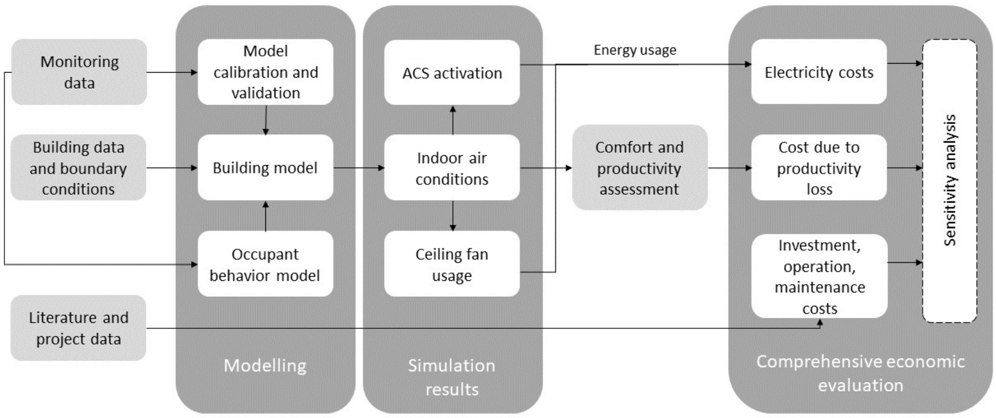

Figure 1. Methodology flowchart.

2.1. Building Description

The district administration building is in Dillingen an der Donau, Bavaria (Germany). The building has four floors and a basement, with 92 service and office rooms. A refurbishment of the existing building was carried out, including improving the façades' thermal transmittance, new windows with a control system for night ventilation, and a decentralized ventilation unit for each office room. Figure 2 (left) shows a typical office room. Further information about the existing building can be found in Table A1. Together with the renovation, the building was extended with new offices equipped with an air-conditioning system. The new building has been excluded from the analysis as it is irrelevant to this work.

Most offices are around 20 m^2 for one or two employees and have two windows with external blinds. The windows can be manually operated and have an automatic opening system for night ventilation. The night ventilation system does not use any additional mechanical ventilation. Ceiling fans integrated into an acoustic panel were added as part of the building renovation to enhance thermal comfort in summer. These fans were installed in every office workspace and can be individually operated. This system is a custom-made solution, shown in Figure 2 (right). More details are available in [11].

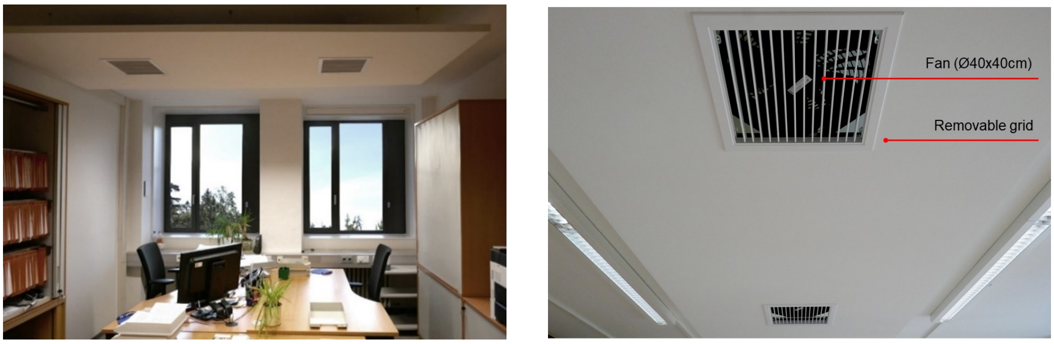

Figure 2. Example of an office room, showing the new window system (**left**) and integrated personal ceiling fan in an acoustic panel with a removable grid to adjust the airflow direction (**right**). Copyright (left image): 2021, Bergische Universität Wuppertal.

2.2. Monitoring Data

The monitoring campaign was carried out between August 2020 and September 2021. Table 4 describes the collected data relevant to this study and its characteristics. Building energy usage was measured, but it was not relevant to this study.

Table 4. Overview of monitoring data: measured parameters, sensor location, measurement interval and range.

Parameter	Sensor Location	Interval	Range
Indoor temperature	All rooms	5-min	0–50 °C.
Humidity	6 rooms	5-min	10–95%
CO_2 concentration	6 rooms	5-min	400–10,000 ppm
Ceiling fan speed	All rooms	By change	0–100%
Window position-tilted	All rooms	By change	Open–closed
Window position-open	All rooms	By change	Open–closed
Night ventilation windows status	All rooms	By change	Open–closed

2.3. Simulation Setup

This section provides a description of the building model and the modeling procedure. Building simulation calculates the cooling energy usage and the indoor air conditions necessary to assess comfort and productivity. Simulations were performed using the software environment EnergyPlus 8.9 [34].

2.3.1. Building Model

This section describes the assumptions for and adaptations to the building model. The basement was not considered as there are no office rooms. Therefore, the setpoint temperature for the night ventilation (the cooling and heating setpoints for the ACS) was used as the boundary condition for the ground temperature. A cooling setpoint of 24 °C was given to the new building with an ACS to model the heat transmittance realistically on the side of the building where the new building was attached. The building was divided into 51 thermal zones following the approach from Klein et al. [35], merging rooms with the same orientation and on the same floor. Figure 3 shows the thermal zones on the ground floor. Floors one to three were modeled similarly due to their similarity in layout.

Building thermal mass included the omitted internal walls. Thermal mass from furniture was neglected as it was negligible compared to the building envelope with internal walls [36]. Regarding the internal loads, the heat gain from people was set to 115 W/Person [37] and from laptops to 61 W/Person. The internal loads from lighting were calculated following the ASHRAE approach [37] in W/m^2. Further details are available in Knudsen [38].

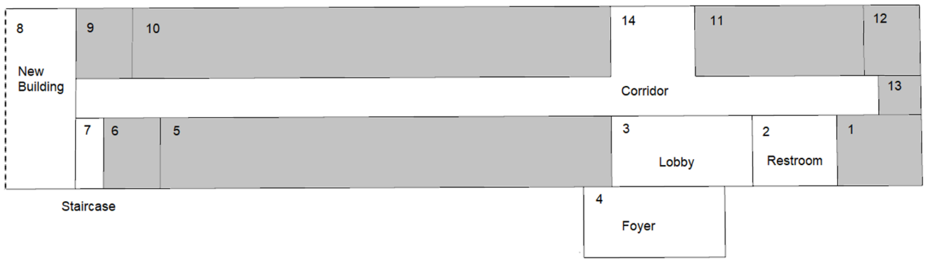

Figure 3. Thermal zones plan on the ground floor. Numbers indicate each thermal zone.

2.3.2. Boundary Conditions

As Ulm is close to Dillingen (50 km), the available typical meteorological year (TMY) weather file from Ulm was used for the simulation. Assumptions regarding building systems operation and occupant presence are described as follows.

Night ventilation window opening and blind position run according to a building automation system (no manual operation). Night ventilation windows are opened between 7 pm and 7 am when the indoor air temperature is 2 °C higher than the setpoint temperature, and the outdoor air temperature is 2 °C lower than the indoor air temperature. Deactivation occurs at a given indoor air temperature and certain outdoor conditions. The blinds close above a radiance threshold value of 192 W/m^2 [39].

