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Energy, SBS symptoms, and productivity in Swiss open-space offices: Economic evaluation of standard, actual, and optimum scenarios

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A B S T R A C T

The fundamental aspiration of new-generation high-performing buildings is to reduce energy use while securing indoor environmental quality conducive to human health and productivity. However, existing frameworks for identifying Key Performance Indicators (KPIs) of buildings are sporadic and limited to a few parameters. Based on two Swiss open-space buildings, this paper demonstrates an *economic comparison* combining three KPIs: *health* (represented by sick building syndrome (SBS) symptoms), occupants' *productivity* (based on the thermal environment and ventilation), and *operational energy for heating* (based on building simulations using measured inputs). Monetization translated various criteria into the same unit currency and compared them on equal terms. Three scenarios for human- and energy-related performance analysis were *actual* (considering measured data), *standard* (using parameters from the national standard), and *optimal* (maximized productivity). The *actual* environment in case studies measured in the Fall and Winter seasons was relatively warm, with poor ventilation in one of the two buildings as no mechanical ventilation was on. Therefore, there was some loss of productivity (0.11–0.4%) and SBS symptoms (e.g., dry eyes, fatigue) present in both buildings resulting in up to 2 times the difference between the energy and human costs. The minimum energy costs for the *standard* scenario indicated that standard settings prioritize energy objectives. Oppositely, energy costs were the highest (47.6–69.6%) in the *optimal* scenario minimizing the human-related costs but not the weekly SBS symptoms. The analysis presented highlights the *conflicting goals* when one parameter is prioritized over another one, thus demonstrating the importance of a multi-criteria approach.

1. Introduction

Reduction of buildings' operational energy and corresponding expenses emerged as a crucial parameter for the reduction of greenhouse gas emissions in the policy of many countries, especially considering the actual geopolitical context [1]. The Directive 2010/31/EU [2] outlines the path toward low and zero-emission buildings in the EU by 2050 by joining, for the first time, the minimum energy performance requirements with cost-optimization. Moreover, the last version of the Energy Performance of Buildings Directive 2018/844/EU [3] is based on a human-centric approach and requires the integration of indoor environmental quality (IEQ) assessment, simultaneously with energy performance and cost-optimal requirements. Ultimately, efforts to improve buildings' energy efficiency must actively contribute to reducing the building stock climate impact while ensuring healthy indoor climate conditions and occupants' well-being. Considering that in modern societies, humans spend up to 90% of their time indoors and a third of their life at the office [4], the assessment of the implications of indoor environmental quality of the workspace on occupants cannot be neglected.

IEQ has an implication not only in terms of comfort and individuals sensation but on people's health and working performance. There is increased research interest in the quantification and monetization of the impacts of IEQ on occupants' productivity, particularly in office and

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school buildings, as summarized by Ref. [5]. Nowadays, the IEQ is addressed under an even broader paradigm, paying attention to its impact on the health and the general well-being of the occupants [6], as it is stressed by the new EPBD. Not by chance, the most recent programs for the certification of buildings (e.g., WELL [7]) focus on criteria related to the health and well-being of occupants among the aspects that building design and management should control. This topic received further attention due to the COVID-19 pandemic. Therefore, buildings have to fulfill two challenges of today: (i) to minimize energy use and negative environmental impact, (ii) to maximize occupants' health and work performance. Thus, buildings must be designed and operated coupling *sustainability goals* (e.g., reduction of operational energy use assessed with performance-based metrics) and *occupants' health* (assessed through human-centric metrics) [8] in order to deliver more performing spaces when multiple criteria are considered. Consequently, it has become fundamental to measure and control the aforementioned building performances.

In many fields, the most common method to control and monitor the quality of an object/process/project refers to the use of Key Performance Indicators (KPIs). KPIs are complex metrics based on more than one variable (e.g., annual energy use per heated square meter) that assess how well an object (i.e., building) carries out a certain function in terms of delivered quality or resource demand. They are typically identified based on the key objectives of performance to be pursued. KPIs can refer to multiple categories, like economic, environmental, users' perspective, and health and safety [9]. The key importance of health (and work performance, in the case of office buildings) in the transition towards more sustainable buildings motivates the definition of KPIs related to such a topic. In this context, shifting the assessment of building design and operation performances from solely *energy-driven KPIs* set by national standards toward *combined energy-, health-, and productivity-related KPIs* would facilitate the transition toward a human-centric approach [8].

There is abundant literature that highlights the IEQ impacts on occupants' health and well-being and also on employees' productivity. In particular, Sick Building Syndrome (SBS) is widely studied [10–13]. The SBS concept was first introduced in 1983 by the World Health Organization; since then, the definition evolved to "*a group of symptoms related but not limited to the irritation of the eyes, nose, throat, skin, breath, and other general symptoms such as headache and lethargy that temporally occur among occupants of a certain building*" [14]. Hence, these symptoms are linked to the time spent in buildings leading to specific conditions. As stated by Kamarulzaman et al. [15], the poor environmental quality of a building could strongly affect the occupants' work performance, leading to economic losses. Given the fact that the operational energy cost of office buildings only represents a small part of the business operational cost [16], and the greatest part is linked to the employees, a built environment favoring high work productivity and fewer sick leaves would strongly decrease the total operational cost of buildings, besides multiple other benefits.

Mendelland Mirer [11], through the cross-sectional US EPA BASE study, developed quantitative relations between the prevalence of SBS symptoms and thermal factors by collecting objective measurements and subjective surveys in almost 100 office buildings in the US. They developed adjusted Odd Ratios between the mean indoor temperature, humidity, and the number of degrees hours *above* (in winter) and *below* (in summer) different threshold points (20–23 °C) and the prevalence of each SBS Symptom using multivariate logistic regression, logistic models and correlation matrix. Adjusted Odds Ratio for each nine-degree hours above 23 °C should be preferred to the one for mean temperature as they reflect the cumulative exposure above a critical point and hence better represent the health effect than a mean continuous temperature through the day. A strong negative impact of high temperatures in winter (above 23 °C) and low temperatures in summer (below 23 °C) was established. The experimental study of Lan & Wargocki [17] looked at the mechanisms behind the effect of the warm environment on SBS symptoms. At the thermal exposure of 30 °C, twelve participants experienced increased fatigue and reduced concentration, but there was no nose, eye, or throat dryness. Acute SBS symptoms such as headache or fatigue are induced in warm environments due to increased heart rate, exhaled CO_2, and respiratory ventilation leading to respiratory acidosis and high concentration of CO_2 in blood flow. Nose, eye, and throat irritation at elevated temperatures were observed in the study by Witterseh et al. [18], with 36 subjects experiencing 6 environmental conditions (temperatures 22, 26, 30 °C and sound levels of 35–55 dBA). Although the same kind of participants was involved in the study by Lan & Wargocki and Witterseh et al., age-wise and clothing-wise, different responses of participants indicate the individual way of developing SBS symptoms.

Inadequately ventilated workplaces have also been linked to SBS symptoms, lower employee productivity, and higher absenteeism [19, 20]. In contrast, supplying excessive ventilation is associated with unnecessary energy use and could compromise occupancy comfort [19, 21]. Therefore, the knowledge of how to optimally ventilate workplaces can improve employee performance and health, while preventing unnecessary energy use of building ventilation and additional cost. Yet, the existing literature has not fully established the optimal ventilation rate that considers combined energy and health-related and productivity-related KPIs. The balance between energy and human goals was studied by Fisk et al. in a quantitative estimation of the benefits and costs of the implementation of four different ventilation rates in US offices [22]. Results have shown that increasing the ventilation rate from 8 to 10 L/s per person could lead to the benefit of $13 billion, or even $38 billion if increased to 15 L/s per person. Milton et al. [23] found that buildings with a high outdoor air ventilation rate of 24 L/s per person in comparison to buildings with a moderate ventilation rate of 12 L/s per person resulted in a net savings of $400 per employee per year – the number which offsets the cost of additional ventilation. MacNaughton et al. [24] showed that doubling ventilation rates costs less than $40 per person per year while resulting in improved performance of workers by 8% – equivalent to a $6500 increase in worker productivity per year. Conversely, decreasing the ventilation rate to 6 L/s per person would only induce a $0.04 billion energy-related benefit which is minor compared to the estimated total energy cost ($12 billion). Seppänen et al. [25] developed a model that links ventilation rate and productivity by using data from nine studies performed either in laboratory-controlled or workplace environments. The model is based on objective measurements of performance, such as the accuracy and speed in text processing, calculations, and handling time on the phone for call centers.

Productivity in offices evaluated by the efficiency of performing certain tasks can also be affected by the thermal environment [26,27]. Per Al Horr et al. [28], the optimal indoor temperature to perform daily tasks could vary depending on the type of task and thermal sensation. Moderate warm conditions *above neutrality* can be beneficial in the case of creative or memory tasks as arousal decreases, leading to more relaxation. The study by Cui et al. [29] showed the optimal temperature range for memory typing was between 22 °C and 26 °C. Conversely, for tasks requiring accuracy, focus, and prolonged mental effort, *slightly cool* to *neutral* temperatures are preferred [5]. The peak of productivity in Seppänen et al. [25] was around 22 °C, and productivity reduced as temperature departed from the optimal one, at a slightly lower rate towards higher temperatures. The optimal performance on neurobehavioral tests and typing tasks in a range of 20°C–30 °C was reached at a predictive mean vote (PMV) of about −0.25 in the study of Lan et al. [17]. The recent experimental work of Geng et al. [30] also established a strong correlation between thermal sensation and productivity and reported the optimal condition when people felt *slightly cool* to *neutral*.

The workspace's environmental quality is also influenced by the office type itself. Open space offices, defined as a workspace uniting multiple employees with no dedicated physical barriers [31], have become a more and more common office space arrangement. This motivates the attention devoted to them as representative typology in modern office buildings, besides the fact that, differently than in the case of a single office, their quality affects multiple people. Initially, open offices were designed to lower real estate costs and also improve communication and cooperation among employees; nonetheless, the benefits could be highly questioned due to strong dissatisfaction linked to the lack of visual and speech privacy [32]. In general, open offices can represent a risk for discomfort and lack of well-being. This is because the presence of multiple people can cause noise, which is one of the causes of the loss of productivity. Moreover, occupants are forced to negotiate with their colleagues the indoor conditions in terms, for example, of thermostat regulations, windows opening, lighting switching, etc., with possible consequences on the occupants' level of satisfaction with the indoor environment. If the office is crowded and the ventilation is not proportionate to the demand for fresh air, indoor air conditions can be compromised and the spreading of diseases can be fostered. Indeed, the building's IEQ and overall performance (i.e., poor ventilation maintenance) could be highly altered by a lack of post-occupancy management. The indoor environmental quality should then be evaluated at the post-occupancy phase to truly assess the health and performance impact.

