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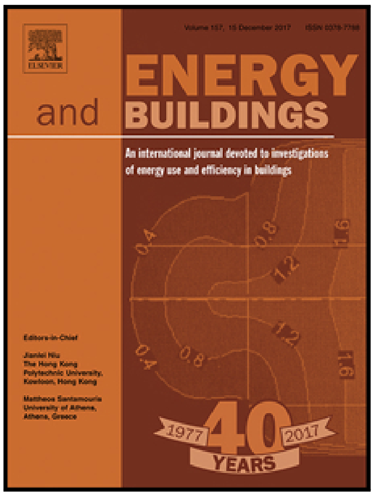

How subjective and non-physical parameters affect occupants' environmental comfort perception

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PII: S0378-7788(18)31305-7
DOI: https://doi.org/10.1016/j.enbuild.2018.08.020
Reference: ENB 8756

To appear in: *Energy & Buildings*

Received date: 27 April 2018
Revised date: 10 July 2018
Accepted date: 14 August 2018

Please cite this article as: Veronica Lucia Castaldo , Ilaria Pigliautile , Federica Rosso , Franco Cotana , Francesco De Giorgio , Anna Laura Pisello , How subjective and non-physical parameters affect occupants' environmental comfort perception, *Energy & Buildings* (2018), doi: https://doi.org/10.1016/j.enbuild.2018.08.020

Highlights

- Indoor whole-comfort yearly experimental test is performed in a working environment
- Multiphysics/multidomain variables are investigated within a 1000-employee sample
- Employees are consistently positively influenced by triggers to improve working quality
- Non-physical triggers are further options to save energy without compromising comfort

How subjective and non-physical parameters affect occupants' environmental comfort perception

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Abstract

Employees' wellbeing and comfort perception demonstrated to largely influence their productivity and tolerability of slight thermal discomfort conditions in the working spaces. Their whole comfort perception indeed depends on several parameters related to physical boundary conditions but also to the adaptation capability of occupants themselves and other personal, difficult to measure, variables. According to the available standards and regulations, only physical and measurable environmental parameters must be considered to evaluate occupants' comfort conditions. Therefore, non-measurable factors such as socio-psychological, physiological, medical ones are currently not systematically considered. The present work aims to identify possible benefits in terms of occupants' comfort perception due to non-physical strategies aimed at improving the work-environment quality and livability. To this aim, the environmental multi-physics and multi-domain performance of a mixed industry-office building is investigated through coupled in-field microclimate monitoring and questionnaires campaigns. The experimental microclimate monitoring and survey campaign were carried out to understand (i) the realistic indoor environmental conditions in terms of physical and measurable parameters and (ii) the personal perceptions and attitudes of the occupants with respect to those same ambient parameters, including also acoustic, lighting and medical investigation. Moreover, the collected experimental data were used to determine occupants' comfort level through the classic comfort models, to be compared to the identified role of non-physical parameters on occupants' final perception about the indoor environment. The main results show that non-measurable factors induced by virtuous company policy to improve employees' working environment are effectively able to positively influence their whole-comfort perception even if the majority of workers do not have the opportunity to control their working environment. In fact, the consolidated comfort theories underestimate people satisfaction, as demonstrated by more than the 80% employees, who declared to be positively influenced by the pleasant aesthetics and livability of the workplace. The year-round experimental campaign demonstrated the need to further investigate the key role of non-physical parameters for possible incorporation into whole-comfort prediction models and standards. The role of such

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strategies could therefore be realistically considered as energy saving opportunities since they make building occupants much more open to tolerate slight uncomfortable conditions.

Keywords: energy efficiency; indoor whole comfort; occupancy behaviour; adaptive model; microclimate; continuous monitoring; thermal comfort.

1. Introduction

The achievement of comfort conditions in the built environment is a crucial topic in present days, and both researchers and policy-makers are increasingly focusing on it in both indoors and outdoors. There are studies on outdoor thermal and visual comfort, aimed at promoting outdoor activities [1] and at increasing comfort conditions for pedestrians [2,3]; while other studies concentrate on indoor comfort conditions also by means of dynamic simulation [4], where typically better controlled variables are considered [5,6] and where people are used to spend about 80-90% of their lifetime [7]. The aim is to improve the conditions of inhabitants and workers, respectively in residential indoor areas and workplace, since Urban Heat Island effect is posing serious issues on urban citizens' comfort and wellbeing [8–10].

Specifically, great attention has been placed on comfort conditions on the workplace, for economic and social reasons. Indeed, companies are directly interested in guaranteeing wellbeing conditions in their work environment, since it has been linked to employees' productivity, satisfaction, absenteeism, etc. [11–13]. In fact, comfort conditions affect health conditions of employees, whereas non-suitable environmental conditions have been linked to health issues and possible diseases related to long-term exposure to environmental forcing [14,15]. Therefore, providing appropriate comfort conditions supports both the social and the economic sustainability of the company [16], and an employee-friendly workplace has also been associated to higher innovation in companies [17]. The importance for companies to achieve sustainability goals is not only related to immediate social and economic benefits, but also to longer-term benefits, for example in terms of company recognition and brand value, are recognized [18].

While the recognition of the need to investigate this field is univocal, different approaches can be employed for comfort studies and indoor environmental quality assessment, considering the complexity of the phenomenon to be analyzed [19]. The work of Al Horr and colleagues provides an exhaustive overview, framing the complexity of indoor environmental quality on occupancy wellbeing and on employees' productivity [7,11]. For thermal comfort assessment, physical parameters, which vary inside a determined threshold, may be usefully aggregated into indices summing up the thermal sensation of indoor space occupants. As described in existing standards ASHRAE 55 [20] and ISO 7730 [21], the heat balance model for the human body considers the comfort perception as dependent on the (1) metabolic rate of the occupant, (2) his/her clothing insulation [22,23], (3) air temperature and (4) mean radiant temperature [24,25], (5) air velocity and (6) relative humidity of the indoor area [26]. The indices that are employed to quantify the thermal perception in conditioned building are the Predicted Mean Vote, referred to as PMV, and the

Predicted Percentage of Dissatisfied, which is indicated with the PPD acronym. While PMV assigns a vote to the thermal perception of a determined area, PPD gives an idea of the percentage of people whose vote falls outside the comfortable perception area, therefore occupants that are not satisfied with the thermal environment. A 5% of PPD is considered almost inevitable, as in any case there are other factors that are subjective and influence each single individual's thermal sensation. A different method is carried out to assess thermal comfort conditions in free floating building indoors, i.e., the adaptive method, which was developed by means of field studies and is based on the concept that occupants adapt to the surrounding environment by interacting with it. The integration of adaptive assessment method and indices has been investigated by previous research [27–30]. To quantify the effects of different adaptation processes, some studies tried to include them within the predicted mean vote (PMV) which, at the moment, is the most commonly used index and is suggested by standards, based on the steady state heat transfer theory. Fanger and Toftum [31] suggested an extension of the PMV index to non-air-conditioned buildings in warm climate by introducing an expectancy factor *e*, which depends on the expectation level (high, moderate or low) and local climate conditions, i.e. duration of the warm period.

Other indicators of comfort in indoor spaces are related to indoor air quality (IAQ), that mainly relies on ventilation to avoid maximum concentration of CO_2 [32] and other pollutants; to acoustic comfort; and to visual comfort which depends on needed versus actual illuminance on the work station. All the above mentioned physical comfort factors contribute to the final, total, comfort sensation. Moreover, other subjective factors, either behavioral, psychological and/or physiological, have an important role towards the final comfort perception. Subjective judgment scales are commonly employed [33] to assess the thermal environment, and are coupled with contemporary in-field monitoring campaigns of the indoor environmental conditions as determined by physical parameters. To provide some example of studies taking into account subjective factors, in Nakano and colleagues' work [34], the same workspace resulted to be differently perceived by groups of employees from different nationality and gender, whereas Yamtraipat et al. [35] observed that indoor thermal comfort sensation varies with (i) occupants' education level and (ii) how much they were accustomed to conditioned areas.

Based on the above reported considerations, the definition of the whole-comfort conditions (thermal, visual et al.) of an indoor environment shows to be a difficult task, which requires to consider many different factors, both physical and subjective, at the same time. Therefore, the aim of this work is to perform an accurate, multi-physics and multi-scope evaluation of indoor comfort sensation on the workplace, demonstrating the need to consider human adaptation capabilities and personal, subjective, sociological factors together with the physical ones. The novel focus of this contribution is not exclusively on thermal or visual comfort, since the analysis considers the variety of multi-physics factors that influences comfort conditions, namely thermal, visual, IAQ, acoustic forcings. Another original aspect of the present work is the coupled assessment method that covers physical and non-physical investigations, with the basic hypothesis that employees' satisfaction with respect to their working environment and, therefore, their productivity, is not only influenced by environmental measurable parameters. To this aim, an integrated method is implemented, whereas in-field monitoring, numerical simulations and subjective judgment scales surveys are conducted, and results of each of the performed assessment are compared, with the above-mentioned objective to investigate the importance of subjective parameter in such an assessment. Both field measurements and surveys were carried out all along a whole year, therefore also seasonal variations are accounted for. The case study was a real company, and the measurements were taken during operating periods. More than 350 employees, out of a total sample of 1000 reached persons, participated to this campaign, providing a sufficiently representative sample for the analyses. In the next section, the motivation of this work is more in depth described.

2. Motivation of the study

Based on the outlined introduction, the present work aims at highlighting the need for investigating the role of non-physical and non-measurable parameters in affecting occupants' overall comfort conditions within the building indoor environment. The hypothesis that behavioral, physiological, health and psychological factors can have a non-negligible role in determining the final user perception, interaction, and adaptation capability with respect to the surrounding environment is verified. This could therefore generate a significant modification of the final energy use and could even affect occupants' satisfaction level and the relative productivity, when referring to a factory/tertiary building, such as the selected case study.

To this aim, coupled experimental microclimate monitoring and survey campaign are carried out over one year to investigate (i) the realistic indoor environmental conditions in terms of physical and measurable parameters and (ii) the perceptions and attitudes of the occupants with respect to those same ambient parameters. Moreover, the collected experimental data are used to determine occupants' comfort level through the classic (i) steady-state heat transfer theory (Fanger model) and (ii) the adaptive model, to verify which one of them fits better the results achieved through field participative surveys, even if the case study is a mechanically conditioned building and therefore is theoretically suitable only for the Fanger model implementation, according to its assumptions.

The final goal of the analysis is to demonstrate the need to consider also non-physical parameters in addition to the traditional physical ones, when assessing indoor wellbeing of occupants within the built environment, and to provide an overall comfort conditions assessment, based on multi-physics, multisensorial and subjective perceptions, on the different components of comfort sensation (thermal, visual, acoustic et al.) and tolerance/adaptability. Therefore, this contribution provides clear insights into the next whole-comfort assessment by means of a holistic approach, where multi-physics measurable parameters are considered together with human adaptation capability and other personal-sociological variables. In fact, the consideration of such non-measurable factors provides a more exhaustive understanding of the human perspective in the built environment and potentially opens the doors to further energy saving opportunities achievable through human-based energy efficiency solutions [36].

3. Methodology

The applied methodology consists of the assessment of indoor comfort conditions in different areas in the same factory complex selected as case study building. The study was carried out by combining (i) the annual in-field experimental monitoring of the environment physical parameters and (ii) the submission of questionnaires surveys to the occupants, i.e. factory employees. Both (i) and (ii) were conducted in all the 4 seasons during the course of the whole monitored year.