For the window opening behavior, the stochastic model by Haldi and Robinson [40] was used. A sensitivity analysis was performed [38], which showed no significant differences between a single opening behavior for all windows or the application of individual behaviors. Therefore, a single window opening behavior for all windows in the building was used. We estimated the flow rates for open windows and night ventilation based on Wang et al. [41].

For the occupancy estimation, an algorithm was developed to estimate occupancy based on CO_2 concentration in every office [38]. As a result, average values of arrival and departure to the office were derived and applied globally to all the offices for the simulation: arrival = 07:55; departure = 15:40 (Monday–Thursday), 12:15 (Friday). The occupancy was then calculated based on the average working hours per week in Dillingen, which were taken from the results of previous comfort questionnaires in the building. A fraction of the occupancy hours was calculated considering absence due to vacation or sick leaves, part-time employees, and home office hours due to the COVID pandemic in 2020.

2.3.3. Ceiling Fan Usage

A ceiling fan manual operation model was developed based on the collected monitoring data. The ceiling fan speed (in %) was monitored for an entire year. For the sake of simplicity, the operation of the ceiling fan was modeled with an on-off approach. The fan was considered active (turned on) when the fan speed was equal to or greater than 5%.

Logistic regression is one of the most popular modeling techniques for variables with a binary output [42] This modeling approach has been extensively used to represent the occupant behavior for building simulation purposes: presence [43], window opening [40], blinds [44], lights [45], thermostat set point [46], and even to model the operation of desk and ceiling fans in offices [47–49]. The algorithm establishes a linear relationship between multiple explanatory variables and the logit function of the probability of an event happening and applies the logit function to this probability p. This linear relationship is expressed in the following equation:

$$ln\left(\frac{p}{(1-p)}\right) = \alpha + \beta_1 x_1 + \cdots + \beta_n x_n \quad (1)$$

p is the probability of an event happening,
α is the intercept,

β is a coefficient,
x is a set of explanatory variables.

For the case of the ceiling fan, the explanatory variables were selected based on the adaptive comfort theory, where the comfort state is proportional to the indoor temperature and the running mean of the outdoor temperature. The modeled probability p represents the probability of observing a fan turned on. Models were fitted using the "stats" package in the software environment R Version 3.6.3 [50]. The total dataset comprises six rooms. Only the data from June 2021 was considered since it is the only month when employees actively used the fan. Table 5 shows the obtained intercept and model coefficients.

Table 5. Coefficients of the logistic regression model to simulate ceiling fan operation (*** = $p < 0.001$, $R^2 = 0.10$).

Intercept	Indoor Temperature	Outdoor Temperature Running Mean
−30.56 ***	0.91 ***	0.26 ***

2.3.4. Calibration and Validation

A comparison between simulated and measured indoor temperatures was performed to validate the model. The results of the monitoring campaign during spring and summer (April–September, when the building is not heated) were used. Weather data were obtained from the installed weather station in Dillingen. The measurements of the German Weather Service-DWD [51] for Dillingen were used to complete the missing data. The simulation setup and boundary conditions are the same as the previous sections.

The comparison was performed separately for each thermal zone in the simulation model. The average of the measured room temperatures was taken for the thermal zones that include more than one room in the office building. The simulation was performed in hourly time steps due to the resolution of the weather data. The results were evaluated using the Mean Bias Error (MBE) and the Coefficient of Variation of the Root Mean Square Error (CV(RMSE)) as suggested by ASHRAE Guideline 14 [52]. ASHRAE Guideline 14 considers a building model to be calibrated when average hourly MBE values are within ±5% and average hourly CV(RMSE) values are less than 15%. Table 6 shows the resulting average zone value for both indicators. Table A2 in Appendix A shows the individual results for each thermal zone.

Table 6. Average zone value for MBE and CV(RMSE).

Value	Mean Bias Error (MBE)	Coefficient of the Variation of the Root Mean Square Error (CV(RMSE))
Average	2.53	5.56

2.4. Comfort, Productivity and Cost Evaluation

Thermal comfort and productivity are assessed as part of the economic evaluation of the cooling strategies. Results from the latter were then translated into monetary values and added up to the cost analysis. Data were analyzed using the software environment R Version 3.6.3.

The simulated indoor air conditions were analyzed to evaluate comfort and the resulting productivity loss due to dissatisfaction. As the focus was on comfort loss due to overheating in summer, the period from April to September was analyzed, and the simulation results were reduced to the occupancy times. The adaptive thermal heat balance model (ATHB) was selected to evaluate comfort due to the high accuracy of the model in predicting thermal comfort and acceptability votes in naturally ventilated buildings [53]. Two indices were used: the predicted mean vote (PMV) [54] and the standard effective temperature (SET) [55]. The original PMV model by Fanger et al. [54] applies to controlled environments with ACSs and an air velocity lower than 0.2 m/s. Therefore, it is only used to evaluate the comfort of the ACS concept. Gagge et al.'s original SET model [55] was used for the concepts NoCooling, NV, and NVandCF, as it was applicable for elevated air speeds. Comfort votes for indoor conditions are expressed in PMV and predicted thermal sensation (PTS) for active and passive cooling strategies, respectively, and were calculated with the package "comf" [56]. The input and output variables for each model are listed in the following table (Table 7).

Table 7. Thermal comfort indices using the ATHB model and their input and output variables. T_a = air temperature; T_r = radiant temperature; RH = relative humidity; AV = air velocity; T_{rm} = outdoor temperature running mean; met = metabolic rate; clo = clothing value; psych = psychological adaptive coefficient.

Index	Input Variables	Output
$ATHB_{PMV}$	T_a, T_r, RH, AV, T_{rm}, met, psych	Predicted mean vote (−3 to +3)
$ATHB_{PTS}$	T_a, T_r, RH, AV, clo, met, psych	Predicted thermal sensation (−3 to +3)

T_a, T_r, and RH values were obtained from the simulation. A value of 0.61 was assumed for clothing insulation level (light clothing: trousers, long-sleeve shirt) and 1.1 for the metabolic rate as an average value of sitting and standing [37]. The air velocity was assumed constant at 0.05 m/s without an active ceiling fan and 0.6 m/s with an active ceiling fan [11]. The psych variable was neglected (value 0).

Several studies have tried to quantify the productivity loss produced by a reduction in thermal satisfaction in buildings. Productivity models quantify the worker's performance regarding indoor environmental conditions. The Maximal Adaptability Model (MAM) developed by Hancock and Warm [57] relates thermal stress to work performance. Contrary to other proposed models [58,59], the MAM includes the concepts of adaptability in both physiological and psychological aspects to human stress and, therefore, attention capability. This way, the model proposes that human performance remains relatively stable in a range of temperatures achieving maximal productivity (100%), but rapidly decreases outside this range (U-shaped function). Porras-Salazar [60] suggested adapting the MAM model to fit different performance databases. The relative performance (RP) of an employee is calculated as a function of the indoor temperature T for different temperature ranges and results in the following equation.

$$RP = \begin{cases} 12.057 \cdot T - 0.257 \cdot T^2 - 41.293, & T < 23\ ^\circ\mathrm{C} \\ 100, & 23\ ^\circ\mathrm{C} \leq T \leq 27\ ^\circ\mathrm{C} \\ 13.657 \cdot T - 0.257 \cdot T^2 - 81.293, & T < 27\ ^\circ\mathrm{C} \end{cases} \quad (2)$$

As the MAM model considers only the indoor air temperature and neglects the cooling effect from elevated air speed, the concept of ceiling fans cannot be correctly represented. Therefore, we propose to calculate the RP using the SET (RP_{SET}) instead of the room air temperature to include air velocity.