Having the need of applying combined performance metrics, this paper proposes an approach for building performance assessment based on combined energy-, health- (i.e., SBS symptoms), and productivity-related KPIs. The paper evaluated two case study buildings with open-space offices in Switzerland from human-, energy-, and economy-related perspectives. Two case studies with different orientations and the operation of heating systems and ventilation lead to different indoor environments, thus enabling showing the differences in the performance metrics. Based on the data available to fit into the models by Refs. [11,17,25], SBS symptoms prevalence at the floor level was analyzed along with the productivity variation due to the thermal environment (at the desk level) and ventilation (at the floor level). Once the energy performance of the two buildings was determined from energy simulations, the economic evaluation was performed considering the human and energy costs. The ultimate goals of the paper were to demonstrate (i) the impact of the indoor environment monitored at the post-occupancy phase on the SBS symptoms and productivity of occupants and how it can contribute to the human cost, (ii) the impact of the operation of buildings on the energy cost, finally, (iii) the tradeoff between energy and human aspects and the factors affecting them.

2. Methodology

The study focused on two open-space offices in Western Switzerland where the monitoring of indoor environmental quality and occupant behavior took place in 2019–2020 within the eCOMBINE project [33]. The methodology of this work has 4 steps presented in Fig. 1. The first step was the review of available Key Performance Indicators (KPIs) evaluating the health and productivity of building occupants and the energy performance of buildings. The second step was the analysis of the case study buildings and the inventory of all available data that would be required for the KPIs evaluation (e.g., monitored data and parameters determined via simulations using measured data as inputs). As the selection of suitable KPIs is data-dependent, there is an iteration between steps 1 and 2. Once KPIs were selected according to the data available, buildings' performance in terms of the SBS symptoms prevalence, productivity loss, and energy use was evaluated (third step). Three distinct scenarios were considered for performance assessment, corresponding to the *actual*, *standard,* and *optimal* conditions. The *actual scenario* considered measured parameters, the *standard scenario* considered inputs per standardized requirements, and the *optimal scenario* was designed as optimal regarding the occupants' productivity maximizing it. Finally, as the fourth step, an economic evaluation was performed regarding the human and energy costs using the results from the performance assessment.

2.1. Case study buildings and data collection

Two open-space offices in Switzerland, one located in Lausanne (Building A) and another one in Geneva (Building B), were studied. They were monitored for two weeks in the Fall and Winter, and the exact periods of the monitoring are listed in Table 1, along with the IDs of cases analyzed in the format of "Building ID - Season ID" (F - Fall season, W - Winter season). The open space office of Building A (259 m^2, height 3.4 m) was on the second floor of a five-story office building with a dominant North-facing exposure (Fig. 2a). Open space office of Building B (242 m^2, height 3.5 m was on the fifth floor of an office building with a dominant exposure to the South-West and South-East (Fig. 2b). The thermal transmittance (U-value) of external walls in both buildings was 0.18 W/(m^2K). In both buildings, freely operable casement windows and

Table 1
Overview of the monitoring periods and campaign IDs.

Case study ID	Case study building	Season	Dates	
			Week 1 (W1)	Week 2 (W2)
A-F	Building A	Fall	28 Oct. - 1 Nov. 2019	4–8 Nov. 2019
A-W	Building A	Winter	27–31 Jan. 2020	3–7 Feb. 2020
B–F	Building B	Fall	18–22 Nov. 2019	25–29 Nov. 2019
B–W	Building B	Winter	17–21 Feb. 2020	24–28 Feb. 2020

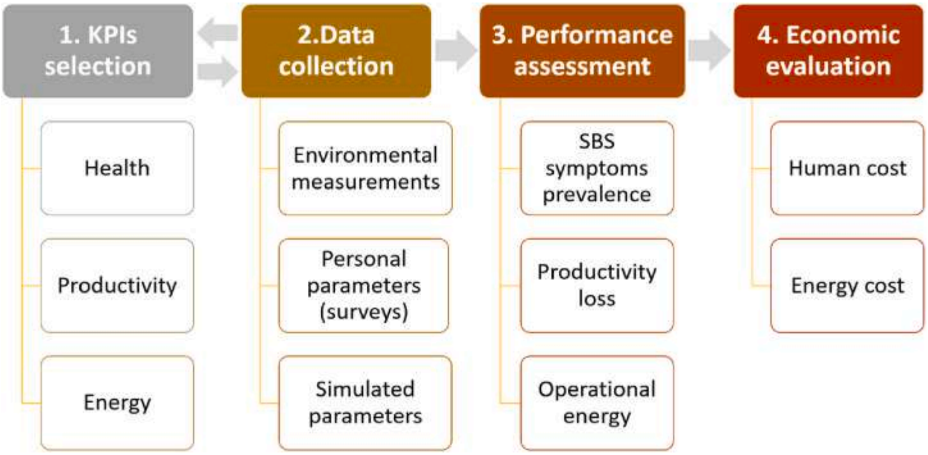


Fig. 1. Overview of the methodology.

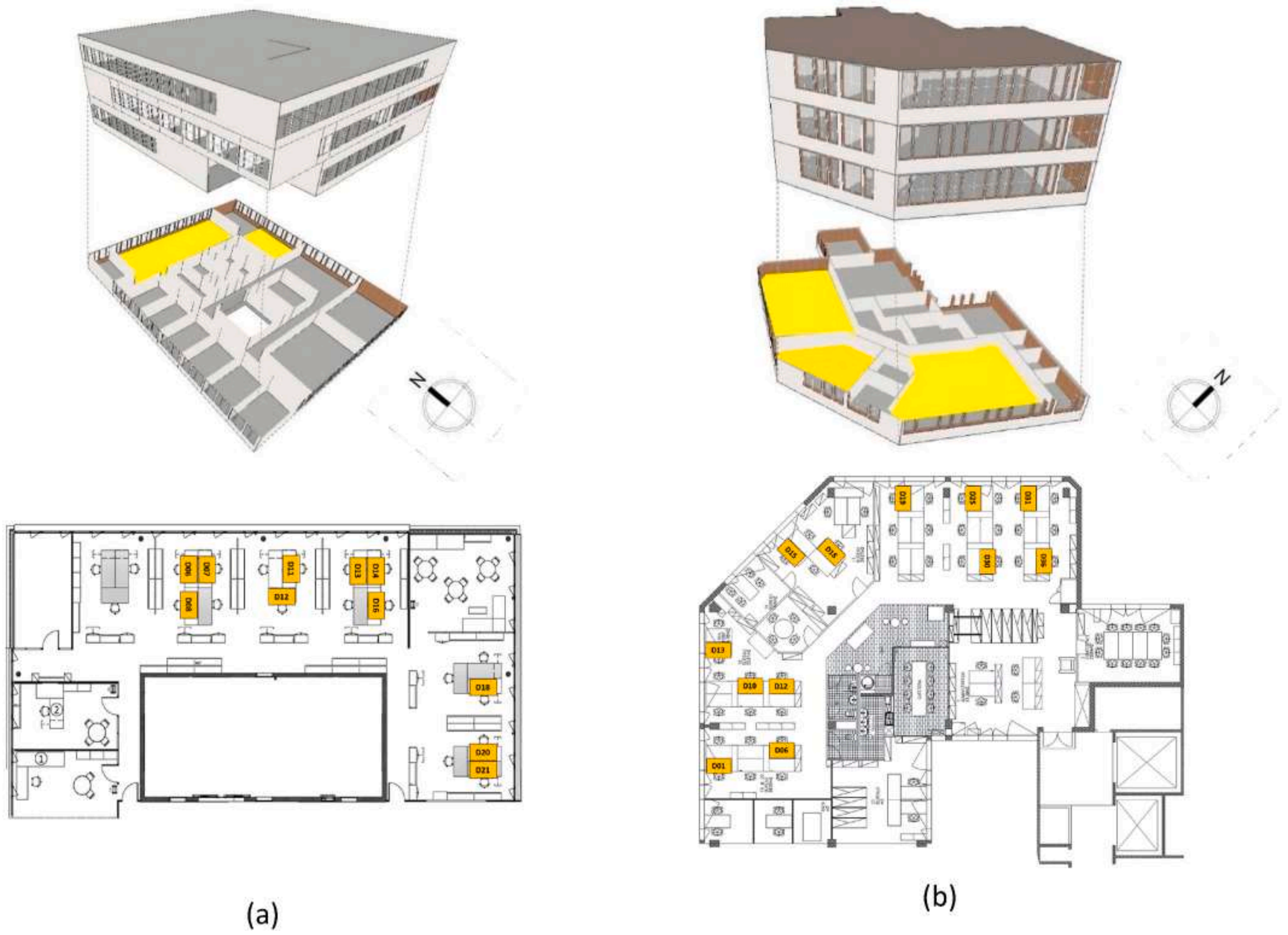


Fig. 2. Overview of the open space offices (studied areas highlighted in yellow, and the desks where the measurements were done are in orange): (a) Building A, (b) Building B. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

external shades could be accessed by people occupying the desks within 5 m, the wall-to-window ratio was 0.42 in Building A and 0.55 in Building B. In both spaces, occupants could not interact with HVAC controls; thus, the operation of windows and blinds were the main possible human-building interactions to restore/maintain their comfort. In Building A, window blinds were regulated automatically but could be overridden by the occupants. In Building B, instead, blinds were solely manually operated. In Building A, a mechanical ventilation system was working throughout all campaigns at a design airflow rate of 50 m^3/h at each inlet, while in Building B, the mechanical ventilation system was not in operation. In both buildings, desk lights were automated, and employees did not actively interact with the lighting systems. The heating in Building A was provided by a hydraulic radiant ceiling panel system connected to the centralized heat pump, while radiators connected to the centralized boiler were used in Building B. Overall, two open-space offices with different orientations and operation of the ventilation and heating systems would lead to different indoor environments, thus, making them interesting to study from the IEQ and energy performance point of view.