The monitoring campaign was carried out by means of a dedicated portable indoor microclimate station collecting physical data of (i) indoor air quality, (ii) illuminance level, (iii) global and (iv) local thermal comfort. Therefore, the sensors included in the station are the ones listed in Table 1. All the sensors were compliant with ISO 7726 [27] and were positioned almost in the centre of each working area, close to employees' workstations at 1.10 m height in order to identify the working seated person perspective.

Table 1. Technical characteristics of the monitoring sensors.

Sensor	**Monitored parameters**	**Measurement features**
Thermal-hygrometer	Air Temperature (°C) Relative Humidity (%)	Resolution: 0.01°C, Uncertainty: 0.1°C Uncertainty: ± 1.5%
Surface and air temperature sensor	Floor Temperature (°C) Air Temperature at ankle level (°C)	Resolution: 0.01°C, Uncertainty: 0.15°C Resolution: 0.01°C, Uncertainty: 0.15°C
Black globe radiant temperature sensor	Mean Radiant Temperature (°C)	Resolution: 0.01°C, Uncertainty: 0.15°C
Hot wire anemometer	Air Speed (m/s) Air Turbulence (%)	Resolution: 0.01 m/s Uncertainty: 0.5÷1.5 m/s Uncertainty: >1.5 m/s = 4%
Luxmeter	Illuminance (lux)	Resolution: 0.5 lux
Net radiometer	Radiant Asymmetry (°C)	Uncertainty: 3%
CO_2 sensor	CO_2 concentration (ppm)	Resolution: 1 ppm, Uncertainty: ±50 ppm (+2%)
CO sensor	CO concentration (ppm)	Resolution: 0.5 ppm , Uncertainty: 1%
VOC sensor	VOC concentration (ppm)	Resolution: 1 ppm , Uncertainty: 3%

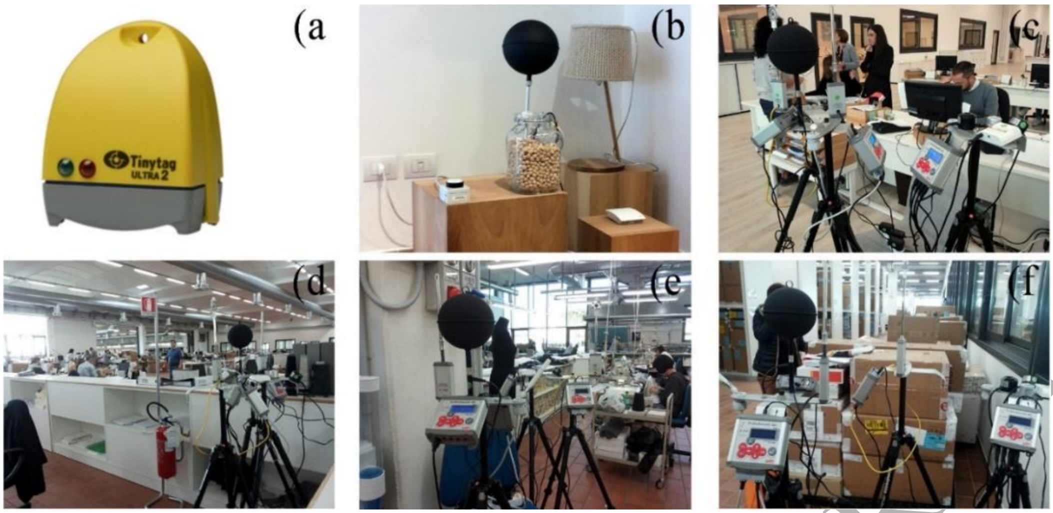

Fig. 1. a) Temperature sensor, monitoring sensors installed in b) the canteen, c) the building C, d) B, e) A, and f) D.

The microclimate station was positioned in all the areas of the case study complex in order to have a whole representative working-week of monitoring per season in each ambient (Figure 1c-f). Moreover, air temperature was collected simultaneously in all the areas by means of portable sensors (Figure 1a) for the whole duration of the seasonal monitored periods which are listed below:

- Fall: October 10th – November 18th, 2016;
- Winter: January 2nd – February 17th, 2017;
- Spring: April 10th – May 19th, 2017;
- Summer: July 11th –August 7th, 2017.

Finally, another monitoring setup was installed within the company canteen (Figure 1b). The collected parameters in this area are as follows:

– Air temperature [°C], relative humidity [%], air velocity [m/s], CO_2 concentration level [ppm], mean radiant temperature [°C], and lighting level [lux] during fall and winter;
– Air temperature [°C], air velocity [m/s], mean radiant temperature, and lighting level during spring and summer.

The purpose of the experimental campaign was to highlight how the indoor microclimate parameters can change with respect to the local and peculiar characteristics of the environment and according to the activity that employees perform in it. Moreover, the collected experimental data were analyzed and compared to reference values given by regulations in order to outline the expected percentage of dissatisfied according to standards. As specifically concerns the thermal-hygrometric comfort evaluation, both the approaches suggested by the UNI EN 15251 were used and the outlined results were compared in order to identify the best one in detecting realistic occupants' perception. Therefore, the thermal-hygrometric comfort is evaluated by means of both (i) the Fanger model and (ii) the adaptive approach. Even if the case study building is mechanically conditioned, the application of the adaptive approach is justified within the frame of the work. Nevertheless, previous studies [28] already applied the adaptive approach in thermal comfort evaluation of air-conditioned spaces highlighting the influence of outdoor temperature seasonal fluctuation on occupants' thermal perception.

Additionally, at the beginning of each seasonal monitoring campaign, questionnaires were submitted via web to 250 occupants, randomly selected among the company employees' list. Therefore, a total number of 1000 employees (the sum of each seasons' participants) was reached during the whole year of surveys and monitoring campaigns.

The selected method to investigate visual and thermal comfort perception consisted of the design and submission of a questionnaire survey, submitted online through the open source "Google Modules" tool in order to obtain less subjective results. The survey was developed according to the ISO 10551 [33] which specifies the questions to be asked to assess the thermal perception of the respondents, as well as the scale to be employed to interpret the results. The standard identifies different types of questions describing the different aspects of thermal perception, i.e. thermal sensation, thermal comfort, thermal preference, acceptability and thermal tolerability with respect to the surrounding environment.

Since there are no standards available in the literature for the evaluation of occupants' visual perception, the same standard was applied for the analysis of visual comfort [3]. Therefore, the questions related to the thermal conditions were mirrored in terms of visual sensation, comfort, preference, acceptability, tolerability depending on the amount of light available in the work-space.

In addition to thermal and visual comfort, the questionnaire was composed by different sections investigating different aspects of comfort and factors that could influence it. In fact, the sections dealt with: (1) working schedule, workplace location and typology, working habits and possibility to control the workplace environment; (2) visual and (3) thermal comfort assessment in terms of visual and thermal (i) sensation, (ii) comfort, (iii) preference, (iv) acceptability, and (v) tolerability; (4) general comfort condition and adaptability, also considering non-physical variables, such as (i) work environment quality perception, (ii) environmental quality of employees' home environment compared to the work place, (iii) health condition, and (iv) personal mood; finally, (5) personal information (gender, age, clothing). Also the analysis of the subjective thermal perception was consistent with ISO 10551 [29-33]. Moreover, the same survey was adapted for acoustic comfort, but in a synthesized form not to overload interviewees with too many questions and long survey filling time.The questionnaire was totally anonymous to ensure false answers from participants during the different seasons. The time for filling the questionnaire corresponded to around 15 minutes and consisted of multiple choice questions. The survey was proposed to the company employees in Italian, since the company is located in Central Italy and not all employees' categories are demanded to speak other languages than Italian.

4. Description of the case study

The case study is a luxury clothing factory and management district located in Perugia (central Italy) composed by four buildings, where the production and administrative activities take place, and a restaurant/company cafeteria and outdoor facilities are located. The whole complex occupies about 80000 m^2 and it is composed by different buildings, which slightly differ from each other for the orientation, construction details and the main activity performed inside them (Figure 2):

- Building A, East-West oriented, is the "machinery area", where the core of the production takes place;
- Building B, North-South oriented, is the "control area", used for control and quality inspections of products and expeditions;
- Building C, East-West oriented, is the "administration area", where administrative computer stations are located;
- Building D, North-South oriented, is the "store area", where all the products are stored before final shipping.

All the areas have been monitored in the four seasons as reported in Figure 1, where the experimental setup is depicted.

The case study factory complex represents a positive example due to the company policy to enhance the environmental quality for employees' wellbeing, thanks to the well-maintained outdoor green environment which is visible from all the work stations and the restaurant service within the company's area (i.e., the company cafeteria) which serves every day organic and sophisticated healthy diet for employees for free (Figure 3).

Fig. 2. Aerial view of the factory complex selected as case study, which is situated in Solomeo (Perugia, Italy) with the indication of the monitored buildings.

Fig. 3. Overview of the case study: a) view of the outside from the inner working area; b) view of the exposition areas, c) building C, “administration area”, d) building B, “control area”.

All the interviewees were selected among company permanent employees performing a wide variety of roles inside the company (laborers, managers, warehouse operators) and working in different buildings and areas of the case study complex, where different activities take place. A total of 360 questionnaires were collected via web, out of 1000 submissions, corresponding to the whole total number of employees that got the survey during the 4 monitored seasons of the whole year. The 36% of effective and complete response rate was registered. During fall, 135 people, i.e. 38.1% of the total sample, replied, while only 75 people submitted their responses during winter and spring, i.e. 21% of the total. During summer, the 19% of the total sample of the interviewed replied to the questionnaire. In general, a slight decrease of participation was registered, despite that only invited employees were informed about their survey, meaning that no multiple invitations were sent to the same workers in several seasons.

5. Results and Discussion

The analysis of the results allowed to assess the complex indoor comfort conditions of the workers through a holistic approach. It was aimed at determining how personal and non-physical parameters related to users' perceptions could influence their well-being in their workplace. To this aim, a multi-physics and multi-domain analysis including the assessment of occupants' thermo-hygrometric comfort, local dis-comfort related issues, visual comfort, health condition, and air quality was carried out.

5.1. **Thermal-hygrometric comfort analysis**

The indoor thermal comfort condition of the workers was evaluated by means of both (i) the steady-state heat transfer theory, i.e. Fanger model, and (ii) the adaptive model. As previously specified, despite acknowledging the different boundary conditions of such models, the proposed assessment wanted to identify possible non-physical drivers, and to compare both the physical-based approaches to experimentally investigate their interpretation potentiality. To compare the obtained results, the dis-comfort evaluation was carried on considering the following three indexes for both the methodologies:

- Performance Index (PI): the percentage of time during which the comfort conditions are met;
- Shift Index (SI): the percentage of time during which the microclimatic parameters fall outside the comfort range.
- Deviation Index (DI): an adimensional index of deviation from the seasonal comfort condition, which considers simultaneously the magnitude of dis-comfort (deviation from the reference values) and the duration of that condition. Its formulation is as follows:

$$XDI = \frac{\int_{P_h}\left[X - X_{M,s}\right]\delta\tau + \int_{P_c}\left[X_{m,s} - X\right]\delta\tau}{XDI_{BC,s}} \cdot \frac{t_s - t_{X,s}}{t_s}$$

Where:

- X indicates the recorded value of the evaluated parameter;
- $X_{M,s}$ e $X_{m,s}$, are the seasonal maximum and minimum limits according to regulation;
- $XDI_{BC,s}$, is the seasonal deviation of the considered parameter compared to a baseline scenario;
- P_h e P_c represent the time intervals throughout the entire monitoring period during which the considered parameter falls below and above the standard limits;
- t_s indicates the duration of the monitoring;
- $t_{X,s}$ is the time period during which the parameter falls within the comfort range.