Monetary costs of the decrease in relative performance were computed according to the following formula:

$$Costs_{PerformanceLoss} = (1 - RP) * \frac{Salary_{year}}{2} * Employees \quad (3)$$

As we assumed half a year (six months) for the cooling period, a factor of $\frac{1}{2}$ was applied to the previous formula. Productivity results are converted into monetary values by considering the time lost by employees to complete their work as salary costs. An average salary ($Salary_{year}$) of €45,000 per year was estimated [61], as no information on the employment structure was available.

The energy (electricity) consumption was a result of the simulation. Costs for electricity were assumed to be 38.25 Cent/kWh [62]. The energy use of the ceiling fans was calculated with total running hours and a nominal power of 10 W. For the split-ACS, the coefficient of performance was presumed to be 3.5. Other considered costs were the investment, installation, planning, and operation-maintenance (O & M) costs. The assumed costs for the cooling strategies are presented in Table 8.

Table 8. Component costs overview.

	Building Control	Acoustic Panel	Ceiling Fans	Night Ventilation	Air Conditioning
Investment [€]	24,900	15,700	73,790	34,750	119,600
Installation [€]	3735	2355	11,069	5213	174,800
Planning costs [€]	6077	3829	11,355	8480	29,171
O & M [€/a]	1245	0	3690	1737	15,640

The assumptions and calculations for each aspect of the cost structure are as follows:

- The investment costs for the building control, night ventilation, and ceiling fans were obtained from the project, and approximately €100 were assumed for the acoustic panel [63].
- Based on the project, installation costs for all concepts excluding ACSs are approximately 15% and were proportionally allocated to the investment costs of building control and automation, ceiling fans, night ventilation, and acoustic panels. The same goes for the planning costs (24.4%). Operation and maintenance costs (O & M) were assumed to be around 5% of the investment costs [64]. O & M costs were neglected for the panels as they have no moving parts, and consequently, minimal maintenance effort.
- The costs for the ACSs were assumed based on the literature [65], having a total of 92 decentralized ACSs (one per room). It was assumed that the planning costs for the ACSs would have the same investment-to-planning ratio as the other cooling strategy components (24.4%).
- Building control costs are common to every concept. The acoustic panels were considered for all concepts due to their positive impact on room acoustics.

One indicator of investment efficiency is the net present value (NPV). The NPV was calculated assuming a service life of 20 years (n) and an interest rate (i) of 8% [66]. A positive NPV implies that the installation was worthwhile, as the cash flows (R_t) during the service time (t) outweigh the initial investment (Y). A positive NPV indicates that the cash flows (R_t) during the service time (t) outweigh the initial investment (Y); thus, the installation is worthwhile. There is no real income (positive cash flows) when a cooling concept or system is planned. However, the cheapest solution can be assessed by directly comparing all associated costs (negative cash flows) throughout the system's life span, such as operative costs (energy, maintenance) and associated discomfort costs represented by productivity losses. Thus, the resulting NPV values will be negative.

$$NPV = Y - \sum_{t=0}^{n} \frac{R_t}{(1+i)^t} \tag{4}$$

The baseline case is a solution without a cooling concept, and the ΔNPV compares the costs for each concept. When a cooling concept provides higher cost savings than the reference NPV ($\text{NPV}_{NoCooling}$), the ΔNPV becomes positive.

$$\Delta NPV_{concept} = NPV_{concept} - NPV_{NoCooling} \tag{5}$$

3. Results

In this section, the results of the energy consumption, thermal comfort and productivity assessment, and cost evaluation are described. Based on the previous assumptions, simulation results, and results from the thermal comfort and productivity models, the different cooling concepts were compared in terms of cost analysis with a baseline case study. A sensitivity analysis was carried out using distinct locations and climate predictions.

3.1. Base Case

3.1.1. Energy Consumption

The energy evaluation was assessed regarding the electricity usage for the ceiling fan and air conditioning concepts, as night ventilation alone and the no-cooling concept have no relevant energy usage for cooling. With the application of the developed behavioral model, the running time of the ceiling fans is 84 h on average per room (for the analyzed period). Table 9 shows the results for energy consumption.

Table 9. Electrical energy consumption for the analyzed cooling concepts.

	NoCooling	**NV**	**NVandCF**	**ACS**
Energy [kWh/a]	0	0	132	1473

3.1.2. Thermal Comfort Evaluation

The PMV and the PTS were calculated using the ATHB model for all concepts for the comfort evaluation. According to ASHRAE [37], PMV values outside of +/−1 are classified as uncomfortable. As the present study focused on summer conditions, only comfort votes within the warm-hot range (greater than +1) were evaluated as discomfort. The percentage of summertime discomfort hours—i.e., hours outside the comfort range—was calculated for the potential cooling period from April to September within the occupancy hours for three different comfort zones: votes greater than +1 ("slightly warm"), greater than +2 ("warm") and equal/greater than +3 ("hot") (Table 10).

Table 10. Percentage of discomfort hours for different PMV/PTS votes for each cooling concept using the ATHB model.

Comfort Zone		**NoCooling**	**NV**	**NVandCF**	**ACS**
PMV/PTS $\geq$ +1	slightly warm	32.52%	17.79%	14.17%	0.00%
PMV/PTS $\geq$ +2	warm	0.45%	0.00%	0.00%	0.00%
PMV/PTS = +3	hot	0.00%	0.00%	0.00%	0.00%

More than 30% of the occupied hours for the NoCooling concept were considered "slightly warm." The introduction of night ventilation reduced this value to 18%. The number of PTS votes "slightly warm" was reduced further to 14% due to the ceiling fan air movement. The ACS always provided maximum comfort by keeping the air temperature at the desired setpoints. For PMV/PTS values greater than +2 ("warm"), the discomfort values were reduced to 0% already for night ventilation, given the overall low ambient temperatures in summer.

Figure 4 displays PMV and PTS values for different indoor temperature values. For the concept ACS, the cooling setpoints of 20 and 24 °C can be seen, and no PMV values higher than zero were observed. However, some PMV values reached a value of −2 ("cool"), exceeding the comfortable range and showing a risk of overcooling. However, comfort votes could be improved (closer to neutral) if greater values for clothing were considered, as the recommended values for activity level (met = 1), and clothing insulation level (clo = 0.5) for an indoor temperature of 26 °C [67] were used for this calculation.

The diagrams for the concepts NoCooling, NV, and NVandCF are similar as the same model was applied. In the NoCooling concept, temperatures higher than 30 °C can be observed, which were perceived as "warm" and "hot." In contrast, for the concepts including night ventilation, the temperature did not exceed 30 °C. For those concepts, a PTS value higher than +2 ("warm") corresponds to a temperature of 29 °C. In the NVandCF concept, two data point areas can be observed. The black area is the same as for NV, while the grey area corresponds to the data points when the ceiling fan was active. This results in a lower SET and, consequently, lower PTS votes.