Overall, 11 desks out of 20 in Building A (Fig. 2a) and 12 desks out of 39 in Building B (Fig. 2b) were monitored, as not every employee gave consent to take part in the study. Although the environment around 50% (Building A) and 30% (Building B) of the desks was measured, the desks monitored were spread in the space, thus, allowing the capture of the spatial variability of the IEQ (e.g., South-oriented vs. South-East-oriented spaces, etc.). In each campaign, indoor parameters were monitored during working hours (7:00–19:00) at certain desks using a combination of sensors arranged on a desk stand. These indoor parameters included air temperature, globe temperature, air velocity, relative humidity, noise level, CO_2 concentration, and light level. The operative temperature was calculated as a function of air temperature and the mean radiant temperature according to ISO 7726 [34]. To better understand the human-building interaction, reed sensors were installed at each window to assess whether they were opened or closed. Additionally, occupancy sensors were placed under the desks of occupants participating in the study. Personal information was collected using comfort surveys given to participants twice a day (10h/15h) to assess their environmental satisfaction and perception. Among the questions on the IEQ perception, the type of activity they performed and the clothes worn were surveyed. This allowed us to estimate their self-reported metabolic rate and clothing insulation. The study was approved by the institutional ethics committee (EPFL Human Research Ethics Committee) under project number 036–2019.

2.2. *Performance assessment*

The study considered three distinct scenarios for performance assessment using the *actual values* from measurements, *standard values* defined by Standards, and *optimal values* with regard to human productivity. A summary of the input parameters used in each scenario is provided in Table 2. Parameters such as light levels, occupancy, openings, and closings of blinds/windows remained unchanged throughout

Table 2
Summary of the input values used in each performance assessment scenario.

KPI	Input parameter	Scenarios		
		Standard	Actual	Optimal
Health (SBS prevalence)	Indoor air temperature (°C)	21	Hourly average of measured temperature	Calculated as corresponding to PMV = −0.25[b]
Productivity	PMV (−)	0	Computed using actual measurements	−0.25
	Ventilation rate (L/s per person)	7	Computed using a single-zone mass balance equation	–
Energy	Indoor operative temperature (°C)[a]	21/16	From actual measurements/16	Calculated as corresponding to PMV = −0.25[b]/16
	Mechanical ventilation ($m^3/h/m^2$)	3.6	3.7 (Building A), 0 (Building B)	–

[a] X/Y with X heating set point during working hours (7–19h) and Y heating set back point.

[b] Median indoor air temperature corresponding to the PMV of −0.25 (slightly cool).

the scenarios. Details of models to compute a specific kind of KPI and input parameters considered are provided in the following subsections.

2.2.1. *SBS symptom prevalence analysis*

The variations of SBS symptoms weekly prevalence were calculated per Mendell and Mirer [11] model as follows:

$$P_{m,w,t} = \left(OR_m^{DG_{av}/9} - 1\right) \times P_{EPA,W} \tag{1}$$

where $P_{m,w,t}$ [%] is the change in the weekly prevalence rate of the SBS symptom i (sneezing, runny nose, dry throat, dry eyes, fatigue, concentration, irritated skin), OR_m [−] is the adjusted odds ratio of the group of symptoms m (in this research, upper respiratory, dry or irritated eyes, fatigue or difficulty concentrating, and irritated skin as in Table A1 in Appendix), DG_{av} [−] is the weekly average of the daily number of degree hour above 23 °C, $P_{EPA,W}$ [%] is the weekly prevalence rate baseline for a symptom i reported in the original EPA Base study (Table A2 in Appendix).

The value DG_{av} was determined by computing the number of degree hours above 23 °C for each day according to the average floor-level air temperature. Weekly averages were computed afterward to assess the fractional variation of weekly SBS symptoms prevalence in the case study buildings in both seasons. In the *actual scenario*, measured air temperature values were used. In the *standard scenario*, the indoor air temperature during work hours was taken as 21 °C as recommended by the Swiss standard SIA 2024-2015 [35]. The air temperature corresponding to the optimal scenario was determined as the air temperature corresponding to the Predicted Mean Votes (PMV) of “slightly cool” (PMV between −0.2 and −0.3) [16]. To this aim, the distribution of measured air temperature in each case (A-F, A-W, B–F, B–W) was analyzed per category of PMV, and by binning the PMV values, the optimal temperature was defined as the median air temperature for the PMV bin in the range of [-0.2; −0.3].

2.2.2. *Productivity analysis*

Productivity-related KPI is defined as *human productivity loss* due to an unfavorable indoor environmental quality. As no productivity model considering the combination of factors such as temperature and ventilation was identified in the literature, the effect of the thermal environment and of ventilation on productivity were analyzed separately.

(a) Effect of thermal environment on productivity

Lan et al. [17] investigated the relationship between thermal comfort and productivity and developed the following equation:

$$RP_{tsv} = -0.0351 \times TSV^3 - 0.5294 \times TSV^2 - 0.215 \times TSV + 99.865 \tag{2}$$

where RP_{tsv} [%] is the relative performance when compared to maximum performance, and TSV is the thermal sensation vote based on the ASHRAE seven-point thermal sensation scale (varies in the range of [-3; +3]). The hourly mean PMV values were used as substitutes for TSV at each desk to assess the hourly variation of productivity per desk. To compute the hourly performance variation compared to the maximum performance, the following formulation was used:

$$F_{P,tsv} = (RP_{tsv} - 100) \tag{3}$$

where $F_{P,tsv}$ [%] is the hourly variation of productivity, RP_{tsv} [%] is the relative performance when compared to a maximum performance computed hour by hour and desk by desk, according to Eq. (2).

As the thermal sensation of participants was not surveyed hourly, the *TSV* was estimated from the Predicted Mean Votes (PMV) index. In the case of the *standard scenario*, thermal neutrality at PMV = 0 was considered. For the *actual scenario*, PMV was calculated using the measured environmental parameters (air temperature, globe temperature, air velocity, and relative humidity) and personal information (metabolic rate, clothing insulation) estimated from bi-daily surveys. The PMV index for the *optimal scenario* was set to “*slightly cool*” (PMV = −0.25) based on the study by Lan et al. [16], reporting people to be productive in the range of the PMV of [-0.3;-0.2].

(b) Effect of ventilation on productivity

The model of Seppänen et al. [25] estimates a relative change in performance at a ventilation V_R relative to the one obtained at a ventilation rate of 10 L/s per person. The relation is applicable in a range of 6.5 L/s per person to 65 L/s per person. The following series of equations are used by the model:

$$RSP_{VR} = exp\left[\left(-76.38V_R^{-1} - 0.78V_R \times ln(V_R) + 3.87V_R - y_o\right) / 1000\right] \tag{4}$$

$$yo = -76.38V_{Ref}^{-1} - 0.78V_{Ref} \times ln\left(V_{Ref}\right) + 3.87V_{Ref} \tag{5}$$

$$F_{P,VR} = (RSP_{VR} - 1) \times 100 \tag{6}$$

where $F_{P,VR}$ [%] is the hourly variation of performance compared to performance at the ventilation rate V_{Ref}, RSP_{VR} [−] is the relative performance as affected by ventilation rate, V_R [L/s per person] is the hourly ventilation rate, and V_{Ref} is the reference ventilation rate (10 L/s per person). The bi-daily (AM and PM) ventilation rate computed for each office per season was used to determine the bi-daily variations of productivity according to a reference ventilation rate of 10 L/s per person.

In the *standard scenario*, the relative change of performance was set to a change of performance at a ventilation rate of 7 L/s per person per Cat. II of EN 15251 [36] relative to the one obtained at a ventilation rate of 10 L/s per person. The ventilation rate for the *actual scenario* was determined by multiplying the air exchange rate λ by the volume of the office V. The air exchange λ was calculated by using the steady-state mass balance equation as follows:

$$C_{CO2,ss} = P \times C_{CO2,out} + \frac{n \times E}{\lambda \times V} \tag{7}$$

$$\lambda = \frac{n \times E}{\left(C_{CO2,ss} - C_{CO2,out}\right) \times V} \tag{8}$$

where $C_{CO2,ss}$ [ppm] is the average CO_2 indoor concentration during steady-state time intervals, $C_{CO2,out}$ [ppm] is the outdoor CO_2 level, P [−] is the penetration factor from outdoors ($P = 1$), n [−] is the number of occupants present in the space during steady-state time intervals, E [L/min] is the CO_2 generation rate per occupant, and V [m^3] is the volume of the space considered. The air exchange rate was calculated for every day separately for the morning (AM) and afternoon (PM) hours. According to the SIA 2024, the maximum and steady occupancy is reached from 10 to 11 o'clock in the morning and at 15 o'clock in the afternoon. Thus, these hours were considered as steady-state hours, and the average CO_2 concentration measured between 10 and 11 o'clock and 15–16 o'clock was used as $C_{CO2,ss}$ parameter. The occupancy was set as the maximum number of desks where the measurements were performed in each building. The outdoor CO_2 concentration, penetration factor P, and CO_2 generated by occupants were fixed as 400 ppm, 1, and 12.96 L/h, respectively. Once the bi-daily air exchange ventilation rate was calculated, it was used to determine the bi-daily ventilation rate per person Q_p (L/s per person) as follows:

$$Q_p = \frac{\lambda \times V}{n \times 3.6} \tag{9}$$

There was no *optimal scenario* implemented, as a concept of *optimal ventilation* has not been introduced in the literature.

2.2.3. Energy analysis

Since there is no direct metering of thermal energy, space heating energy use of case study buildings was computed by dynamic simulations using the software DesignBuilder. The Energy Management System (EMS) was used to introduce customary set-points for different parameters. In all cases, the real occupancy, window, and blind openings were implemented. Six different scenarios combining various set-points of the operative temperature and ventilation rate were considered as listed in Table 3. The scenarios describe *actual* (TA), *standard* (TS), and *optimal* (TO) temperatures. Additionally, two distinct ventilation scenarios, *actual* (VA) and *standard* (VS), were considered as the supply of outdoor air affects the heating needs.

The *standard scenario* conditions were set using the Swiss national norm SIA 2024:2015, which recommends a heating set-point of 21 °C during work hours (16 °C nighttime setback) and a mechanical ventilation rate of 3.6 $m^3/h/m^2$ for open offices. For the *optimal scenario,* as it is difficult to set an optimal ventilation rate (as discussed in the Introduction) only the optimal temperatures computed for PMV of −0.25 were implemented.