These indexes were therefore calculated by taking into account the PMV comfort ranges, i.e. ±0.5 accordingly to the ISO 7730, and the operative temperature comfort ranges, i.e. ±3°C with respect to the optimal temperature as specified in EN 15251, for the steady-state and the adaptive model respectively. For the DI calculation, the reference scenarios considered as base case were the following:

- Fanger model, scenario deviating from the regulatory range of +0.5 points for the entire duration of the monitoring;
- Adaptive model, scenario deviating from the regulatory of +1°C for the entire duration of the monitoring.

More in details, the Fanger model analysis was performed according to the indications of the UNI EN ISO 7730. The PMV (Predicted Mean Vote) and the PPD (Predicted Percentage of Dissatisfied) were calculated for each working area based on the specific performed activity in each monitored area, and with varying season. Two clothing conditions were considered, i.e. light and warm clothing for spring/summer and fall/winter periods (Table 2).

Table 2. Occupants' parameters used for the PMV calculation.

Personal parameters		**Machinery area (Building A)**		**Control area (Building B)**		**Administration area (Building C)**		**Warehouse (Building D)**	
		F/W	Sp/Su	F/W	Sp/Su	F/W	Sp/Su	F/W	Sp/Su
Metabolic energy	[met]	1.3	1.3	1.6	1.6	1.6	1.6	2.0	2.0
	[W/m^2]	78	78	93	93	93	93	116	116
Thermal resistance of clothing	[clo]	0.8	0.7	0.9	0.7	0.9	0.7	0.7	0.6
	[m^2°C/W]	0.14	0.11	0.14	0.11	0.12	0.11	0.12	0.10
F:Fall	*W: Winter*			*Sp: Spring*			*Su: Summer*		

Figure 4 shows the distribution of PMV and PPD with respect to the monitored indoor operative temperature for each area and season.

The main issues were detected in the area where flat and ironing machines operate (i.e. building A), where the average PMV value over the whole working week is +0.6, both in spring and in summer, while the maximum limit is +0.5 according to the standard. Building A presents also the absolute maximum PMV, i.e. +1.2 during spring.

About the adaptive model analysis, the optimal operative temperature (OptOT) for the indoor monitored environment was calculated as a function of the running mean external temperature obtained from data collected by the weather station located at the Engineering Faculty of Perugia's University, 8 km as the crow flies from the case study.

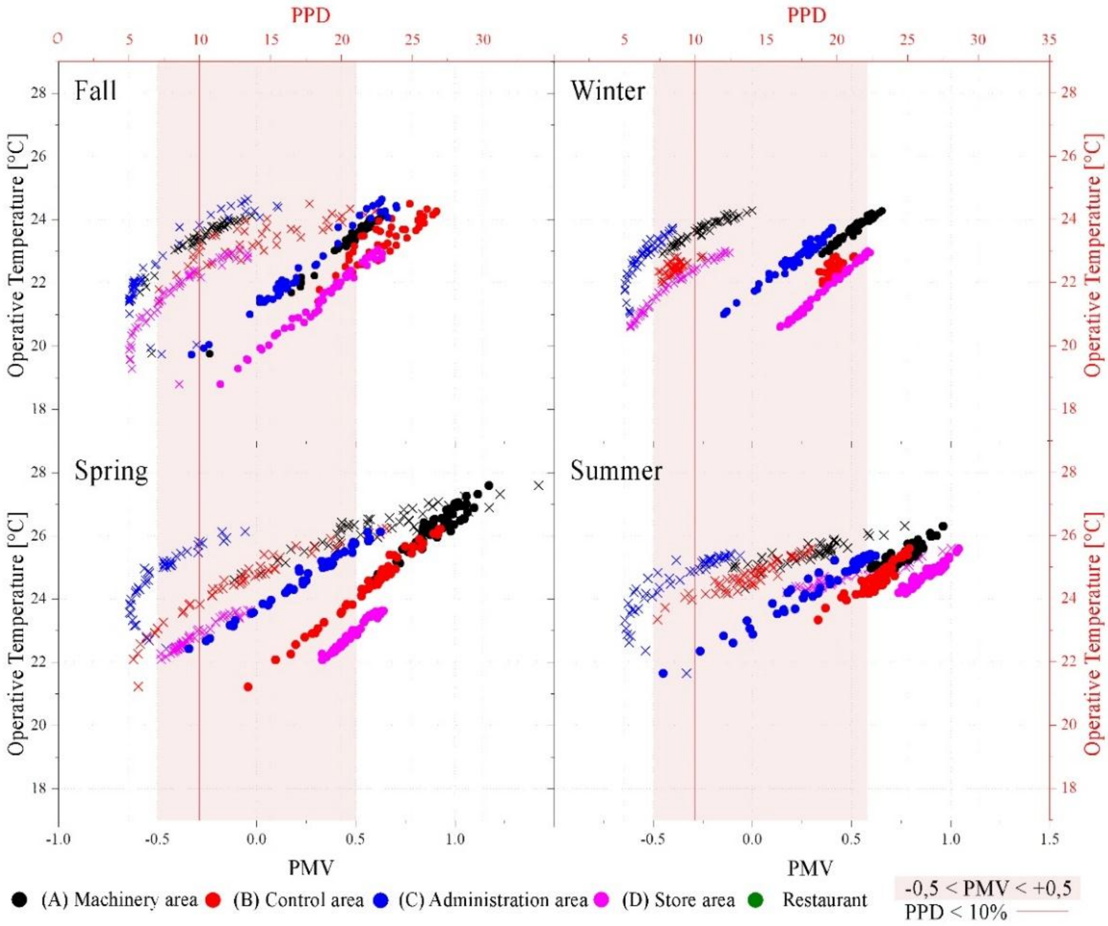

Fig. 4. PMV and PPD distribution in the four monitored working areas and in the four different seasons with respect to be monitored indoor operative temperature.

The PI, SI and DI values calculated considering both the steady-state and the adaptive approaches, for all the seasons and the monitored working spaces, are reported in Table 3.

Table 3. PI, SI, and DI calculated accordingly to the Fanger and the adaptive thermal comfort model for all the monitored areas and seasons.

Fanger model												
Monitored area	**PI (%)**				**SI (%)**				**DI**			
	F	W	Sp	Su	F	W	Sp	Su	F	W	Sp	Su
Machinery area (A)	46.0	40.8	0.00	0.00	54.0	59.2	100.0	100.0	0.00	0.04	0.81	0.55
Control area (B)	23.4	93. 5	29.2	10.0	76.6	6.5	70.8	90.0	0.24	0.00	0.19	0.26
Administration area (C)	75.5	100.0	90.7	54.0	24.5	0.0	9.3	46.0	0.02	0.00	0.00	0.02
Warehouse (D)	75.5	77.6	68.0	0.00	24.5	22.4	32.0	100.0	0.01	0.01	0.02	0.75

Adaptive model												
Monitored area	PI (%)				SI (%)				DI			
	F	W	Sp	Su	F	W	Sp	Su	F	W	Sp	Su
Machinery area (A)	98.0	100.0	98.0	100.0	2.0	0.0	2.0	0.0	0.00	0.00	0.00	0.00
Control area (B)	100.0	100.0	95.8	84.0	0.0	0.0	4.2	16.0	0.00	0.00	0.00	0.01
Administration area (C)	93.9	100.0	100.0	62.0	6.1	0.0	0.0	38.0	0.00	0.00	0.00	0.14
Warehouse (D)	100.0	100.0	100.0	36.0	0.0	0.0	0.0	64.0	0.00	0.00	0.00	0.17
F: Fall		W: Winter				Sp: Spring				Su: Summer		

A general comfortable condition was detected by means of both the approaches.

According to the Fanger model, despite the deviation of the monitored parameters from the optimum conditions was, in some cases, prolonged in time, i.e. high values of SI, it did not generate dis-comfort situations since the DI is always lower than 1. Moreover, the adaptive approach gave back even a more positive judgement of the same indoor environment in terms of indoor thermal comfort. The optimal operative temperature deviation index was always zero, and the only exceptions were for the administration and the warehouse area where a OptOT_DI of 0.14 and 0.17 is calculated respectively. Moreover, the recorded values out of comfort during the fall and summer monitored periods were due to detected operative temperature under the minimum evaluated threshold, while the dis-comfort conditions detected by means of the Fanger model were always related to PMV higher than +0.5, i.e. slightly hot environment.

Finally, Figure 5 shows the indoor temperature distribution in different environments compared to the dry bulb temperature recorded at the same time by the weather station.

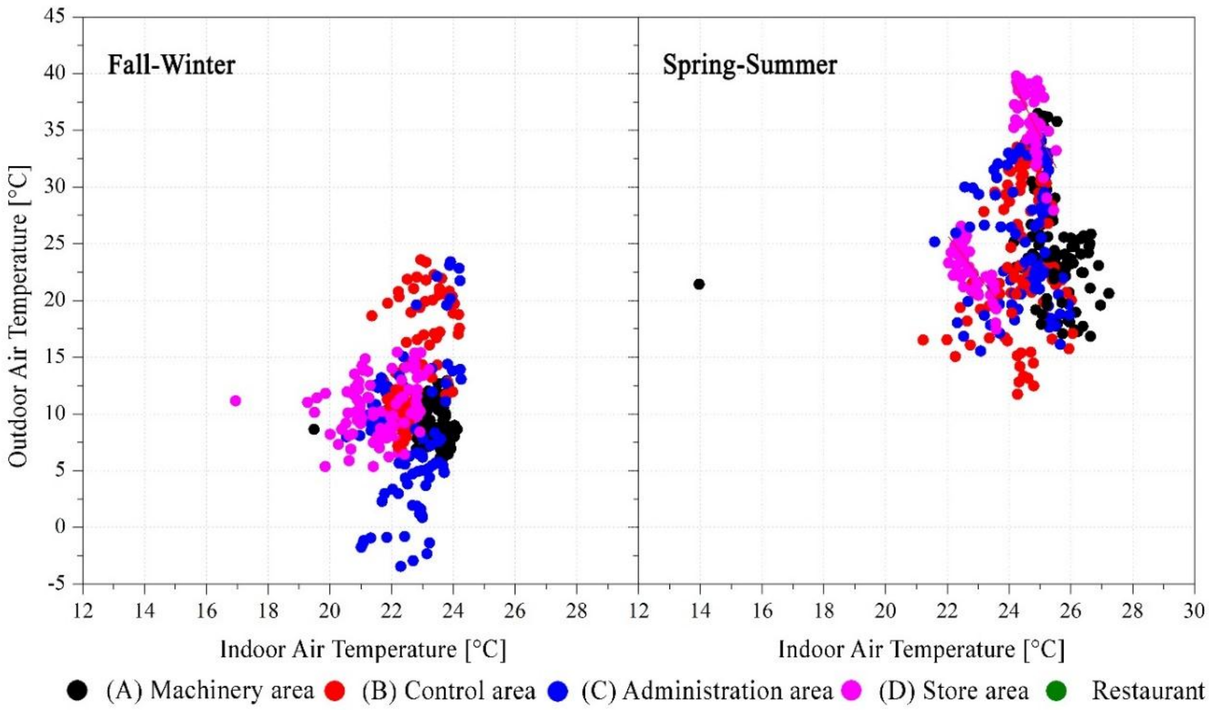

Fig. 5. Distribution of the indoor temperature for the four monitored areas and for each season with respect to the dry bulb temperature.