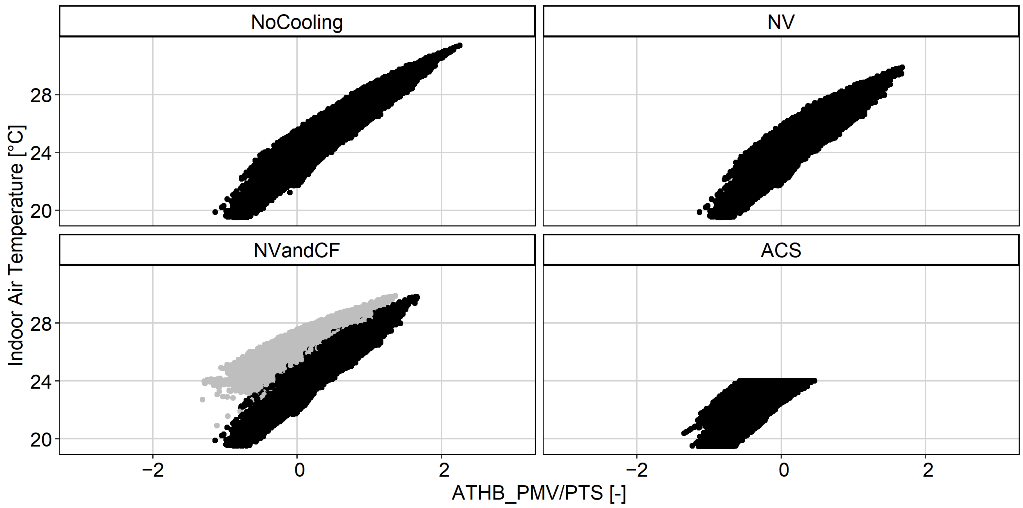

Figure 4. PMV (ACS) and PTS (NoCooling, NV, NVandCF) values vs. indoor air temperature using the ATHB model (black points). The grey points correspond to the data when the ceiling fan was active.

3.1.3. Productivity Evaluation

The relative performance (RP) was calculated according to the productivity model from Hancock and Warm [57] previously introduced. The results can be seen in Table 11. The difference in relative performance between all concepts seems to be marginal. The impact of the productivity losses on the cost assessment is therefore analyzed in the next section.

Table 11. Average productivity for each analyzed concept.

	NoCooling	NV	NVandCF	ACS
$RP_{ATHB-SET}$ [%]	99.44	99.80	99.85	100

3.1.4. Costs Evaluation

The results of the economic evaluation are displayed in Table 12. An ACS's investment and O & M costs are around two times higher than the ceiling fan and night ventilation concept. The same relationship applies between the ceiling fan and the night ventilation concept. The electricity costs of the ACS are 10 times higher than the ceiling fan concept. Compared to the costs due to productivity losses, the electricity running costs are lower, especially when using the ceiling fan. The ΔNPV is positive for only night ventilation, as savings in productivity losses do not compensate for the initial investment in the case of the ceiling fan and ACS.

Table 12. Cost overview and the difference between NPV for all cooling concepts.

	NoCooling	NV	NVandCF	ACS
Invest [€]	52,861	96,090	192,304	354,468
O & M [€/a]	1245	2982	6672	15,640
Electricity [€/a]	-	-	51	564
Productivity [€/a]	19,782	7065	5299	0
ΔNPV [€/employee]	-	445	−247	−1417

To assess the impact of different salaries and interest rates in the base case, the boundary values for ΔNPV = 0 were calculated. Figure 5 shows the results for an interest rate from 0% to 10%. The value combination of salary and interest rate that leads to a ΔNPV = 0 is the minimum value in which the investment of the installed cooling system is economically viable. For lower salary costs and high-interest rates, the concept without cooling is always more profitable, as the associated costs to productivity losses decrease. For lower interest rates or higher salary values, the future operative costs of the cooling system are more relevant to the total costs. To sum up, the most profitable investment is the curve with the lowest values on the y-axis. The ACS concept becomes profitable with a salary of 110,000 and an interest rate of 8%, while the ceiling fan becomes profitable with a salary of around 60,000. The interest rate plays a secondary role compared to the salary for the investment efficiency calculation. Thus, in the next section, the interest rate is further assumed to be 8% without analyzing the sensitivity to this variable.

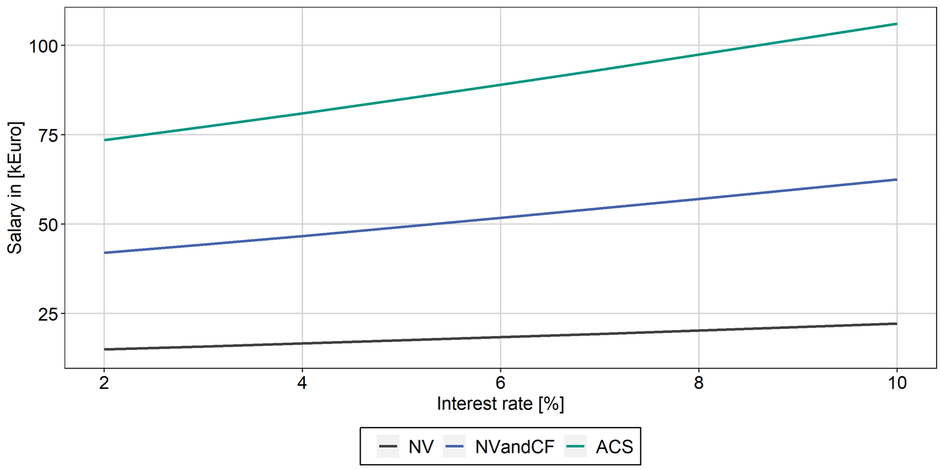

Figure 5. Interest rate and salary for ΔNPV = 0.

3.2. Sensitivity Analysis

A sensitivity analysis simulating other locations in Germany with different climatic scenarios was carried out to comprehensively evaluate the personal ceiling fans' performance and costs. The cities of Mannheim and Potsdam were selected, as Potsdam is often used as a reference location for the climate in Germany, and Mannheim has shown elevated temperatures compared to the German average. Figure 6 shows the cumulative distribution of the outdoor air temperature for Ulm (baseline case) as well as for Mannheim and Potsdam for a typical meteorological year (TMY) of the early 2000s and for a predicted test reference year 2035 (TRY 2035). The highest temperatures correspond to the prediction of Mannheim in 2035, while Ulm shows the lowest temperatures.