For the *actual scenario*, the hourly average of measured air temperature was scheduled in the EMS. The actual ventilation in Building A and B was determined in a different manner. In Building A, the technical plans suggest an airflow rate of 70 m^3/h for each air inlet and the diffusion of air through the perforated surface of the ceiling panels, which leads to a ventilation rate of 3.7 m^3/h per m^2 of the floor surface. In Building B no mechanical ventilation was present during the studied seasons, and the windows were the only means of ventilating the building. Thus, based on the tracked window statuses of every single window by means of reed sensors, detailed venting schedules were determined. The schedules were linked to the corresponding window with the EMS in DesignBuilder. Assuming a tilt opening degree of 15°, the percentage of the openable area was determined as 25% for windows in both buildings (considering the total area of the window as 1.19 m^2 in Building A and 0.8 m^2 in Building B). To account for *real* outdoor conditions during the monitoring campaigns, measurement-based weather files (.epw) were created and assembled using the software Elements [37]. Local measurements performed by the Laboratory LESO-PB at EPFL [38] during the years 2019 and 2020 were used as weather data for Building A. For Building B, a weather file for all seasons was created based on our own measurements taken with the weather station installed on the rooftop of the building. Since the weather station did only track global solar radiation and not diffuse solar radiation (needed in the.epw files), this parameter was adjusted based on measurements available on the IDA WEB [39] platform for Geneva Airport.

Table 3
Overview of energy simulation scenarios.

		Operative temperature set-points		
		Standard (TS)	Actual (TA)	Optimal (TO)
Ventilation rate settings	Standard (**VS**)	TS-VS	TA-VS	TO-VS
	Actual (**VA**)	TS-VA	TA-VA	TO-VA

The hourly space heating energy (kWh) for each zone of the building was set as an output from DesignBuilder simulations. The building energy use was then computed as the sum of the hourly value of the different zones highlighted in Fig. 2, and a weekly amount was calculated. Finally, the comparison in terms of percentage variation with a baseline which is the temperature scenario TS coupled with actual (TS-VA) and standard ventilation (TS-VS).

2.3. Economic evaluation

As the last step of the methodology, an economic evaluation was performed regarding the human and energy costs using the results from the performance assessments. The economic evaluation allows to organize all the metrics of the performance assessment under a common evaluation framework, where KPIs are all translated into the same unit of measure and compared. A quantitative-economic-monetary approach was adopted. The objective of the appraisal was to measure the economic performance of the building in terms of extra costs and benefits for the employer. To do so, the performance must be measured against a counterfactual scenario, namely a baseline, represented by the *standard scenario*.

All the KPIs assessed in the previous step were monetized according to different approaches in order to compute their economic impacts in terms of SBS symptoms costs, productivity costs, and energy costs. This was done per each of the three scenarios; in the case of the *optimal scenario*, productivity cost is always zero. The last stage consisted of the comparison of *actual* and *optimal scenarios* against a baseline situation, the *standard scenario*. Results in terms of each of the monetized impacts under the *standard scenario* were subtracted from the results of both *actual* and *optimal* scenarios, in order to assess the extra costs and benefits that they bring compared to the baseline. Since a reduction in those costs is desirable, benefits are the impacts that result in being smaller under actual and optimal scenarios, so the subtraction has a negative sign (because they are savings). On the contrary, if some impacts result in being bigger in the *actual* or *optimal* scenario, they are considered as extra costs, and the subtraction has a positive sign.

The approach to the monetization of the identified KPIs (SBS symptoms prevalence, productivity, energy use) were the following (summary of costs considered provided in Table 4).

- **SBS symptoms cost** was computed starting from the change of weekly prevalence rate calculated per each relevant SBS symptom according to Eq. (4). It represents the number of extra cases due to

Table 4
Overview of the productivity and energy costs (in Swiss Francs, CHF).

Human Cost		Energy Cost	
Weekly cost for SBS [CHF/occ week]	Hourly labor cost [CHF/occ hour]	Electricity [CHF/kWh]	Natural gas [CHF/kWh]
17.5	61.9	0.2116	0.1202

the risk factor of overheating over the total number of exposed occupants. Thus, it can be multiplied times the number of occupants to know the number of extra cases per week. Afterward, the result was multiplied times the cost for SBS, and weekly monetary results were summed up.

$$SBS\ cost = \Sigma_z \left(P_{m,w,t\ \ z} \times occ_z \times cost_z \right) \tag{10}$$

Where $P_{m,w,t\ \ z}$ [%] is the change of weekly prevalence rate of symptom m computed according to Eq. (1) per each week z, occ [−] is the number of occupants at week z, and $cost$ [CHF/occ week] is the weekly cost for SBS at week z. The number of occupants was estimated based on monitored data as the daily average per week. The daily number of occupants is the average between the number of present occupants in the morning and in the afternoon. An occupant was considered present if he/she was occupying the desk for more than half of the morning or of the afternoon. This was done to consider the permanence of the space.

Special attention was put into defining the cost for SBS, which is not available in the literature for the European context. Indeed, there are multiple approaches to monetizing health hazards [40,41]. The willingness-to-pay (WTP) approach was applied. From the point of view of the employer adopted in this research, the WTP was defined as how much he would be willing to pay to safeguard employees' health. In Switzerland, employers finance mandatory accident insurance, dealing with the economic consequences of professional accidents, non-professional accidents, and occupational diseases. The annual finance by the insured/employer of this insurance schema has been, in 2020, 6437 MCHF [42]. Given an average annual number of employed people of 5.1 M persons [43], it means 1267 CHF/employee, 3.5 CHF/employee per day, and 17.5 CHF/employee per working week. The latter was adopted as the cost of SBS in Eq. (10), as it represents how much employers value health safety.

- **Productivity cost** was computed starting from the hourly performance variation computed hour by hour and desk by desk according to Eq. (3). Results were multiplied by an occupancy variable [1/0] computed desk by desk based on monitored data, where "1" means that the desk was occupied in a specific hour and 0 means the opposite. In this way, only results from occupied hours influence economic performance. Monetization was done by multiplying hourly results times the hourly labor cost per employee. The latter represents how much the employer values a productive hour of an employee, and it was assumed from Ref. [44]. The computation is summarized in the following formula:

$$Productivity\ cost = \Sigma_i \Sigma_j \left(-F_{P,tsv\ i,j} \right) \times occ_{i,j} \times cost_i \tag{11}$$

with $F_{P,tsv\ i,j}$ [%] is the hourly performance variation at hour i and desk j, parameter $occ_{i,j}$ [1/0] is the occupancy variable at hour i and desk j, and $cost_i$ [CHF/occ hour] is the hourly labor cost at each hour i (i refers to the working hour of the two weeks under evaluation). The parameter $F_{P,tsv\ i,j}$ has a minus sign to turn a loss (negative variation in productivity) into a cost (positive productivity cost).

- **Energy cost** was computed by multiplying the simulated total energy use for space heating (in kWh) times the energy cost per kWh assumed from Ref. [45], knowing the energy carriers supplying the buildings (namely electricity for Building A and natural gas for Building B).

3. Results

3.1. Human-related performance of case studies

The overview of the *actual* and *optimal* temperatures is presented in Table 5 as they are input for the results of the human-related performance analysis. The mean values over two monitored weeks for air and operative temperature are shown for the *actual* scenario; while to determine the *optimal* temperature, the values corresponding to the median temperatures when PMV is in the range of [-0.3; −0.2] were determined. Comparing actual and optimal temperatures, we can observe that the optimal values were greater in almost all cases except in Building B in Winter (B–W case). Surveying of clothing and activity types twice daily allowed us to estimate participants' clothing insulation and metabolic rate (Table 6). Generally, people were lightly clothed (0.53–0.62 *clo*) in both seasons, while the metabolic rate corresponded to the regular office activity (e.g., sitting typing).

Table 5
Overview of actual and optimal temperatures in case studies.

Scenario	Parameters	Case study ID			
		A-F	A-W	B–F	B–W
Actual	Mean air temperature [°C]	23.9	23.4	24.1	24.2
	Mean operative temperature [°C]	23.4	23.5	24.1	24.7
Optimal[a]	Median air temperature [°C]	24.4	23.9	24.3	24.0
	Median operative temperature [°C]	24.2	24.2	24.4	24.5

[a] Temperature corresponding to the PMV optimal range of [-0.3; −0,2].

3.1.1. SBS symptoms prevalence (floor-level weekly analysis)

The hourly fractional temperature change (degree hours above 23 °C) in the *actual scenario* is detailed in Fig. 3. Building B was generally warmer compared to Building A, particularly closer to noon and in the afternoon due to its Southern orientation. When Fall and Winter data are compared, it was warmer in Fall in Building A, and warmer in Winter in Building B. Consequently, the increases in the prevalence of SBS symptoms were higher in Fall than in Winter in Building A, on the contrary, they were higher in Winter in Building B. Results in Building A were more consistent as temperatures were usually higher in Fall than in Winter; the results in Building B indicate an important overheating in Winter leading to a significant increase in SBS symptoms prevalence.

The fractional variation of weekly SBS symptoms prevalence in both buildings according to the *actual* and *optimal* scenarios is presented in Fig. 4. In the *standard* scenario, as the air temperature was set to 21 °C, there was no increase in the SBS symptoms; therefore, it is not plotted. In *actual* and *optimal* cases, a warm environment with indoor air temperatures above 23 °C increased the weekly prevalence of all SBS symptoms. The symptoms "dry eyes" and "fatigue" were the most profound as they have higher baseline prevalence of 19% and 15%, respectively, and they are part of group symptoms with important odds ratios of 1.82 and 1.77. Regarding the results for the *optimal* scenario, two different kinds of the impact of the optimization strategy were observed. The optimization strategy, in most cases, led to an increase in the indoor air temperature, as indicated in Table 2, leading to extra degree hours above 23 °C and hence a higher increase in SBS symptoms prevalence compared to the *actual* temperature scenario. The highest optimal temperature set was in Building A in Fall (case A-F), with a strong prevalence increase of over 30%. On the opposite, in Building B in Winter (case B–W), the optimization strategy led to a decrease in temperature. In this case, the optimal scenario translated into a decrease in prevalence regarding the actual temperature scenario. However, the

Table 6
Actual clothing insulation and metabolic rate of occupants (estimated from bi-daily comfort surveys).