The graph showed almost a total decoupling of the indoor environment if compared to the outdoor environment, which is typical for mechanically controlled buildings. Despite the high outdoor thermal span observed between different seasons, the indoor temperature values fallen within a range of 18°C to 28°C. The correlation between the two parameters was always below 0.30, except for the case of the warehouse area during autumn (R^2 = 0.54) and the administration area in spring (R^2 = 0.52), which were the seasons during which the air conditioning system was not always operating.

The graph also allowed performing a comparative analysis of the different working areas with the same outdoor boundary conditions. Once again, building A presented the highest indoor temperatures due to the higher internal gains.

5.2. **Local dis-comfort analysis**

This section concerns the analysis of local dis-comfort conditions in the monitored working areas. Therefore, while assessing workers' thermal comfort, thermal dissatisfaction was also investigated, as generated by local overheating (or overcooling) phenomena perceived by human bodies.

Figure 6 summarizes the reasons for a possible local dis-comfort condition, according to UNI EN ISO 7730 standard.

The target conditions were always met, except for the floor temperature monitored in the warehouse area during autumn. In this case, a few hours with temperatures below 19°C were detected. Moreover, the percentage of unsatisfied employees due to turbulence and streams risk (Figure 7) was always less than 10% for building A during spring and summer, with peaks of 15.2% and 14.0%, respectively.

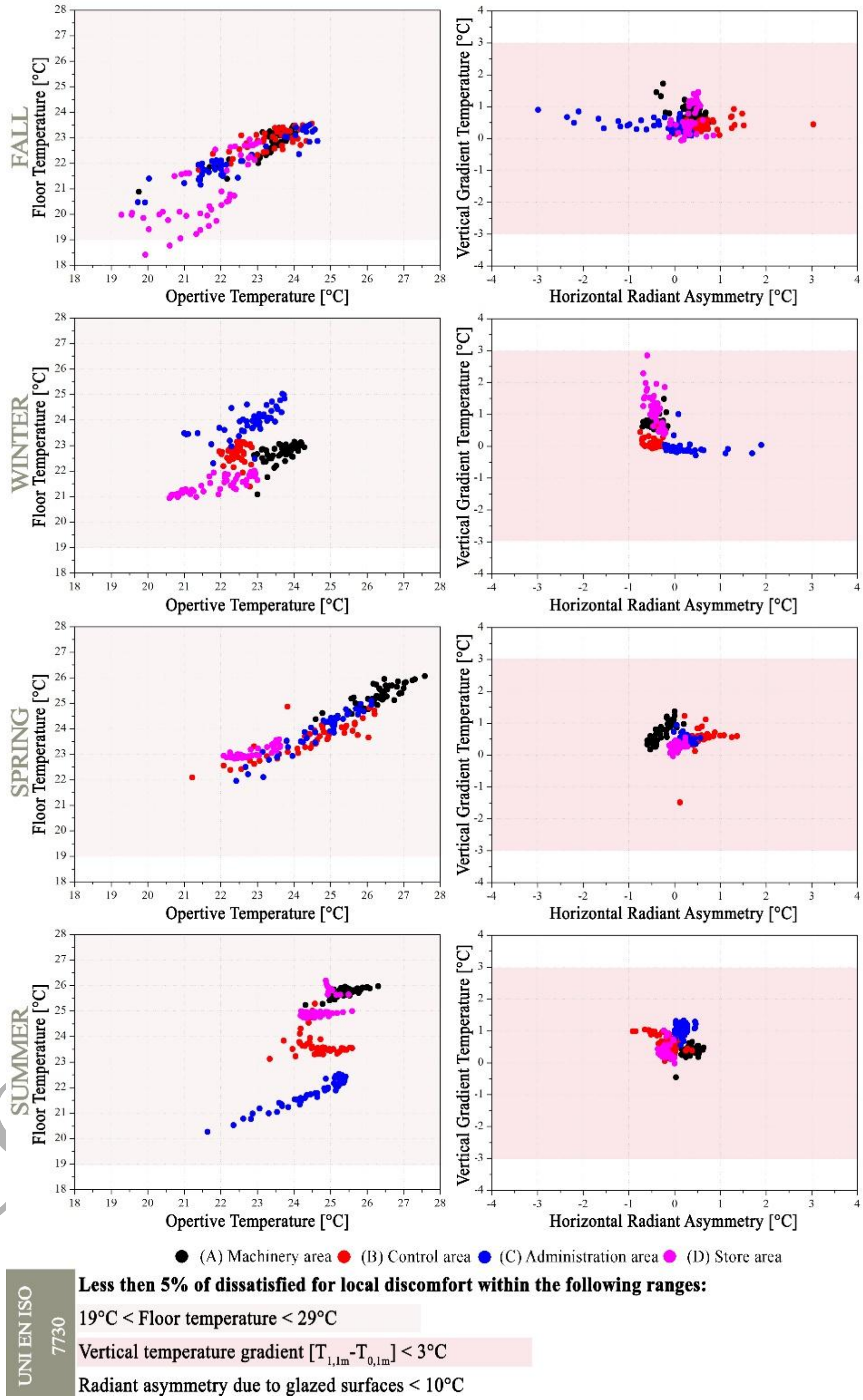

Fig. 6. Local dis-comfort analysis.

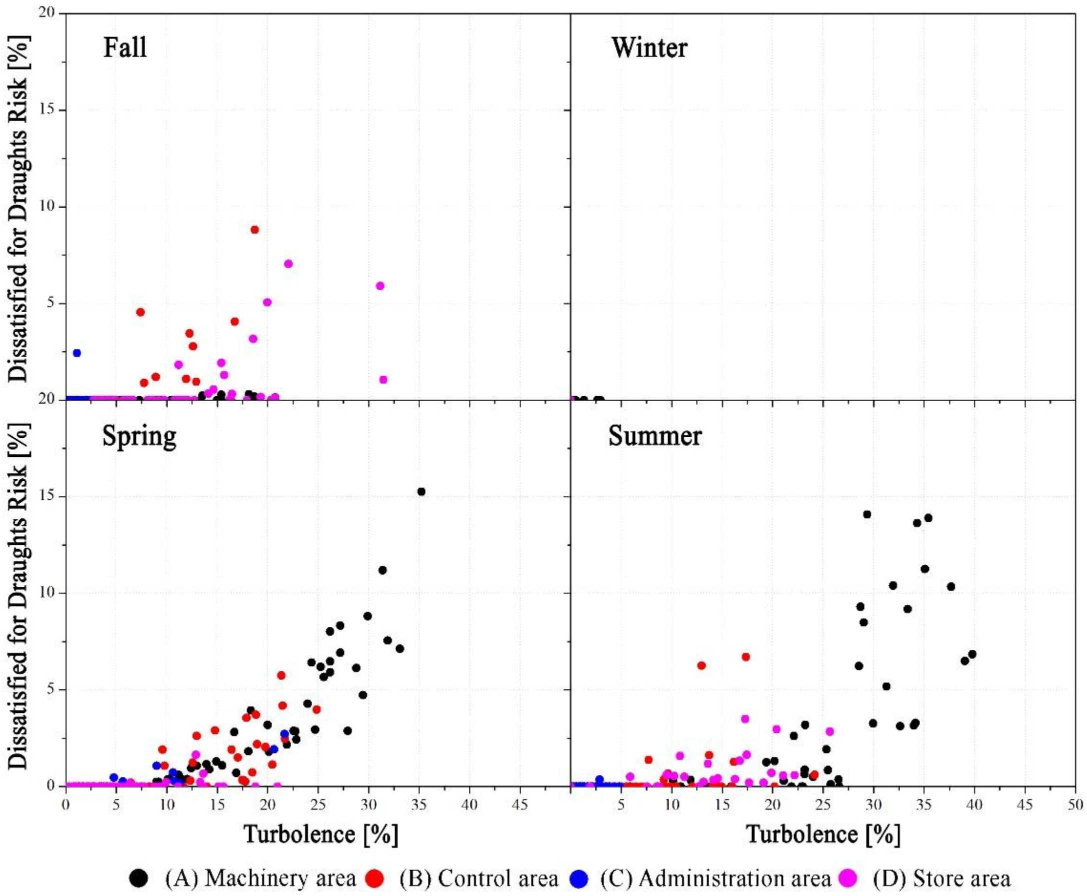

Fig. 7. PPD due to the streams risks for air turbulence in the different monitored areas over the year.

5.3. **Visual comfort analysis**

The UNI EN 12464 standard provides guidelines on the level of illumination to be guaranteed in indoor workplaces. Given the use of the monitored areas, the requirements for textile production have been considered while selecting the optimum targets to achieve. Figure 8 shows the average hourly illuminance level over the work plane recorded during working hours (08:00 a.m. - 6:00 p.m.) as the combination of daylight and artificial light reaching employees' work-places, in the different seasons for each working area. The reported values refer to the entire monitored week in order to provide an indication of the average value and the dispersion of light. Among the whole recorded dataset, extremely high values were collected in buildings C and D during winter and fall, i.e. up to 3200 lux, and were not considered as representative of real conditions. Such values are probably imputable to differential sensor location, i.e. luxmeter too close to the glazed façade and reached by direct solar radiation (building C, autumn), and are not going to be considered in the following analysis. The lighting system consists of ceiling tubes and specific lamps for each work station, located only in buildings A and B.