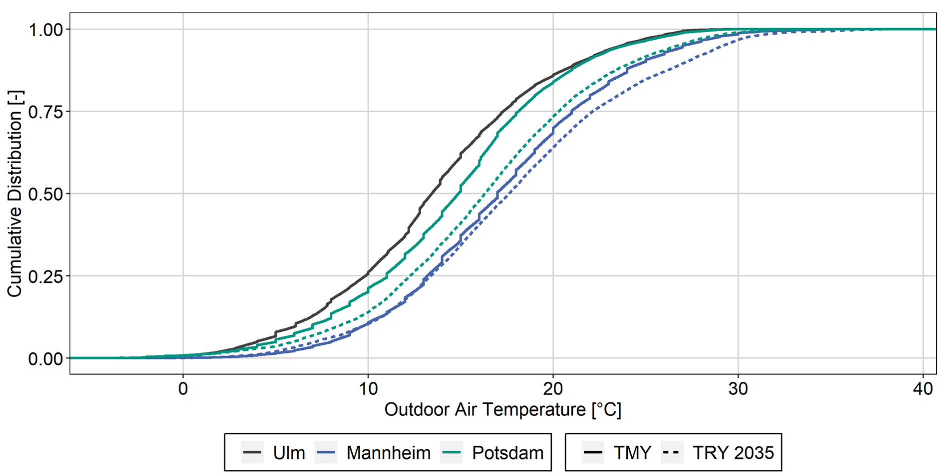

Figure 6. Cumulative outdoor air temperature distribution for the selected locations and climate scenarios.

3.2.1. Energy, Thermal Comfort and Productivity

Table 13 shows an overview of energy-related indicators, including the maximum power and electricity usage for the ACS concept and the usage hours and related energy consumption for the ceiling fan concept. Results for Ulm and Potsdam TMY are similar for all indicators and values for Mannheim TMY and Potsdam 2035 as well. Energy consumption for ACSs and ceiling fans increases by a similar factor of around two between the baseline and Mannheim TMY/Potsdam 2035 and around three between the baseline and Mannheim 2035. The maximum cooling power for the building differs by 30% between the two extreme scenarios (Ulm TMY and Mannheim 2023).

Table 13. Overview electricity usage for all locations and climatic scenarios.

Concept	Indicator	Ulm TMY	Potsdam TMY	Potsdam 2035	Mannheim TMY	Mannheim 2035
ACS	Maximum power [kw]	30.22	29.2	34.69	36.31	39.66
ACS	Electricity cooling [kwh]	1473	1503	2955	3181	4519
Ceiling fan	Hours of usage per person [h]	84	96	181	213	291
Ceiling fan	Usage energy [kwh]	132	151	284	334	457

Figure 7 shows the energy consumption and the percentage of hours where PTS votes were above +1 ("slightly warm") for the ceiling fan concept. Three groups with similar energy and comfort values can be identified: Ulm and Potsdam TMY, Potsdam 2035 and Mannheim TMY, and Mannheim 2035. Each group's representative location and scenario will be kept for further analysis: Potsdam TMY, Mannheim TMY, and Mannheim 2035.

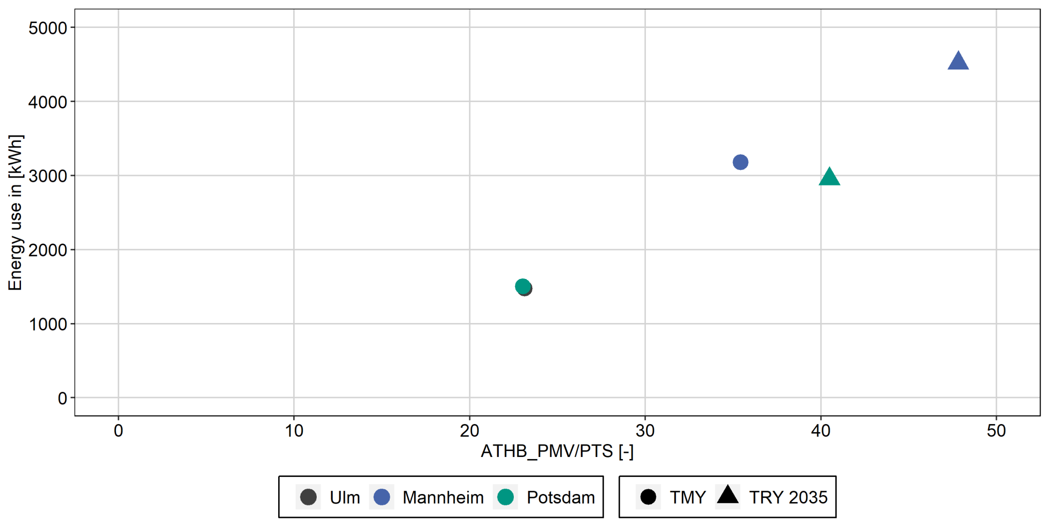

Figure 7. Energy use and percentage of discomfort hours for PMV/PTS greater than 1 ("slightly warm") for all locations and climate scenarios.

Figure 8 shows the cumulative distribution of PMV and PTS votes for all four cooling strategies for the different climatic scenarios. In each cooling concept, all scenarios show a similar pattern. The higher impact of warmer climates (Mannheim 2035) can be seen in the NoCooling and NV concepts. This shows the positive impact of ceiling fans on thermal comfort.

Table 14 shows the percentage of PMV/PTS values greater than +1 ("slightly warm") and +2 ("warm") for the different scenarios and cooling concepts. In warmer climates, the potential of the ceiling fan to reduce discomfort hours is higher: for a PMV/PTS > 1 category, the ceiling fan reduces discomfort in Potsdam by 19%, and in Mannheim 2035 by 35%. For PMV/PTS > 2 categories, a night ventilation strategy decreases discomfort significantly.

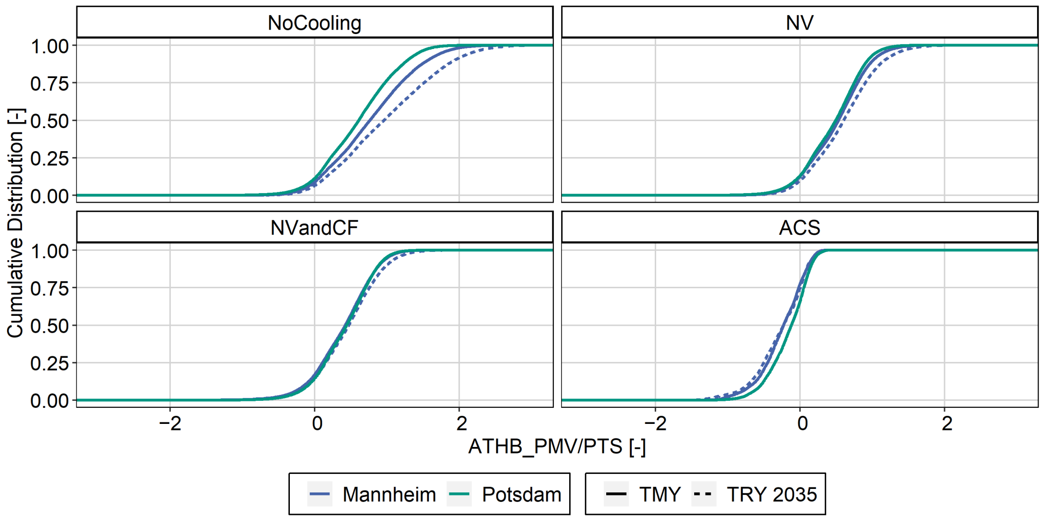

Figure 8. Cumulative PMV (ACS) and PTS (NoCooling, NV, NVandCF) values for all climate scenarios, using the ATHB model.