Parameters	Case study ID			
	A-F	A-W	B–F	B–W
Clothing insulation [*clo*]	0.57 ± 0.09	0.62 ± 0.10	0.55 ± 0.10	0.53 ± 0.13
Metabolic rate [*met*]	1.19 ± 0.22	1.21 ± 0.23	1.17 ± 0.20	1.14 ± 0.15

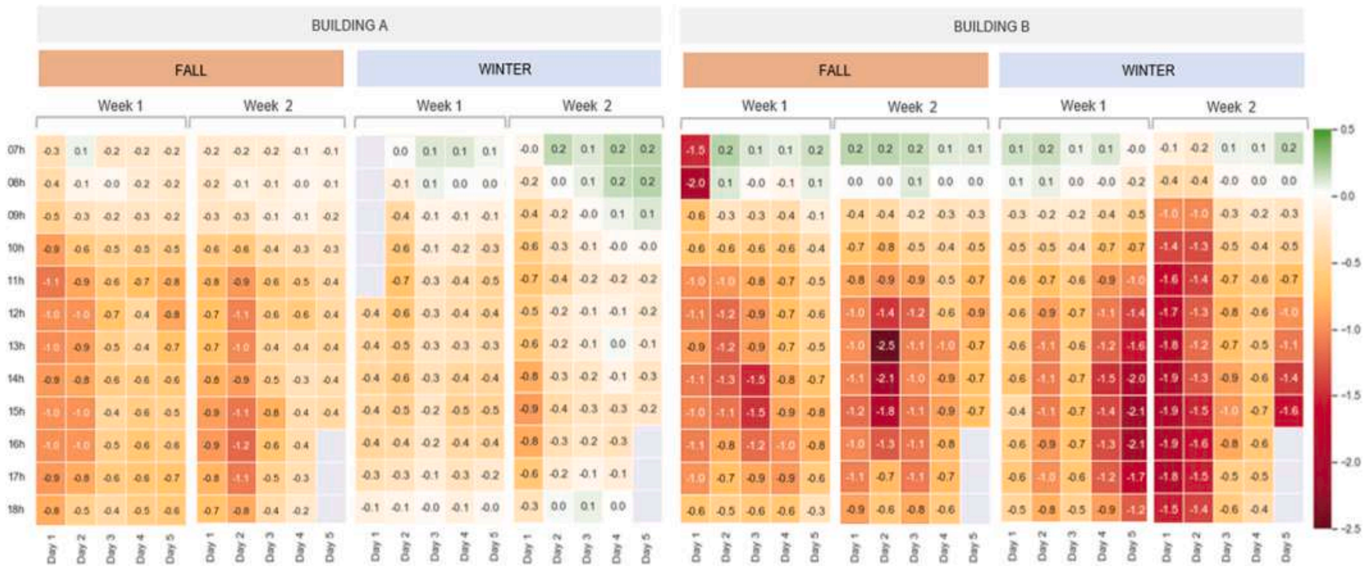


Fig. 3. Hourly fractional change of actual temperature (in °C) at the floor level in Buildings A and B.

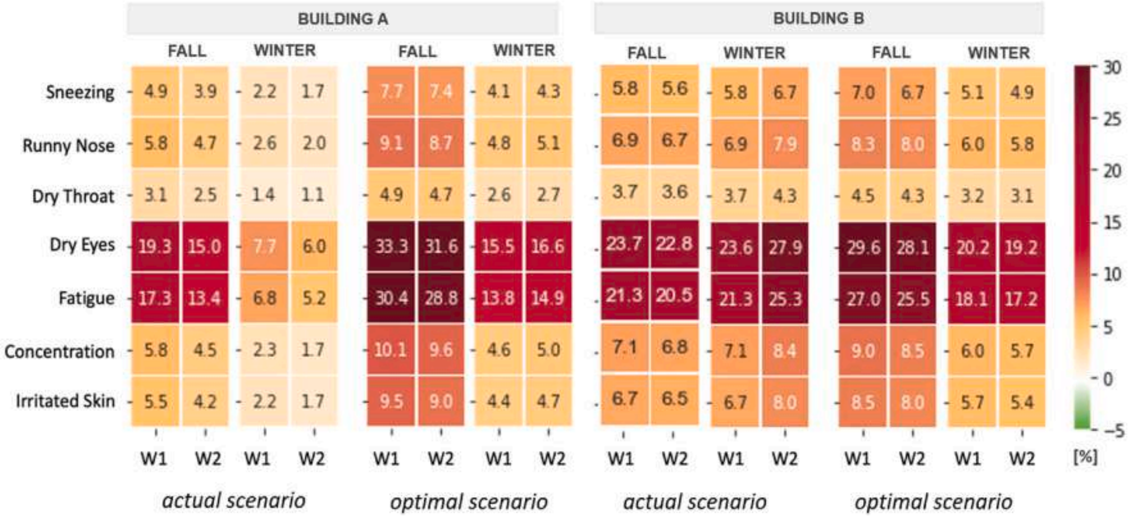


Fig. 4. Fractional variation of weekly SBS symptoms prevalence in Building A and B according to the actual and optimal scenarios.

optimal temperature for "concentration" was not the best when compared to the *actual* scenario in almost all cases except B–W.

3.1.2. *Productivity loss*

The productivity-related KPI in terms of the productivity change affected by thermal environment and ventilation was analyzed by looking at the effects separately.

(a) Effect of the thermal environment (desk-level hourly analysis)

The fractional productivity variation affected by the *actual* thermal environment shown in Fig. 5 is presented in Fig. 6 hour-by-hour for each monitored desk. The desks were arranged from the ones closest to the facade toward the ones more inward. In Building A, the hourly variation of productivity was nearly zero, just around −0.11%. No particular punctual important losses were observed conversely to Building B. Indeed, as for Building A, a productivity loss baseline in Building B around −0.11% could be observed with the presence of local peaks of −0.4% productivity losses. These ones were punctual in Fall and mainly concerned desks D15 and D18 situated in the area with South exposure. In Winter, peaks of loss of productivity were more recurrent and concerned a wider range of desks (D01-D12), all present in the same South-East area of the office, suggesting an orientation-specific local discomfort. Regarding the *standard scenario*, subjects were considered thermally neutral leading to a constant hourly loss of productivity of 0.135%. In the *optimal scenario*, no losses of productivity are considered. Overall, productivity losses are more important in the *standard* scenario except punctually in Building B during Winter, where some participants experience important productivity losses.

(b) Effect of ventilation (floor-level bi-daily analysis)

Two case studies had different ways of ventilating them, resulting in distinct differences in the level of CO_2 concentration. Building A was mechanically ventilated, and the mean steady-state CO_2 concentrations were 518 ± 96 ppm in Fall and 666 ± 43 ppm in Winter. Building B was naturally ventilated by manually opening the windows as mechanical ventilation was off. As ventilation rates were low, the measured steady-state CO_2 concentrations were 1710 ± 318 ppm in Fall and 1562 ± 335 ppm in Winter, on average, throughout two weeks. Therefore, the

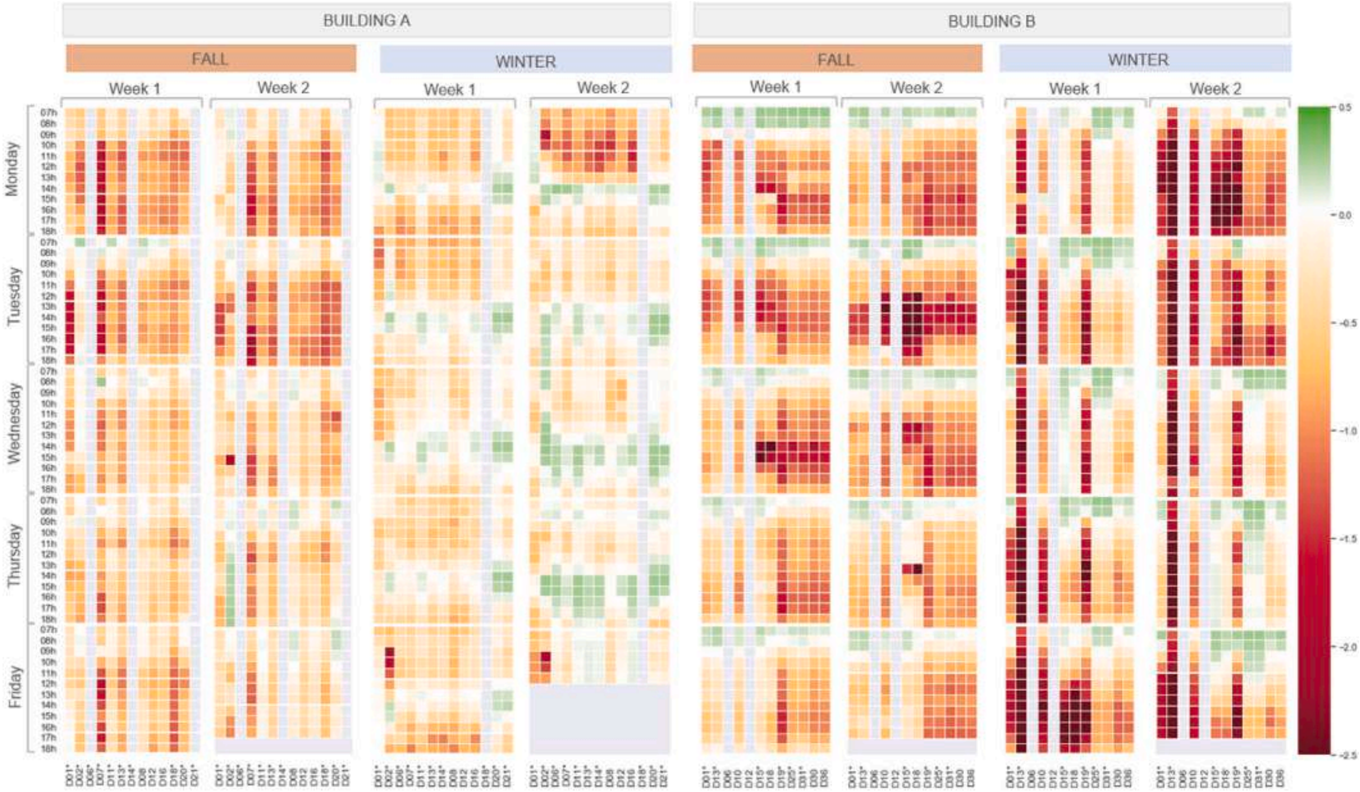


Fig. 5. Hourly fractional change in actual temperature (in ^{o}C) at the desk level for Buildings A and B.