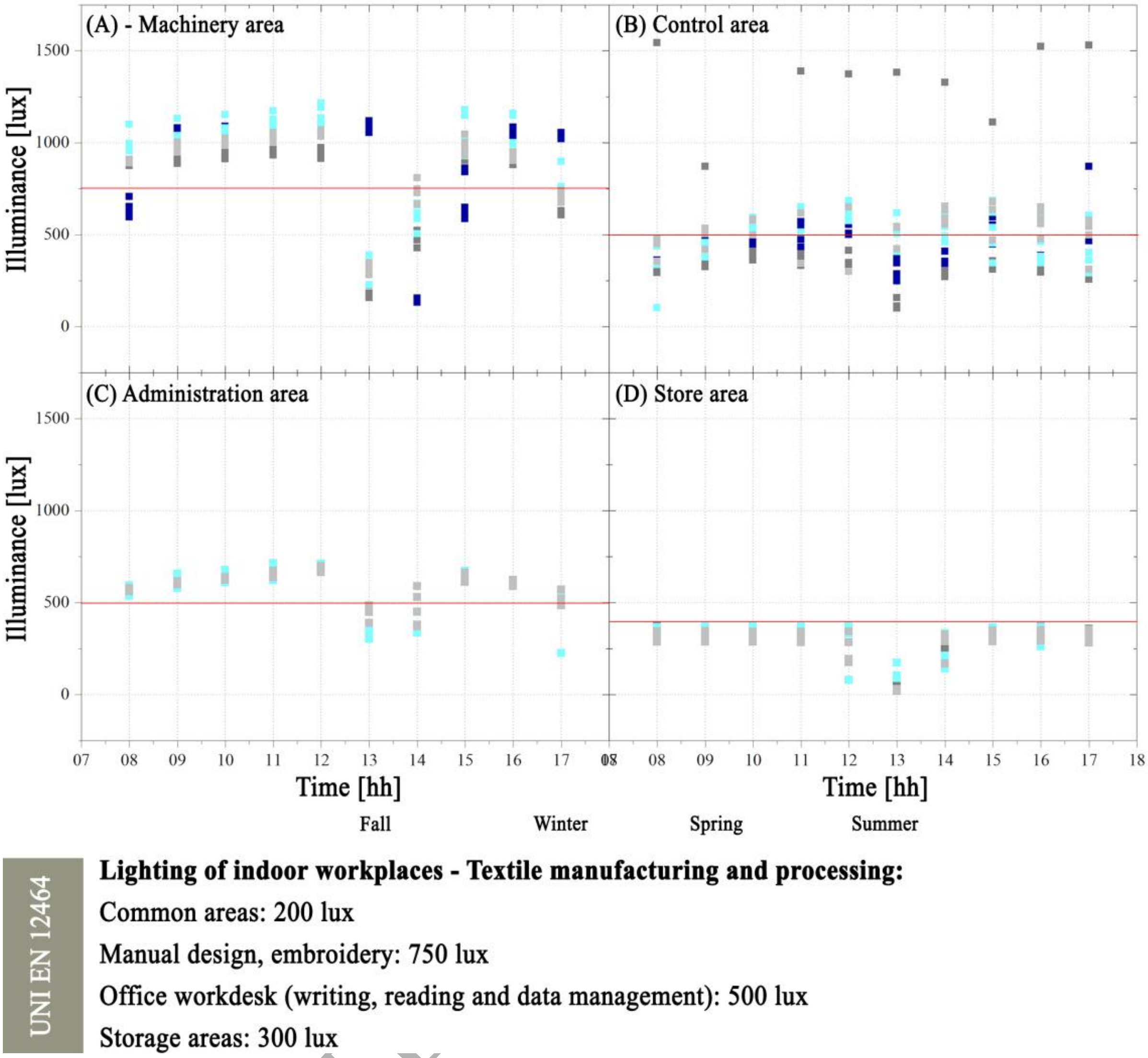

Fig. 8. Average lighting distribution over the work plane in all the areas during the monitored season with respect to the standard limits.

The minimum level of lighting recommended by the standard for the fulfillment of different visual tasks was generally respected in all the monitored environments. More specifically, in building A, where a precision activity dealing with sewing machines is carried out by the employees, the average illuminance level recorded during the working week was always over 750 lx (i.e. 897 lx in autumn, 779 lx in winter, 924 lx in spring, and 866 lx in summer). As for buildings B (control area) and C (administration), the minimum limit was 500 lx (with reference to writing, reading and data processing activities). While such limit was met in the administration area, where the average lighting levels were 569 lx and 582 lx in spring and summer, respectively, a slightly low illuminance was recorded in the control area. During spring, the minimum average hourly peak was detected to be 97 lx and the weekly average value is 453 lx. Finally, in the warehouse area, the weekly average values were slightly below the reference value of 300 lx, i.e. 299 lx in spring and 274 lx in summer. Nevertheless, in this storage area, the visual task can be considered as not so demanding, therefore the detected lighting level was consistent to the limits imposed by the current standards. Table 4 shows the average seasonal lighting levels recorded in all the case study areas.

Table 4. Average illuminance level in the different areas for each season.

Monitored areas	Average lighting level [lux]			
	Autumn	Winter	Spring	Summer
Machinery area (Ed A)	897	779	924	866
Control area (Ed B)	**458**	509	**453**	548
Administration area (Ed C)	-	-	569	582
Storehouse (Ed D)	-	303	**299**	**274**
Canteen	**171**	**118**	**164**	**187**

***Lower than the standard requirements for the visual task mainly performed in each monitored working area**

5.4. **Indoor air quality assessment**

Figure 9 shows the hourly average values of CO_2 and VOCs recorded during the monitored working weeks in such a way to provide average values and dispersions within a typical day for each season and working area.

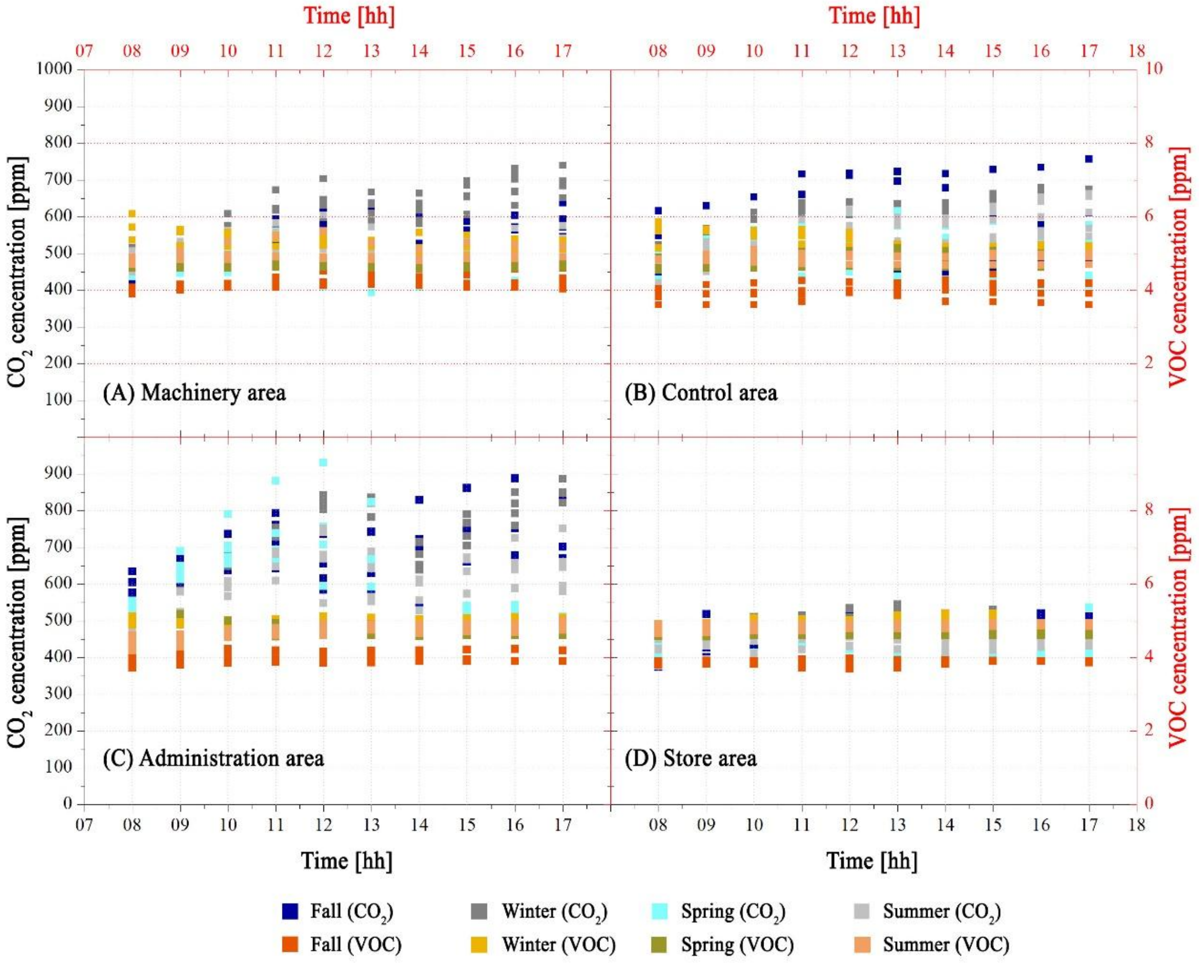

Fig. 9. Hourly average CO_2 and VOC concentration in the working hours (08:00 a.m. – 6:00 p.m.) in the four monitored working areas over the year.

The gas concentrations within each monitored environment did not differ during the course of the seasonal variation. The VOC concentration is linked to the specific monitored environment, and it is therefore almost constant during the working day, while the CO_2 level depends on the occupancy schedule. Table 5 shows the average VOC recorded during the monitored weeks, the maximum CO_2 peak and the time when it occurred.

Table 5. Weekly average VOC concentration and maximum CO_2 concentration for each area and each monitored season.

Monitored area	Ave VOC [ppm]				Max CO_2 [ppm]/[hh:24]			
	A	I	P	E	A	I	P	E
Machinery area (A)	4.23	5.19	4.70	5.00	637/17:24	740/17:24	560/12:24	449/08:24
Control area (B)	3.98	5.28	4.85	4.89	757/17:24	680/16:24	617/13:24	662/17:24
Administration area (C)	3.99	4.96	4.64	4.72	888/16:24	887/17:24	930/12:24	751/17:24
Storehouse (D)	3.88	4.95	4.62	4.88	521/16:24	544/13:24	537/17:24	480/12:24
Canteen	-	-	-	-	**1535**/14:24	**1040**/14:24	-	-

A: Autumn I: Winter P: Spring E: Summer

The maximum limits recommended by the available international standards are widely respected within the monitored working areas. In fact, the maximum concentration of VOCs was detected in the control area (i.e. Building B) and corresponded to 5.28 ppm (i.e. <10 ppm). As for the peak CO_2 concentration, this occurred in the administration area and was equal to 930 ppm (i.e. <1000 ppm suggested by the regulations). By focusing on the company cafeteria, concentration values above the standards limits were detected only around 2:00 p.m. This was directly attributable to the fact that such area has a reduced volume compared to the others, but hosts typically a greater number of occupants during the hours of use (between 1:00 p.m. and 3:00 p.m.). Figure 10 shows the trend over time of the CO_2 concentration recorded in autumn and winter. In particular, the graphs in Figure 10a, c show the single values collected every 10 minutes by the monitoring station, for two typical working days. Clearly, these graphs show the rapid increase of CO_2 concentration rate associated to employees' presence in the area. Figure 10b, d shows the averages values in time collected during two weeks of continuous monitoring. In this case, the two closing days of the building (i.e. Saturday and Sunday), when the CO_2 concentration was further reduced due to the prolonged absence of occupants, can be highlighted. Therefore, the minimum values reached in those two closing days represent the CO_2 basic level in the environment (i.e. 404.9 ppm in autumn and 379.6 ppm in winter) without any occupancy.