Table 14. Percentage of discomfort hours for PMV (ACS) and PTS (NoCooling, NV, NVandCF) using the ATHB model, values greater than +1 and +2 for different locations and climatic scenarios.

Comfort	Scenario	NoCooling	NV	NVandCF	ACS
PMV/PTS ≥ 1	Potsdam TMY	30.92%	16.24%	12.47%	0.00%
	Mannheim TMY	37.85%	16.72%	9.76%	0.00%
	Mannheim 2035	46.26%	21.06%	11.09%	0.00%
PMV/PTS ≥ 2	Potsdam TMY	0.41%	0.01%	0.00%	0.00%
	Mannheim TMY	1.93%	0.06%	0.01%	0.00%
	Mannheim 2035	4.36%	0.20%	0.01%	0.00%

Table 15 shows the relative performance of all cooling strategies for the three groups. The lowest relative performance can be observed for Mannheim 2035, with 98.62% for the NoCooling strategy. The ACS always provides 100% comfort. The higher the temperatures from the climatic scenario, the higher the difference in relative performance between cooling strategies.

Table 15. Relative performance values [%] for the three representative groups.

Scenario	NoCooling	NV	NVandCF	ACS
Potsdam TMY	99.46	99.81	99.87	100
Mannheim TMY	99.13	99.78	99.89	100
Mannheim 2035	98.62	99.69	99.88	100

3.2.2. Costs and Investment Evaluation in Future Scenarios

In this section, the results of the investment efficiency in different climates and a sensitivity analysis of the affected variables (salary and energy costs) are reported. Table 16 summarizes the values of the ΔNPV for the different climates and cooling concepts. In line with the results in Section 3.1.4, night ventilation is always profitable compared to NoCooling. The ceiling fan becomes profitable in warmer climates (Mannheim, both present and future climate); however, it is always behind night ventilation. Especially in future climates, this indicates that a technology cost reduction might help compensate for the investment in the ceiling fan with the additional performance losses economically. The ACS becomes slightly positive compared to the NoCooling strategy in future climates.

Table 16. ΔNPV for different climates and cooling concepts.

ΔNPV	NoCooling	NV	NVandCF	ACS
Potsdam TMY	-	423	−248	−1463
Mannheim TMY	-	1099	536	−760
Mannheim 2035	-	2046	1660	355

Furthermore, we studied the sensitivity of the ΔNPV to changes in the cost structure, namely salary and energy costs. Figure 9 shows the impact on ΔNPV when changing the assumed salary costs. The interpretation relates to the description in Section 3.1.4, where it was explained that the cooling concept with the lowest curve along the y-axis provided the lowest cost. The best investment efficiency is provided by night ventilation in all scenarios. The curves are mostly parallel, confirming that the obtained results are also valid for other salaries. In future climates, the ΔNPV is more affected by salary changes, as the performance costs are higher.

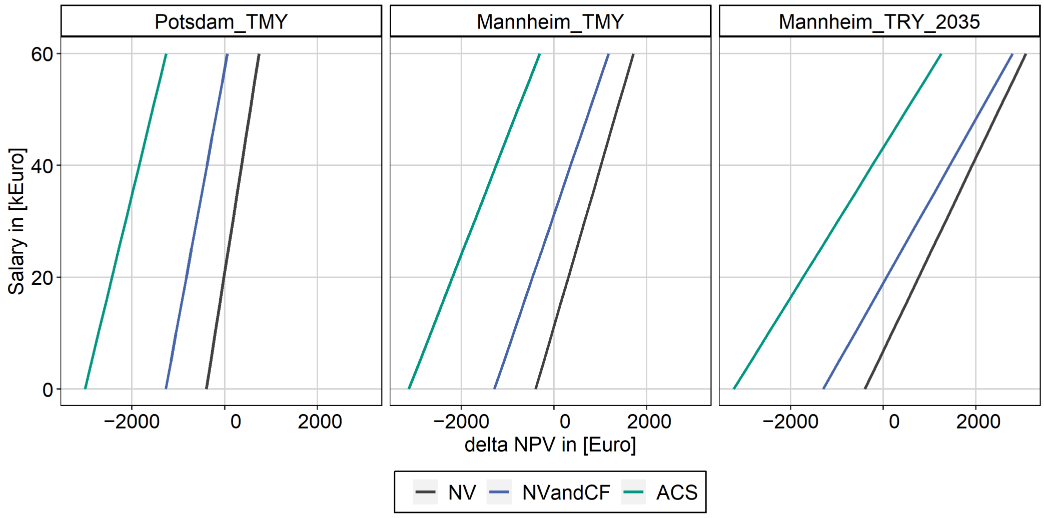

Figure 9. ΔNPV sensitivity to salary changes.

Figure 10 shows the impact on ΔNPV when changing the assumed energy costs. The interpretation relates to the previous figure, where night ventilation provides the best investment efficiency in all scenarios, and the curves are mostly parallel. The NV curve is vertical since it is not affected by energy cost changes (energy consumption of the automation system was neglected in the simulation). ΔNPV results are less sensitive to energy cost changes than salary costs.

3.2.3. Technology Cost Structure in Present and Future Scenarios

In the previous section, we concluded that it was impossible to make the ceiling fan more profitable than night ventilation alone when varying the salary or energy costs. Therefore, a technology cost reduction was calculated to estimate the maximum ceiling fan costs to make it profitable against night ventilation alone. Figure 11 shows the increase of the investment efficiency with falling investment costs, with a salary of €45,000 and an interest rate of 8% as boundary conditions.

The current customized solution comes with approximately €613 per ceiling fan investment. In the case of colder locations (Ulm and Potsdam TMY), the cost savings due to additional comfort (performance increase) are considerably low compared to the additional investment—which results in a required ceiling fan cost of €152. In warmer climates, the contribution of the ceiling fan becomes economically more significant. To be profitable against night ventilation alone, the ceiling fan must cost €203 in Mannheim TMY and €287 in Mannheim TRY 2035. This emphasizes the need for a cost reduction in the ceiling fans to be profitable in future scenarios.

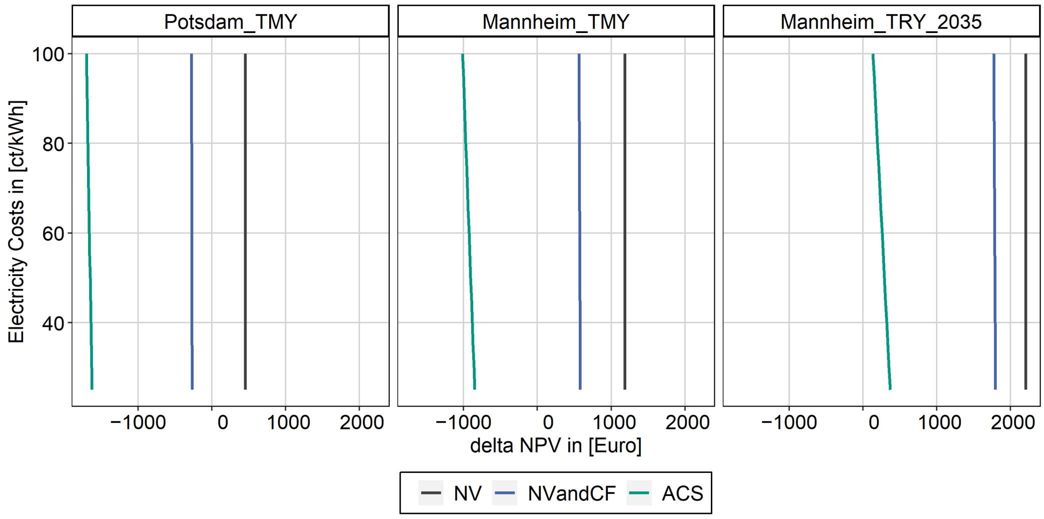

Figure 10. ΔNPV sensitivity to costs changes.