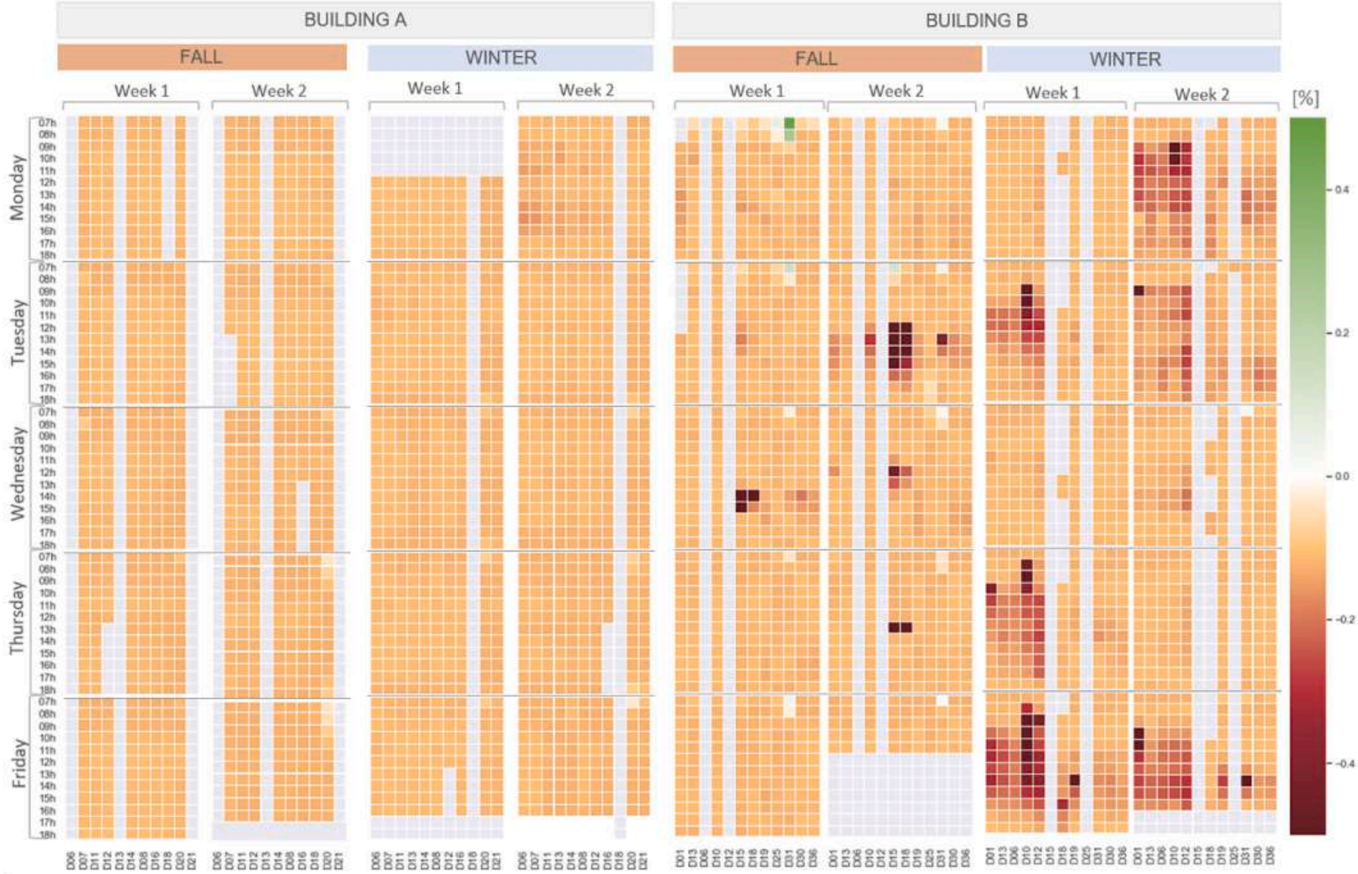


Fig. 6. Hourly fractional variation of productivity in the actual scenario in two case studies A and B.

actual productivity loss could not be computed for Building B using the model of Seppänen et al. as ventilation rates were lower than the applicability range of the model (6.5–65 L/s per person). The loss of productivity for Building A due to a change in the *actual* ventilation rate regarding a reference ventilation rate of 10 L/s per person is presented in Fig. 7. The ventilation rate in Building A, determined based on the simulations, was higher than the reference one, positively affecting productivity. On the other hand, the *standard* ventilation was set to 7 L/s per person in the *standard scenario*, which is lower than the reference ventilation rate of 10 L/s per person, implying a decrease in productivity. The results for the *actual scenario* should be carefully considered as the calculated ventilation rate might have been overestimated; only the participants seated at the desk where measurements were considered for the occupancy while more people could have been present in the space.

3.2. Energy-related performance of case studies

The heating energy, in kWh/m^2, or each case study computed using energy simulations for the *standard* temperature cases (TS-VS and TS-VA) are provided in Table 7. They are used as a baseline to compare with *actual* and *optimal* scenarios listed in Table 3. The energy use in Building A in Winter was nearly 2.5 times greater than in the Fall, while it was lower by 40% in Building B in Winter compared to Fall.

The variation of space heating use according to the standard temperature scenario in Buildings A and B are shown in Fig. 8. In all cases, the heating use increased as, in both *actual* and *optimal* scenarios, the setpoint temperatures were higher than the *standard* one. However, lower variations were observed in Winter, as temperatures in these two scenarios were closer to 21 °C. Similarly, when the optimization strategy led to increased operative temperature, it led to higher heating energy, and this was the case for all cases except Building B in Winter.

The impact of ventilation can also be observed as ventilation influences heating energy use as fresh air is inputted and has to be heated. Two ventilation cases were illustrated using *standard* (VS) and *actual* (VA) ventilations. In Building A, the *actual* ventilation was higher than the *standard* one leading to an additional supply of fresh air and hence, additional use of heating energy. Moreover, for the same ventilation, the TO scenarios lead to the highest heating need; at identical temperatures, the VS scenarios lead to the highest heating need. In Building B, as no mechanical ventilation was present in the *actual* scenario, the energy use for *standard* ventilation was higher. In this case, the VA scenarios lead to the highest additional heating at identical temperatures.

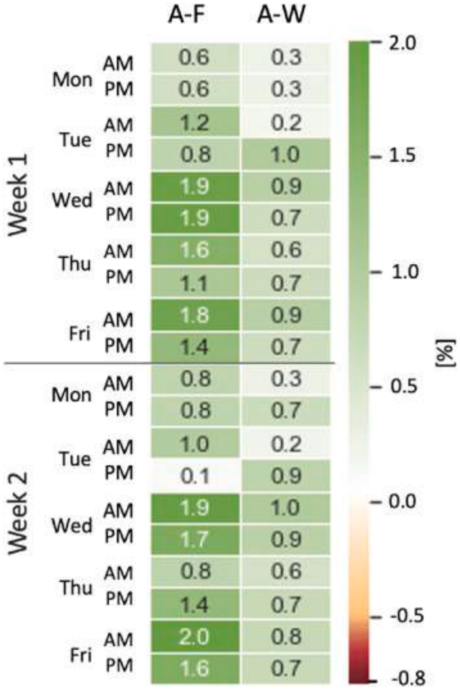


Fig. 7. Variation in productivity in Building A affected by the ventilation (actual scenario).

Table 7
Heating energy use for the baseline cases (in kWh/m^2), computed for two monitored weeks.

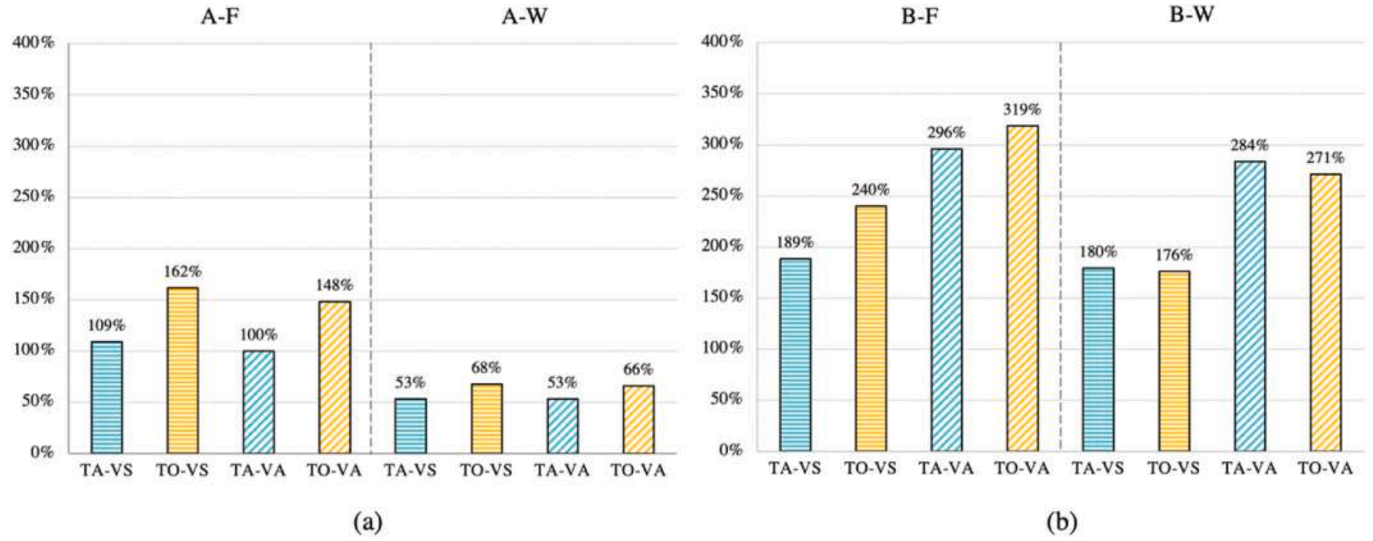
Scenario	Case study ID			
	A-F	A-W	B–F	B–W
TS-VS	0.66	1.69	1.01	0.63
TS-VA	0.75	1.80	1.02	0.57

3.3. Economic evaluation of case studies

All the costs, including *human-related costs* (productivity and SBS symptoms cost) as well as *energy costs* for each scenario, are summarized in Table 8. The energy costs were affected by the ventilation settings. The actual ventilation (VA) setting in Building A resulted in greater energy cost than the standard (VS) one, while it was opposite in Building B since no actual ventilation was operating in the building. As human-related costs are proportional to the occupancy, comparison of costs based on only measured (i.e., tracked) occupancy and the full occupancy of the offices is compared. As measured occupancy was only 30% of the full occupancy (Building A: 6 tracked vs. 20 in total, Building B: 12 tracked vs. 39 total), there is a three-fold difference in *productivity* and *SBS symptoms* costs. Human costs were mainly related to productivity, especially in Building B, affected by higher temperatures above the setpoint of 23 °C. When only the measured occupancy was considered, energy costs were the highest, however, it was opposite when the full occupancy was considered. In reality, the actual occupancy of the case study offices was in-between.