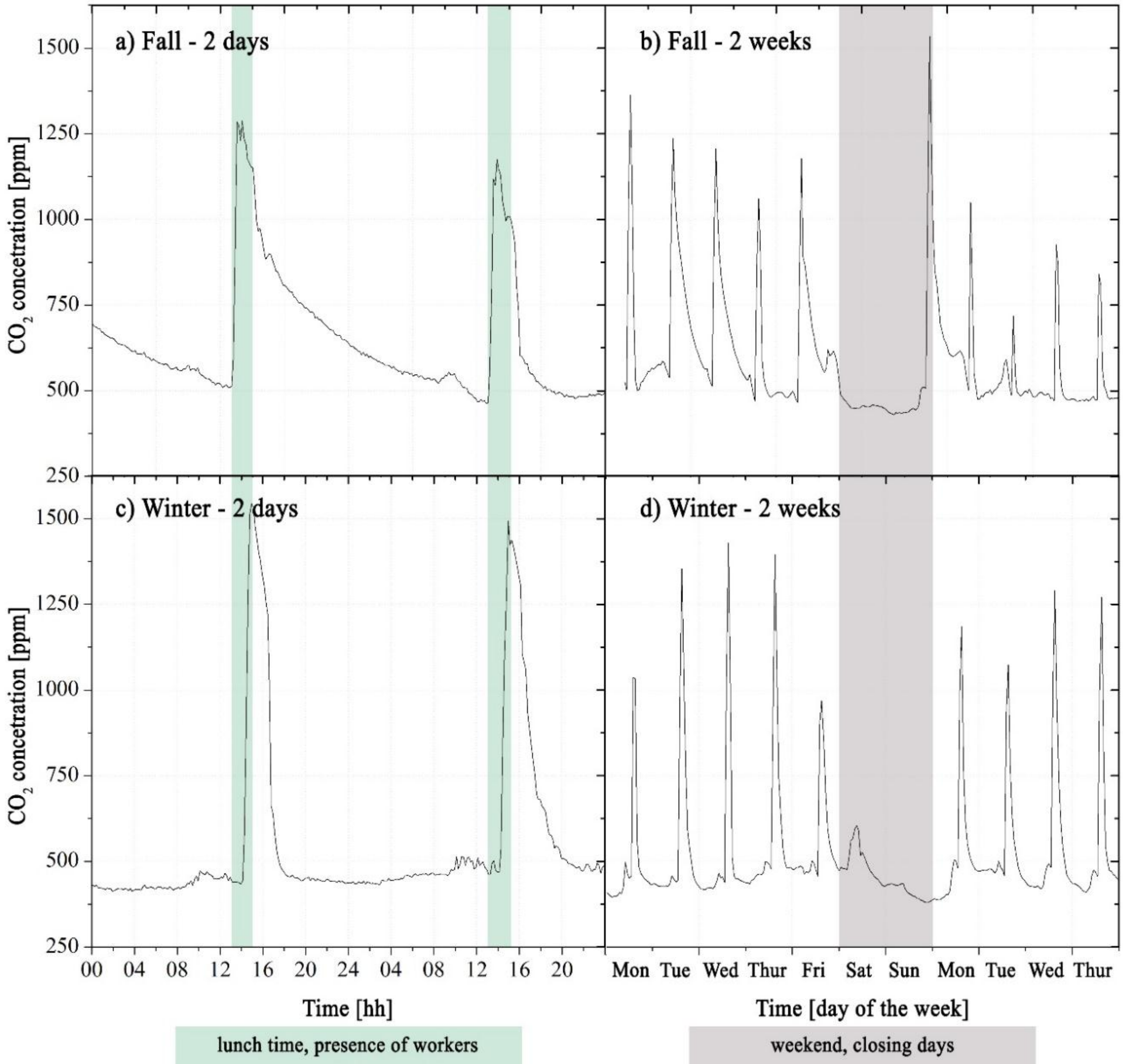

Fig. 10. CO_2 concentration in the canteen during autumn and winter: single values in two working days (a, c) and average hourly value during two consecutive weeks (b, d).

Lastly, the monitoring campaign of air quality indicators confirmed the total absence of CO (carbon monoxide) which is highly dangerous for human health.

5.5. **Impact of non-physical parameters: questionnaire survey**

Previous sections dealt with environmental monitoring of the physical parameters and the assessment of comfort conditions by means of physical parameters influencing occupants in the case study factory. In this section, a wide questionnaire survey is described to evaluate comfort conditions as directly sensed by interviewees. The results of the questionnaire campaign were then compared to the results of the microclimate monitoring performed and the

comfort indexes calculated (i.e. PMV, PPD) throughout physical parameters measurements, with the purpose of investigating the impact of non-measurable parameters on the indoor comfort of the occupants. Differences in the comparison would then evidence the impact of non-physical (non-measurable) parameters on occupants' comfort conditions. Moreover, a comparison of the results obtained in the different seasons was also carried out. Such comparison showed a non-negligible difference in the number of participants within different seasons, almost 150 workers submitted their responses in autumn (the first analyzed period), and only 75 in winter, spring and summer.
Interviewees' working habits, work-place characteristics and perceptions are described in the following sub-sections and finally the comparison with results of the monitoring campaign is presented.

5.6. **Description of the sample composition**

With respect to the considered sample, the age of respondents varies between 18 and 68 years old, with an average interviewees' age of 40.7 years. However, most of the workers were between 26 and 33 years old and 45.8% of them are between 26 and 33 years old. 50.5% of the workers is represented by traditional employees, while 22.8% corresponds to storehouse managers, 12.8% concerns warehouse workers, and 5% is apprentices and models. In Figure 11 separate seasons sample composition is taken into account. It can be noticed that the majority of the workers are women during fall, while during the other seasons there is almost an equal proportion in gender. Moreover, the education level achieved by employees is mainly high school diploma. The clear majority of the employees worked in the company for more than three years. Considering the results of the whole year, 89.5% of the interviewed employees had previous working experience; 70.3% of respondents has been working in the company for more than three years, while 22.9% has been working there for 1-3 years. Only 6.8% has been employed for less than one year.

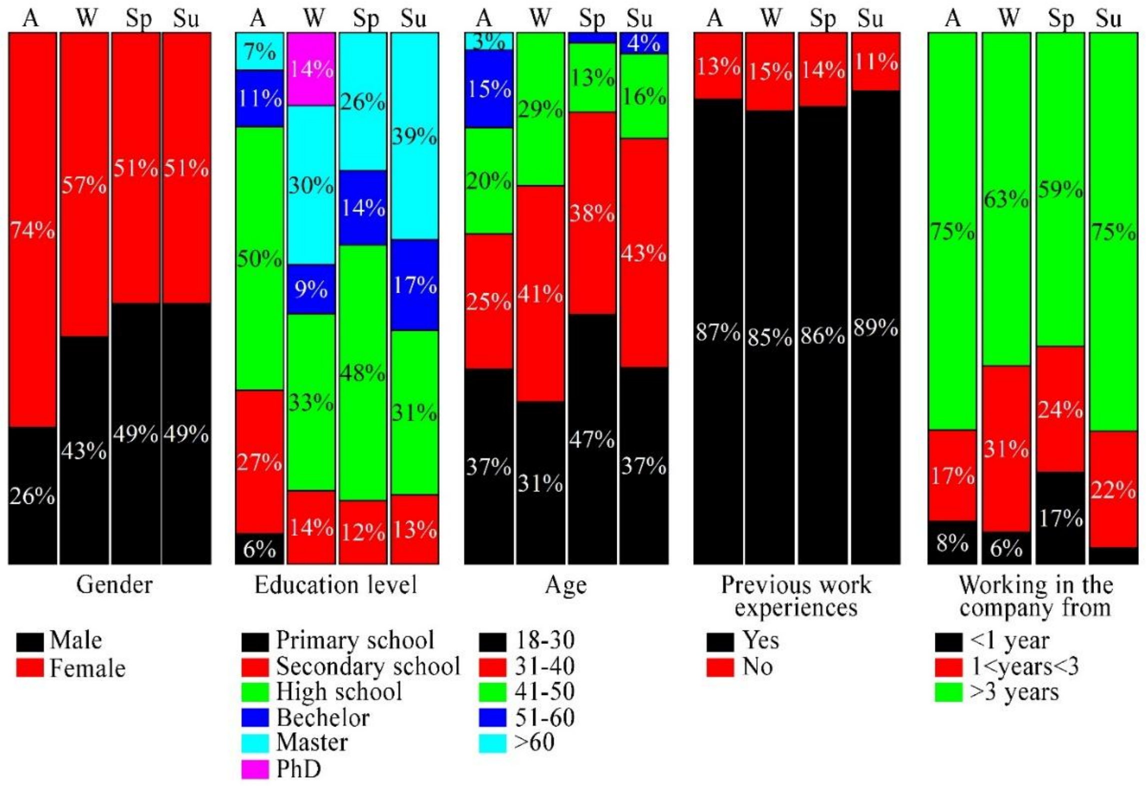

Fig. 11. Sample composition during autumn (A), winter (W), spring (Sp), and summer (Su) questionnaires' campaigns.

5.7. **Analysis of the working habits and workplaces**

By considering the working habits of the employees (Figure 12), almost all the participants work every day from 8:00 a.m. to 5:30 p.m., with a 1.5 hour break, which is mostly spent in the company cafeteria (54.1%), at home (29.0%), and in pub/restaurants (14.4%), at the gym (1.4%). Most of the workers participating to the questionnaire work in environments with more than four workstations, i.e. "open space" (84.5%). Most of the respondents works in Building A (i.e. 40.5%), while only 33.6% works in building C, and 15.0% and 10.9% works in Building D and B, respectively.

As regarding their office habits, 45.4% of the participants stated that they cannot control the opening of the windows, compared to 34.9% who can and is used to open the windows sometimes when they arrive to the office. Additionally, 16.1% declares not to open windows and 3.7% always opens them. With respect to lighting control, 65.1% of the company employees does not turn on the light of their workstation compared to the 32.4% who has the possibility to control it and the remaining 2.5% that can manage lighting and declares to turn it on only occasionally. Finally, 67.6% of respondents cannot control the temperature of the workplace and 54.0% would like to be able to do so. Similar numbers were found for the ventilation control, since 64.6% of the participants cannot handle ventilation at the workplace and 50.0% would like to be able to do it.