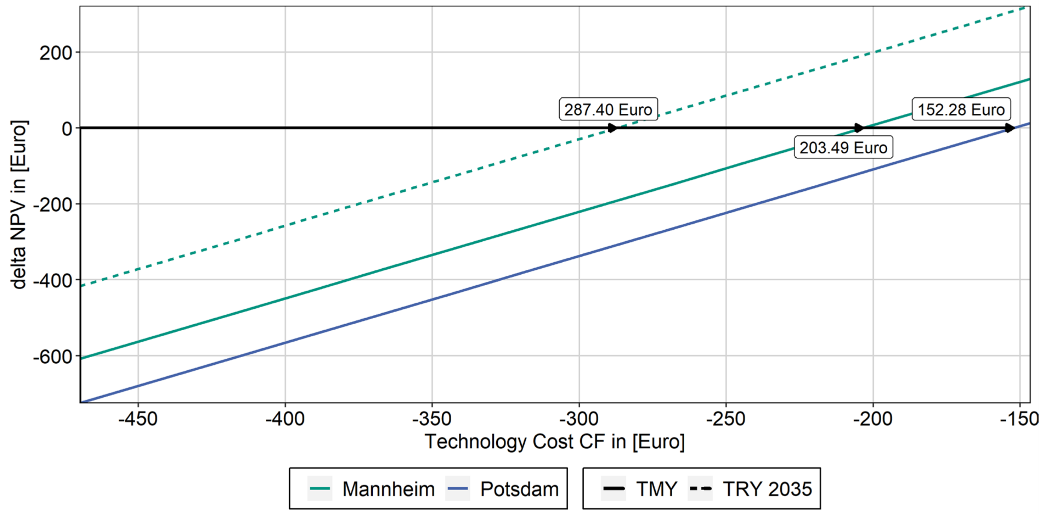

Figure 11. ΔNPV of the ceiling fan strategy against night ventilation for the three representative locations and climatic scenarios.

4. Discussion

The discussion is organized in the following subsections, where we thematically discussed the results and the limitations of each part of the study.

4.1. Fan Use Model

For the purpose of this study, we developed a fan-use behavior model for the district building in Germany. Results showed that the probability of using the fan ranges between 71–96% and between 94–99% at 28 °C and 30 °C indoor temperature, respectively (within a range of outdoor running mean temperature between 23–32 °C). These probabilities are comparable to the fan model developed by Nicol [47]. He found that 80% of building occupants use fans at 28 °C, and the operation is almost universal above 30 °C in Pakistan and Greece. However, probabilities corresponding to temperatures lower than 25 °C differ between studies, being relatively low in the present study. These differences might be related to the data collection method for the fan operation, as the model presented here is based on monitoring data (Nicol's model is based on survey data) and includes outdoor running mean temperature as a predictor variable. Moreover, cultural and climatic differences between Germany and other countries might lead to differences in operation. For instance, in the experimental study from Schweiker et al. [49], the authors found that below an operative temperature of 26 °C, the probability of German participants using the ceiling fan was lower than 20%, while the study from Zhang et al. [28] also showed lower probabilities of using a ceiling fan in a hot, humid area. The model presented in this study presents limitations in terms of generalization due to limited data from the monitoring. The model was fitted with data from one month, as it was the only period in which active use of the ceiling fan was observed.

4.2. Thermal Comfort Analysis

The resulting thermal comfort votes for the different cooling strategies, locations, and climatic scenarios were analyzed. Results showed that including night ventilation in the analyzed building design can reduce occupants' slightly warm sensation by 50% and reduce to zero their warm sensation. The discomfort hours were reduced to less than 18% during the year. As shown in the simulation study from Pfafferott et al. [20], the level of operative temperatures in a German office building could be lowered by incorporating automated night ventilation in combination with mechanical ventilation, reducing the indoor temperature above the comfort range to 10% during working hours. Including the ceiling fan in the night ventilation solution can reduce the slightly warm sensation by around 20% compared to the night ventilation solution alone. The positive effect of air movement on thermal sensation and comfort has been investigated in previous studies [11]. The presented sensitivity analysis showed that at higher observed outdoor temperatures, the impact of the ceiling fan on reducing thermal sensation votes increased by around 10%. However, the positive effect of perceived control on thermal satisfaction [68,69] could not be accounted for in the analysis with the used thermal comfort models. A reduction in occupants' perceived warm comfort sensation could be expected by incorporating personal control of cooling strategies as predicting factor in the thermal comfort models.

4.3. Productivity Analysis

We assessed the impact of the different cooling strategies in terms of productivity. Using Hancock and Warm's model [57] to calculate relative performance did not allow the inclusion of airspeed provided by fans. Therefore, we proposed replacing the indoor temperature with the SET to calculate the effect of elevated air speed on productivity. However, the validity of this calculation remains questionable and further proof is needed. Moreover, previous studies [70–72] indicate that users' control over thermal conditioning systems is a key aspect affecting people's satisfaction and can help improve workplace productivity. Like the comfort analysis, the positive effect of personal control over the fan could not be accounted for in Hancock and Warm's model, which might underestimate a potential increase in relative performance. Regardless of the model limitations, existent productivity assessment methods present a series of uncertainties regarding their theoretical foundations and applicability. Some authors [29,73] suggest that productivity is mostly influenced by thermal comfort and could not find any relationship between temperature and work performance [60]. Moreover, they suggested that current methods for measuring productivity are quite simplistic and prone to bias. However, the authors could not provide a model with a better prediction performance than Hancock and Warm's model. This may question the assumptions in productivity models based on indoor temperature, and their validity in assessing the performance in the workplace.

4.4. Cost Analysis

The cost structure is comparable with results from Olesen [74], who calculated average costs for improving indoor environmental quality from a lower to a higher building category regarding ventilation rates. In the present study, we compared the ACS solution with the higher category from Olesen. Olesen's results showed a cost structure of the improved building category of 97% for investment costs, 2% for maintenance, and 1% for energy, which is in line with our results. Slightly higher values correspond to the electricity and investment costs for Olesen's structure, which can be explained by the fact that he calculated the costs for the whole building system, including heating and cooling.

Given the high influence of productivity losses, the variation in the salary affects the NPV calculation. We proposed a calculation method to transfer productivity losses into monetary costs based on salary, number of employees, and cooling period. Even though the sensitivity of the results to variations in the salary was studied, different combinations of assumptions were not assessed. They could lead to different results from the ones presented. Considering the assumed interest rate, previous publications [75,76] suggest that higher interest rates might jeopardize the breakthrough of clean energy technologies in the market. In this study, those interest rates for private loans are above 8%, which was chosen following a conservative approach. This assumption is key to properly evaluating the ceiling fans' economic potential. Further studies may focus on developing validated productivity assessment methods and the qualification of productivity loss in terms of economic values.