The cost difference with respect to the *standard scenario* as the *baseline* is demonstrated in Fig. 9, costs for two weeks in each season were summed. Positive values represent extra costs compared to the baseline, while negative ones are benefits brought by the two scenarios. The *actual* conditions caused additional energy costs for heating as well as SBS symptoms extra-costs. Conversely, the thermal neutrality characterizing standard conditions was not optimal for productivity; hence in Building A during both seasons and in Building B during Fall, benefits were observed in productivity as occupants felt cooler than in the standard scenario. An exception was observed in Building B during Winter, where additional costs regarding productivity were observed. In this case, occupants were farther from feeling slightly cool (the optimum for productivity) than they would be under the standard conditions, probably due to the effect of low clothing insulation measured in Building B.

In the *optimal* scenario, the temperature was optimized to the best interest of productivity, which was maximum for a slightly cool sensation. As expected, the benefits related to productivity were greater for both buildings and all seasons compared to the actual scenarios, where in most cases, a benefit in productivity was already observed. However, in most cases, this negatively impacted health (i.e., SBS symptoms) and energy costs. Indeed, in three out of four cases, the optimization implied an increase in indoor air and operative temperature, which induced additional costs for SBS symptoms and energy use compared to the *standard* and *actual* scenarios. Only in Building B the optimization strategy had a positive impact, as decreasing the temperature led to lower costs for SBS symptoms and energy than the actual conditions.



(a) (b)

Fig. 8. Change in energy use with respect to standard scenarios (simulation outcomes): (a) Build. A, (b) Build. B.

Table 8
Summary of the costs (in CHF) of the three KPIs for the two weeks considered in each season (operative temperature set-points: TS – standard, TA - actual, TO – optimal; ventilation scenarios: VS – standard, VA - actual).

Category of the KPI		Building A						Building B					
		Fall			Winter			Fall			Winter		
		TS	TA	TO	TS	TA	TO	TS	TA	TO	TS	TA	TO
Energy (heating)	VS	36.3	75.8	94.9	92.8	142.1	155.6	27.4	79.0	93.1	29.7	83.2	82.1
	VA	41.1	82.4	102.1	98.5	151.1	163.6	17.1	67.5	71.4	16.6	63.5	61.5
Productivity	Tracked occupancy	23.7	20.0	–	22.6	19.1	–	29.8	26.3	–	33.6	36.1	–
	Full occupancy	76.8	65.0	–	84.5	71.6	–	94.3	85.3	–	94.1	104.6	–
SBS symptoms	Tracked occupancy	–	9.6	16.0	–	4.0	9.0	–	17.2	21.3	–	19.2	14.8
	Full occupancy	–	27.4	45.8	–	6.3	14.7	–	44.3	56.5	–	49.0	37.7
Human costs[a]	Tracked occupancy	23.7	29.6	16	22.6	23.1	9.0	29.8	43.4	21.3	33.6	55.3	14.8
	Full occupancy	76.8	92.44	45.8	84.5	77.9	14.7	94.3	129.6	56.5	94.1	153.6	37.7

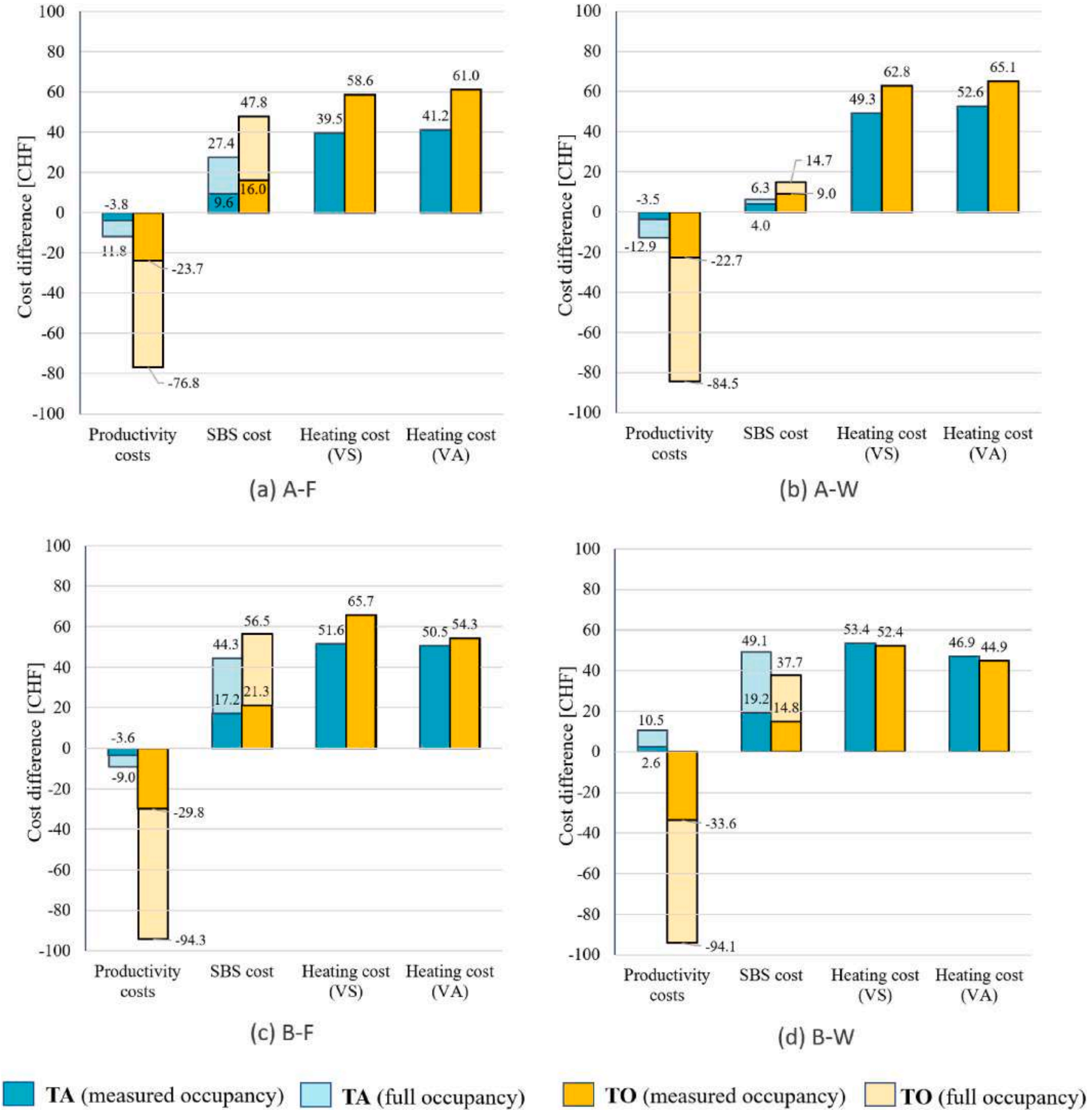
[a] "Human costs" refer to the sum of productivity and SBS symptoms costs.

4. Discussion

The results of the monetization show somewhat comparable *energy* and *human-related* costs for full occupancy although the latter are usually reported in the literature to be higher than the energy costs and represent the major component of operational costs. A few factors can explain this inconsistency in the results. First of all, the human costs could have been underestimated in our analysis; the health cost was only considered through SBS analysis considering the thermal environment, but not considering poor indoor air quality (e.g., the case of Building B with high CO_2 concentrations) or other aspects of the indoor environment. While human cost might have been underestimated because it was calculated only for a fraction of total occupancy (30% both in Building A and B), the energy cost was overestimated as it was calculated for the entire office. In addition, the energy cost in the actual scenario might have been elevated, compared to typical buildings, as Buildings A and B were generally overheated, and the occupants were lightly dressed, perhaps, as an adaptive action to the warm environment. Thus, energy costs reported for our case studies are relatively high, and the general ratio of energy-to-human costs should be related to other office conditions with care.

The cost difference between case studies in the *actual scenario* emerges from the difference in the indoor environment conditions. In Building B in Winter (case B–W), some occupants located at desks with greater environmental discomfort resulted in strong productivity losses compared to occupants in the rest of the space. In the other cases, all occupants were exposed to a more homogeneous thermal environment; thus, the loss of productivity across the office space was uniform. The clothing habit was also different in the cases, and it was at a wider range Building B during Winter. When the thermal environment was *optimized* to the best interest of productivity, an increase in the temperature in three (A-F, A-W, B–F) out of four cases led to additional costs in heating use and SBS symptom prevalence. Only in Building B during Winter (case B–W), the optimization strategy leads to a decrease in temperature and hence lower costs in the *optimal scenario* compared to the *actual scenario,* but greater than the *standard scenario.* The optimization was highly dependent on the occupants as the optimal temperatures for each case were identified based on the PMV index considering personalized parameters such as metabolic rate and clothing insulation. The metabolic rate considered was typical for a seated working person, but the mean of clothing insulation adopted from measurements was much lower than those suggested for heating seasons (i.e., 1 *clo*). If occupants were clothed in a more standard way for the heating season, extra insulation of the clothing would shift down the optimal temperatures. Education and communication about more effective adaptation strategies could be a soft strategy to reduce buildings' energy use.