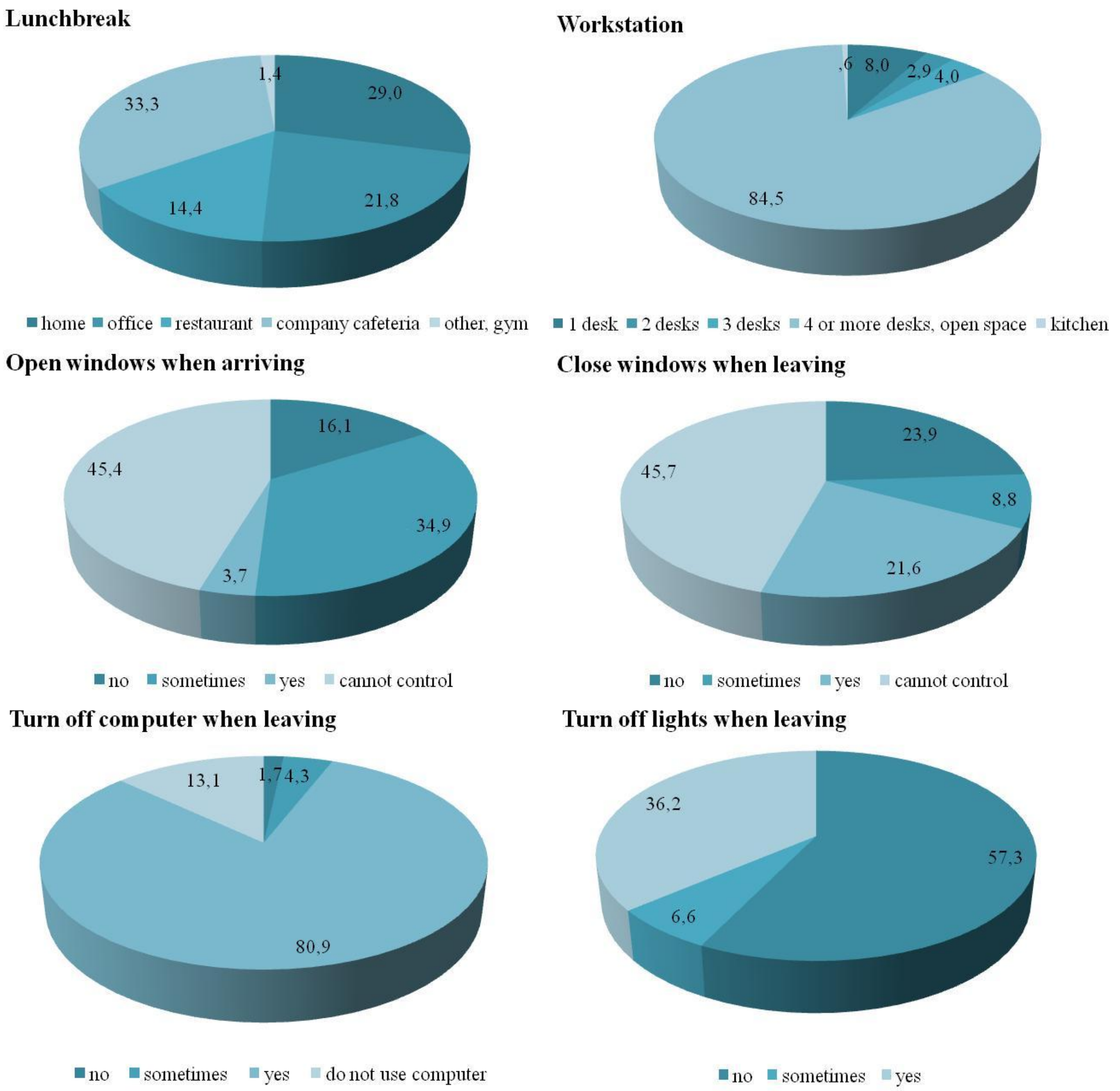

Fig. 12. Working attitudes of the respondents (%).

5.8. **Visual comfort analysis**

In this section, the results of the questionnaires concerning the visual perception of the workers in their working environment are described (Figure 13 and Figure 14). Such results include the questionnaire carried out all along the year, i.e. autumn, winter, spring, and summer. With respect to the visual comfort analysis, as already described in section 5.7, 65.1% of the company employees does not turn on the light of their workstation compared to the 32.4% who has the possibility to control it and the remaining 2.5% that can manage lighting and declares to turn it on only occasionally. Therefore, some participants could adjust the lighting environment, while others were not able to do it.

As above mentioned, the visual comfort is evaluated by considering detailed aspect of visual perception, namely visual sensation, comfort, preference, acceptability, and tolerability that are achieved by interviewees depending on the illuminance level in the work environment.

As for visual sensation, most interviewees (76.2%) declared “visual” neutrality with respect to their surrounding working environment, i.e. they did not consider it as too dark or too bright. Only a minor percentage of employees found the environment too dark (6.2%), too bright (13.0%), or absolutely too bright (4.2%). Only 0.3% of the workers defined the work space as absolutely too dark.

With respect to visual comfort, 47.9% of employees found the work environment visually comfortable and 32.7% of them defined it as visually very comfortable. Therefore, in total, 80.6% perceived the workplace as comfortable/very-comfortable. 14.4% of the company employees defined the working area as a neutral space, neither comfortable nor dis-comfortable, while only 3.9% defined it uncomfortable, and only 1.1% found it very dis-comfortable. Such data were also confirmed by the visual preference expressed about the work space: 72.3% of respondents wanted the work space exactly as it was from an illuminance level perspective; 13.6% would have preferred it less bright, 11.6% brighter and 1.7% instead would have liked to have it much less luminous, against the 0.8% who would have wanted it much brighter. Finally, considering acceptability and tolerability, while most workers found the work environment visually acceptable and tolerable, only 2.3% found the environment slightly unacceptable and 3.1% slightly intolerable.

For comparison purposes, interviewees were also asked to give their opinion in terms of visual sensation and comfort on the company cafeteria, given the high percentage of interviewees that declared to spend their lunch-break there, as by work-habits analyses. The company canteen resulted to be highly appreciate: 95.2% of the workers found the environment visually neutral, i.e. not too dark or too bright; 51.2% and 32.9% considered it visually very comfortable and comfortable, respectively. None of the employees expressed a minimum level of visual dis-comfort relative to this area of the factory. It is worth considering that the view from the cafeteria, as well as from the majority of the office areas, opens up on well-maintained outdoors, company parks with fountains and greenery.

By considering the different working environments located in all the buildings of the factory, a statistical analysis was carried out to assess whether visual comfort statistically varied with the variation of the type of office or building. Results assessed no significant difference in visual comfort in different buildings. The type of working environment, however, had an impact on the visual acceptability and visual tolerability, since both get worse as the number of workstations in the workplace increases, shifting from "absolutely acceptable / tolerable" to "quite acceptable / tolerable". When taking into account the different seasons instead, both visual sensation and preference varied throughout the seasons.

Concluding, the survey highlighted that the workers judge their working environment as globally visually "comfortable", with lower acceptability and tolerability in open working spaces than in single offices. In open offices lighting control is often impossible, while in offices with few desks it is usually possible to control illuminance level on each workstation. However, on average, respondents declared not to perceive the working area as too bright, to prefer neither brighter nor less bright, and to find it visibly acceptable and tolerable.

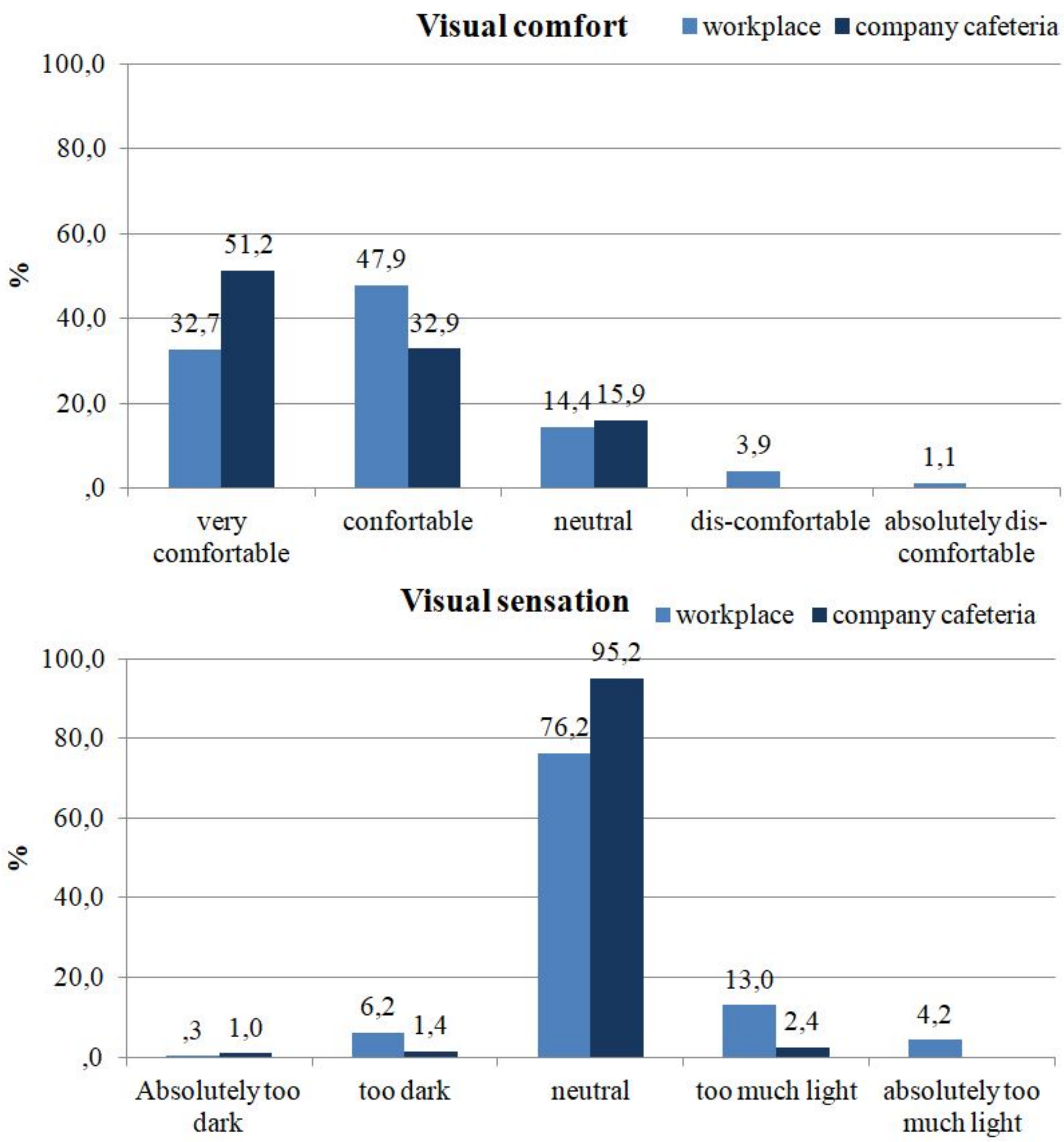

Fig. 13. Visual sensation and comfort: employees' perception.

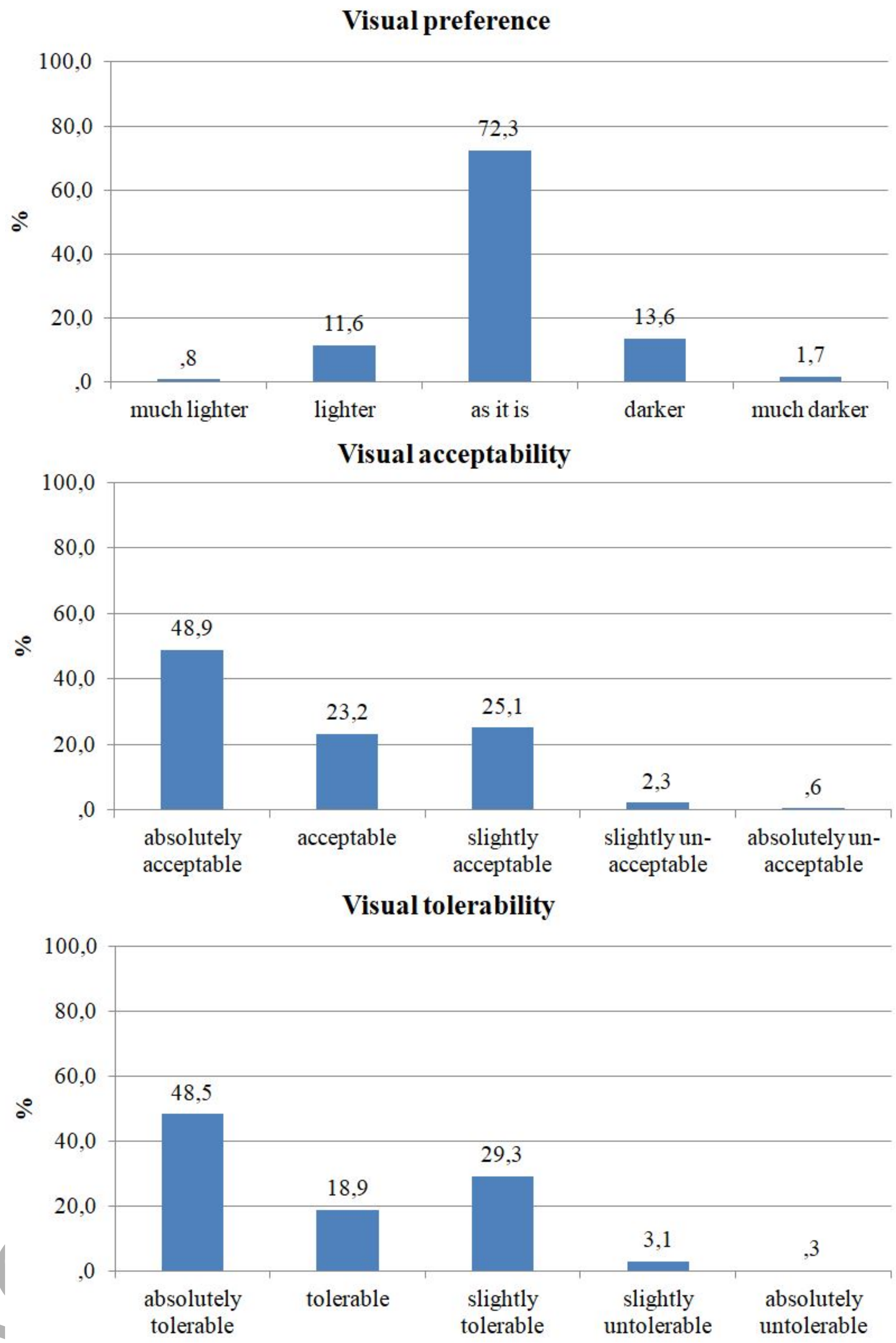

Fig. 14. Visual preference, acceptability and tolerability: employees' perception.