Technology cost reduction was assessed in Section 3.2.3. As mentioned before, the existing cost structure of the ceiling fan corresponds to a customized solution from a field trial. On the one hand, industrializing the manufacturing process may seem a possible path to significantly reducing costs. On the other hand, to further support the installation of passive cooling technologies, different incentive schemes (i.e., from the government) could be considered to supplement the cost reduction threshold in the manufacturing process.

4.5. Assessment Method for PECSs: Uncertainties and Challenges

Finding a compromise between the provision of high satisfaction levels in buildings and the reduction of energy usage and costs is yet to be researched in depth [77]. In the context of climate change and increasing warm outdoor temperatures, this takes particular importance when implementing passive and active cooling strategies. We focused this work on the cost-benefit analysis of personal environmental control systems. We proposed a detailed assessment method in terms of economic viability to promote the incorporation of personal ceiling fans over conventional air conditioning methods. Following the proposed framework of Rawal et al. [14], we compared conventional cooling systems (without a PECS) and a system with a PECS, in this case, a personal ceiling fan. The work was based on building simulation and modeling techniques to compare different climatic and building scenarios. Apart from the limitations of the fan model and productivity calculations mentioned above, this comes with a series of limitations concerning the reproducibility of this assessment method due to the inherited assumptions and uncertainties proper to the nature of simulation methods. Further research could focus on developing a series of indicators to facilitate the assessment of and comparison between cooling systems and contribute to the standardization of a cost-benefit analysis for PECSs. Zhang et al. [9] developed the standardized indicator, the corrective power, to assess the comfort increase and energy savings potential of PECSs. A similar concept could be extended to assess the overall economic viability of PECSs based on the assessment proposed within this study. Additionally, future monitoring campaigns could be designed in such a way as to gather relevant data necessary for the proposed cost-benefit assessment, and in turn, serve as simulation work validation. As we conducted a single-case assessment, results cannot be generalized, but they serve as the first attempt to assess the cost-benefit of PECSs broadly.

4.6. Practical Implications

As mentioned by Prieto et al. [3], even though there is an increasing amount of cooling research, there is a need for specific research regarding possibilities for application, architectural integration, and performance issues of cooling systems. Within this study, we performed a real case building assessment, where not only the system's cooling performance was evaluated but also its incorporation into the building in terms of compatibility with the existing building features and employees' real behavior was assessed. The proposed PECS brings along benefits in terms of comfort requirements, maintaining energy consumption, and running and investment costs to a minimum extent. Indirect benefits of this system were not quantified within this work, such as the low environmental impact of this passive solution and the flexible design that allows easy integration within the building design, especially in existing buildings. The latest trends in building design focus on methodologies that minimize costs during the life cycle and maximize environmental benefits, showing that energy savings can be higher than the initial investment cost [78]. Within this study, we intend to follow this approach by promoting a sustainable building design in line with economic targets and climatic conditions.

5. Conclusions

This study evaluated the economic viability of personal ceiling fans within an office building renovation in Germany. A comprehensive cost-benefit analysis of energy consumption, direct and indirect costs, operation and labor costs, and thermal comfort was performed. The implemented ceiling fan solution was compared to alternative active and passive cooling strategies for different locations, and climatic scenarios through building performance simulation. Results showed that personal ceiling fans, assisted by night ventilation, are an effective and profitable cooling solution for warmer locations in Germany. These findings may have implications for applying personal environmental control systems (PECSs) and passive cooling strategies against purely active cooling solutions in buildings in favor of sustainability and economics. Additionally, we presented a cost-benefit assessment method for a PECS, including the calculation of labor costs, which contributes to the economic assessment of personal comfort system literature. Further research should focus on broadening the economic evaluation of PECSs in real-case buildings.

Author Contributions: Conceptualization, R.R., N.C. and M.S.; methodology, R.R. and N.C.; software, M.K. and N.C.; formal analysis, R.R. and N.C.; writing—original draft preparation, R.R. and N.C.; writing—review and editing, R.R., M.K., N.C., M.S. and A.W.; visualization, M.K.; supervision, R.R., N.C., M.S. and A.W.; project administration, R.R.; funding acquisition, M.S. and A.W. All authors have read and agreed to the published version of the manuscript.

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Abbreviations

The following abbreviations are used in this manuscript:

PECS	Personal Environmental Control System
NoCooling	No night ventilation or air-conditioning
NV	Night ventilation
NVandCF	Night ventilation (NV) and ceiling fans (CF)
ACS	Air conditioning system
HVAC	Heating, Ventilation, and Air Conditioning
PMV	Predictive Mean Vote

ATHB	Adaptive Thermal Heat Balance model
SET	Standard Effective Temperature
PTS	Predicted Thermal Sensation
MAM	Maximal Adaptability Model
T_a	Air temperature
T_r	Radiant temperature
RH	Relative Humidity
AV	Air velocity
$T_r m$	Outdoor temperature running mean
met	Metabolic rate
clo	Clothing value
psych	Psychological adaptive coefficient
RP	Relative Performance
NPV	Net present value
ΔNPV	Delta Net present value
O & M	Operation and Maintenance
TMY	Typical Meteorological Year
MBE	Mean Bias Error
CV(RMSE)	Coefficient of Variation of the Root Mean Square Error

Appendix A

Table A1. Building characteristics and additional information.

Parameter	Value
Gross floor area	5500 m^2
Net floor area (ground floor to 3rd floor)	3488 m^2
Building orientation	345°
Thermal transmittance north façade	0.13 $W/m^2 \times K$
Thermal transmittance roof	0.713 $W/m^2 \times K$
Infiltration (assumed)	0.1 ACH
Night ventilation window size	0.239 m^2
g-value window and glazing	0.55
Window/wall ratio	0.22
Number of employees	157

Table A2. Absolute value of Mean Bias Error (MBE) and the Coefficient of Variation of the Root Mean Square Error (CV(RMSE)) for each building thermal zone.

Thermal Zone	MBE	CVRMSE	Thermal Zone	MBE	CVRMSE
TZ01	2.32	5.17	TZ27	3.31	7.42
TZ05	0.89	1.98	TZ29	3.36	7.31
TZ06	2.45	0.56	TZ32	2.41	5.24
TZ09	0.94	2.06	TZ33	2.07	4.54
TZ10	0.90	2.00	TZ36	3.14	6.61
TZ11	0.90	2.04	TZ37	2.87	6.17
TZ12	2.02	4.67	TZ38	4.14	9.20
TZ13	1.03	2.35	TZ40	5.59	12.27
TZ15	2.22	4.95	TZ43	3.67	8.05
TZ19	1.46	3.22	TZ44	3.83	8.34
TZ20	1.03	2.27	TZ47	4.40	9.64
TZ21	0.64	1.42	TZ48	4.05	8.90
TZ24	2.14	4.52	TZ49	4.59	9.95
TZ25	1.71	3.72	TZ50	6.36	13.77
TZ26	1.24	2.77			

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