The adoption of a monetary approach to evaluate the economic performance of *actual, optimal*, and *standard* scenarios, when multiple KPIs are considered, implies the need to monetize every component of KPI (health, productivity, and energy). As there are multiple approaches to monetizing health, assessing the cost of SBS symptoms requires particular attention. One approach is to adopt a cost-of-illness and to compute all the medical costs that the occupants would incur to overcome the health issues. Such an approach is impractical because SBS



(a) A-F (b) A-W (c) B-F (d) B-W

Fig. 9. Differences in costs for productivity, SBS weekly symptoms, and energy for actual (TA) and optimal (TO) scenarios with respect to standard scenario (baseline) over two seasonal weeks.

symptoms are not specific, and their treatment is not foreseeable. Therefore, the employer's, rather than employees', perspective is adopted in this work as he is the payer of energy bills and the main beneficiary concerning the productivity of employees. As a result, we deployed the "willingness-to-pay" (WTP) approach, according to which health is valued in monetary terms by assessing how much people would be willing to spend *ex-ante* to safeguard it. The resulting numerical value chosen (3.5 CHF/employee per day) is close to the average between how much Swiss citizens pay per day in healthcare (4.9 CHF) and their pharmaceutical spending (2.3 CHF) [46], so it is considered as a good approximation of the monetary value for health in this context. Generally, the monetization allowed us to translate all the criteria into the same unit of measurement (i.e., currency in CHF) to compare them on equal terms, closing a gap in quantitative understanding and communication of the health impacts of buildings. Indeed, monetizing the latter is not trivial; thus, assessing the return on investment in healthy buildings is not a common practice yet [8,47].

The models chosen for the evaluation of health (e.g., SBS symptoms) and productivity were not free of limitations. The model by Seppänen et al. [25] was characterized by some uncertainty as it was based on studies with different thermal environments. The type of tasks typical for call centers was the common factor among the field and lab experiments considered in the model. While the performance was assessed through objective measurements of speed and accuracy, the model included an element of subjectivity as studies were weighted based on the authors' judgment of the relative relevance of the performance outcome to real work. Nevertheless, the model was implemented because of its relevance to the office environment, and it is widely recognized in the literature as a reference to assess the impacts of ventilation on performance. The only difficulty of working with the model from Seppänen et al. [25] relates to precisely assessing the ventilation rate per person. In the case of no mechanical ventilation present, as in the case of Building B, it was difficult to deploy such a model. For quantifying work performance as a function of indoor air temperature, another well-established model by Seppänen et al. would have been used. However, as reported in the meta-analysis done by Porras-Salazar et al. [48], its reliability is under question. Therefore, the model to determine the effect of thermal environment on productivity by Li Lan et al. [17] was selected instead. Although the model was developed based on a few laboratory experiments involving mental tasks and simulated office tasks, it was recently confirmed by the same authors [49]. Finally, the model by Mendell and Mirer [11] was based on self-reported SBS symptoms of occupants of actual US office buildings four weeks before the week when objective measurements of the indoor environment were performed. The model considered solely the US office buildings that most certainly have different working and thermal conditions than the European ones. Nevertheless, the model by Mendell and Mirer was chosen to compute the KPI based on the Odds Ratios (OR) as it allowed the evaluation of potential risks to health due to the indoor thermal environment. It is important to stress that the Odds Ratio is a statistical measure of the level of association between two events (e.g., high temperature and prevalence of SBS symptoms). Since correlation does not imply causation, causation can only be assumed based on the fact that if OR is different from 1, the two events are not independent, and the presence of one increases ($OR>1$) or reduces ($OR<1$) the probability of the other one. Thus, the variation in prevalence computed based on the Odd Ratios should be interpreted by the reader with care. Overall, the applicability of these models outside the context they were initially developed (e.g., call centers, lab experiments, field studies at different climates, and building types) is an open question. Despite certain limitations of the models used, they allowed the estimation of the SBS symptoms and productivity risks to be considered in the economic evaluation of the case studies as they used as input parameters that can be commonly measured.

In the assumption of the accurate models and accurate estimation of the weekly cost for SBS and hourly labor cost, the main uncertainty contribution to the human-related cost would be coming from: (i) the measurements of the indoor air temperature to compute the number of degree hours (DG_{av}) above the threshold temperature (input for SBS symptoms prevalence analysis), (ii) estimation of the thermal sensation votes TSV via PMV to calculate the relative performance (RP_{tsv}) input into the productivity cost, (iii) the occupancy rate (occ) that is input into both SBS symptoms and productivity costs. If the physical parameters were measured with adequate accuracy, then the resulting uncertainty of the SBS cost and productivity cost could range from under 10% for cases yielding high costs (e.g., TO and TA scenarios for SBS cost and TO scenario for the productivity cost in case of the Building B), and much greater uncertainty in cases yielding low costs (e.g., scenario TA for productivity cost in both buildings and scenario TA for SBS cost in the case A-W). Overall, accurate input parameters along with an accurate model, are required to minimize the resulting uncertainty of the health monetization outputs.

The uncertainty of the energy-related costs primarily depends on the input parameters considered for the energy simulations and the accuracy of the physical modeling embedded in the energy simulation tool as DesignBuilder. Quantifying the uncertainty of energy results is challenging, as building energy simulation workflow is complex, and it isn't easy to track all the links between the input and output parameters. While the uncertainty of the simulation of a *standard* scenario would be minimal, as prescribed parameters were used, the uncertainty of the results for the *optimal* and particularly for the *actual* scenario, would be highly dependent on the accuracy of the measured parameters input into the model. To maximize the accuracy of the *actual* scenario simulations, we input the carefully measured parameters such as local outdoor weather conditions, natural and mechanical ventilation, indoor air temperature, and building construction. In the case of the optimal scenario, the estimation of the operative temperature corresponding to the optimal productivity PMV value had the main contribution. Apart from the input parameters, intermediate calculations and assumptions would contribute to the uncertainty of the results.

The above-mentioned discussion on the accuracy and factors contributing to the uncertainty of the monetization analysis underlines that current research efforts should be focused on the development of more reliable models for the estimation of human-related costs considering the difficulty or easiness of measuring the required input parameters and their uncertainty contributions. In particular, it's fundamental to diversify models depending on the building's final use, climatic conditions, presence of natural or mechanical ventilation, occupants' clothing habits, and automation level of the building. The fundamental basis for the development of these types of models consists of wide monitoring campaigns in order to collect the needed data.

5. Conclusions

The impact of indoor environmental quality on occupants' performance and health has been gaining attention in the past decade; however, it has been challenging to quantify its economic implications [46]. This paper demonstrated an integrated economic comparison of two Swiss buildings with open-space offices considering three KPIs: operational energy, SBS symptoms, and occupants' productivity. Three different scenarios (*standard*, *actual*, and *optimal*) were defined to present their effect on the performance of case studies. Setpoints suggested by the Swiss national standard SIA 2024:2015 were contrasted to the actual post-occupancy measurements and setpoints corresponding to optimal productivity. Human health was analyzed by determining SBS symptoms prevalence at the entire office (e.g., floor) level, while the fractional productivity variation was analyzed both at the desk level (due to the indoor temperature) and at the floor level (due to the ventilation). Spatially detailed monitoring of the thermal environment and air quality (i.e., CO_2 concentrations) of the case study buildings allowed for performing such a fine analysis.

Monitoring the case studies, Building A and B, during two seasons, Fall and Winter, revealed that the offices were almost 2.5–3.5 °C warmer than the setpoint suggested by the standard (21 °C). The PMV index analysis based on the measurements of the thermal environment and survey of self-reported activities and clothing indicated that people were actually *cool* as they were lightly clothed. Thus, the optimized temperature setpoints corresponding to the PMV in the range of [-0.3; −0.2], as suggested by Lan et al. [16], were elevated by 0.2–0.5 °C in three cases (Building A in Fall and Winter, and Building B in Fall) and lower by 0.2 °C in the case of Building B in Winter as it was initially the warmest case. Accordingly, three optimized scenarios lead to an increase in energy use for heating that is also consequently reflected in the increase in energy cost. In *actual* and *optimal* cases, indoor air temperatures above 23 °C led to an increase in the weekly prevalence of all SBS symptoms. The *optimal* productivity scenario was not optimal regarding weekly SBS symptoms and led to increased energy use highlighting the *conflicting goals* when one parameter is prioritized over another one. Thus, a multi-criteria approach should be adopted to consider all important metrics [50].

The results of the analysis, particularly the *actual* and *optimized* scenarios, are primarily determined by the models implemented. The energy performance of the case study buildings was evaluated using a dynamic building energy simulation model that was refined using the actual data measured in the case studies (e.g., indoor environment, occupancy, the opening of windows, etc.). Despite no possibility of validating the model, the relative comparison of the results for different cases allowed to highlight the important effect of the building's operation and human behavior on the energy performance. SBS prevalence and productivity models by Mendell and Mirer [11], Lan et al. [17], and Seppänen et al. [25] were used with caution as the models were originally developed for the context of call centers, lab studies, field experiments at different climates, and building types. Nonetheless, they enable relative comparison of the human performance in the case studies and provide input to demonstrate the approach to monetize the human costs. The employer's perspective was adopted in the economic evaluation as he is the payer of energy bills. The "willingness-to-pay" approach was implemented for the monetization of human health, according to which health is valued in monetary terms by assessing how much people would be willing to spend *ex-ante* to safeguard it. Generally, monetization allows translation of energy-, health-, and performance-related criteria into the same unit currency to compare them on equal terms, closing a gap in quantitative understanding and communication of the various factors in buildings. Finally, the presented analysis highlights the need for special attention to the adverse effect of IEQ on human occupants and costs. As humans are valuable assets of businesses, assuring their well-being and high performance should have the same weight, if not greater, in evaluation of the performance buildings, as minimization of energy use.

CRediT authorship contribution statement

Dolaana Khovalyg: Writing – original draft, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Cecile A. Berquand:** Writing – original draft, Visualization, Software, Methodology, Formal analysis, Conceptualization. **Giulia Vergerio:** Writing – original draft, Methodology, Formal analysis. **Verena M. Barthelmes:** Investigation, Data curation. **Arnab Chatterjee:** Visualization, Software, Investigation. **Cristina Becchio:** Writing – original draft, Supervision, Methodology. **Dusan Licina:** Writing – original draft, Supervision, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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APPENDIX

Table A1

Adjusted odds ratios of symptom prevalence increase for each nine-degree hours above 23 °C [10].

SBS group of symptoms m	Odd Ratio OR_m [−]
1. Upper respiratory	1.33
2. Dry or irritated eyes	1.72
3. Fatigue or difficulty concentrating	1.81
4. Irritated skin	1.77

Table A2

Weekly prevalence baseline from the EPA base study [10].

SBS symptom i	Weekly prevalence $P_{EPA,W}$ [%]
1. Stuffy runny nose	13
2. Sneezing	11
3. Sore dry throat	7
4. Dry irritated eyes	19
5. Fatigue	15
6. Concentration	5
7. Irritated skin	5

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