5.8.1. **Comparison of the different seasons results**

After the collection of the data about visual comfort throughout all the considered seasons, the season variation was analyzed (Figure 15). The collected data in terms of sensation and thermal preference were significantly different from a statistical point of view during the course of the year. The visual sensation was better in the fall, while the worst feeling (however still close to zero) was achieved in the summer. Regarding visual preference, zero corresponds to visual neutrality, positive values corresponded to preference for a lighter environment (i.e. in winter, spring and summer), while negative values corresponded to preference for darker environments (i.e. autumn result). However, visual acceptability, tolerability, and comfort were not affected by seasonal variation.

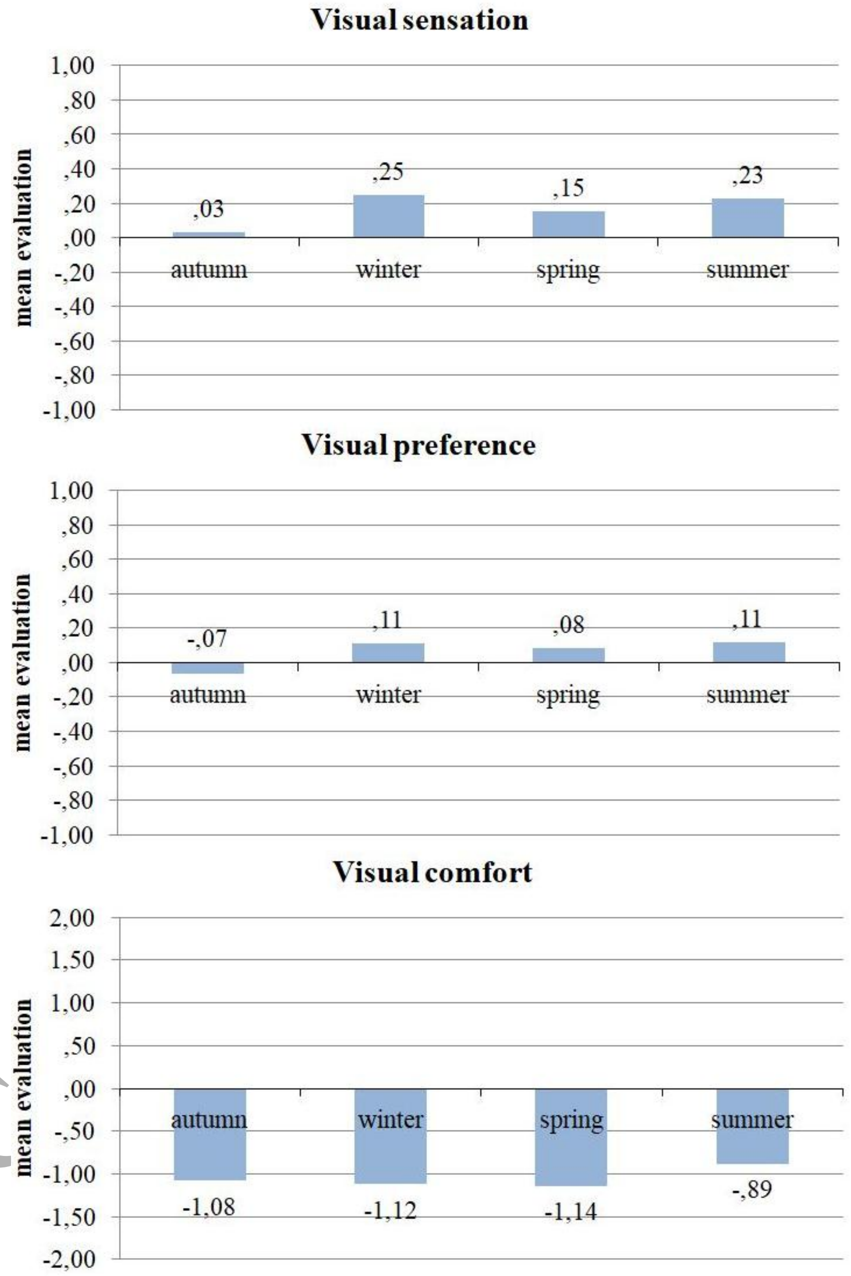

Fig. 15. Variation of visual perception with varying season during the course of the year.

5.9. **Thermal comfort analysis**

According to the visual comfort perception, the responses of the company employees in terms of thermal comfort were generally positive (Fig. 16 and Figure 17). Again, the thermal sensation, comfort, preference, acceptability, and tolerance of the workers have been considered. The majority (75.6%) of workers had a neutral feeling with respect to the working environment, while 9.8% found that the environment was a bit hot, 9.6% cool. Only 2.0% of the workers found the environment warm and the 3.1% cold. Therefore, 69.5% found the environment thermally comfortable, 22.0% found it thermally neutral. Only the 0.8% described the environment as dis-comfortable, while the 7.6% only defined it as only slightly dis-comfortable.

A further confirmation of the thermal comfort of the workers was provided by the results of the survey in terms of thermal preference: the 75.7% of workers wanted the temperature as it was, neither hotter nor cooler. The 14.4% would have preferred to have a cooler environment, the 9.3% warmer, while only the 0.6% of the participants who would have preferred a much warmer environment.

Acceptability and tolerability rates were very similar, in fact the environment was defined as absolutely acceptable and tolerable by 36.7%, acceptable from 34.7% and tolerable by 33.3% of participants, quite acceptable from 22.9% and quite tolerable by 24.3% of respondents, while only 5.1% think the environment is rather unacceptable and heat-intolerable. Only the 0.6% of the workers perceived the working space as absolutely unacceptable and thermally intolerable.

When referring to the canteen, consistently with the results in terms of visual comfort, most of the respondents said that they had a good thermal sensation when inside (i.e. 75.4%), while the 15.5% had a cool feeling and the 4.3% was hot. Consequently, the 21.6% of workers found that the canteen was very comfortable, the 38.0% defined it as comfortable and the 34.1% as thermally neutral. Only the 6.3% thought that the canteen was not comfortable from the thermal point of view.

By analyzing the thermal perception of different work environments (office type and building/work area), the thermal comfort appeared to be significantly influenced by the type of workstation: in working spaces with fewer desks the comfort was higher than in open space or environments with multiple desks. In this case, however, there were no significant differences between the various evaluated buildings. Regarding thermal sensation and thermal preference instead, the building/work area, and no longer the kind of office, generated statistically significant variations. In the case of thermal sensation, building B was perceived more "cool" than neutral. Very few differences were detected in terms of thermal preference, although the neutrality condition was reached only in building B, while the workers in buildings C, and D preferred a "cooler" environment and in the building A preferred a slightly "hotter" environment. Considering again the canteen, where many of the participants spent their lunch breaks, users' thermal sensation and comfort was considerably better than the one experienced in the offices (Fig. 16). Consistently to the results in terms of visual comfort, these results globally showed that the work environment was thermally comfortable for the workers. In fact, the latter declared to want the work environment neither hotter nor cooler. The work environment was thus thermally acceptable and tolerable.

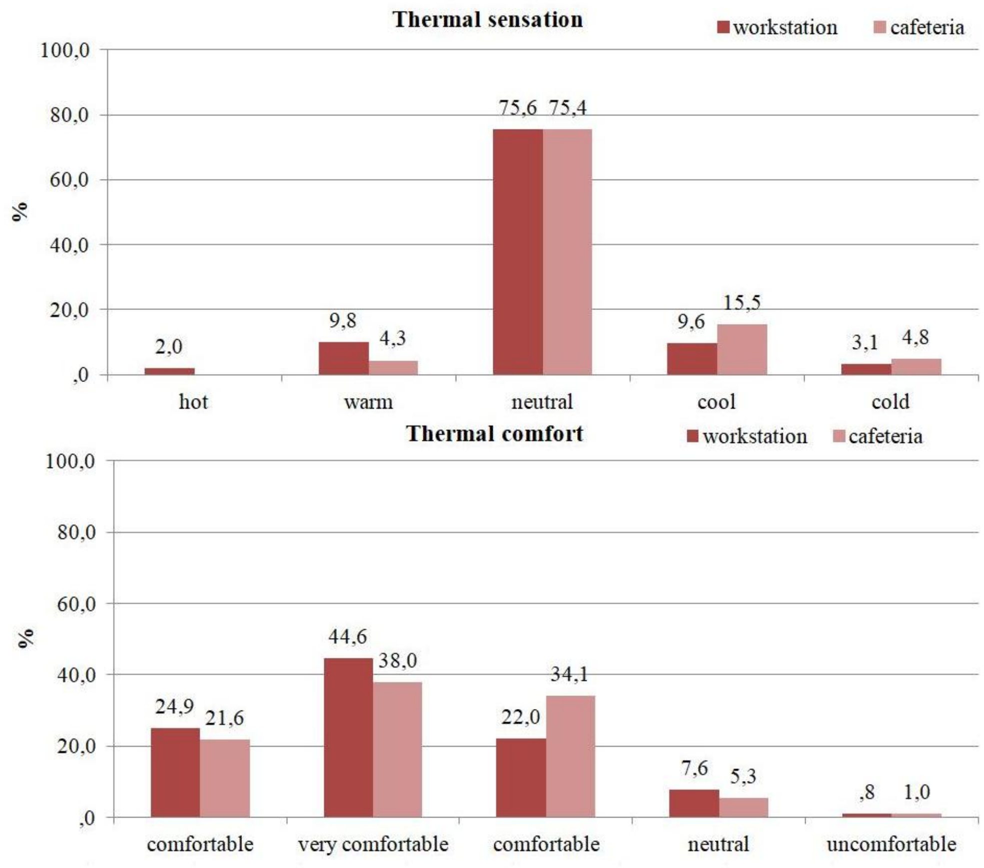

Fig. 16. Thermal sensation and comfort: employees' perception.

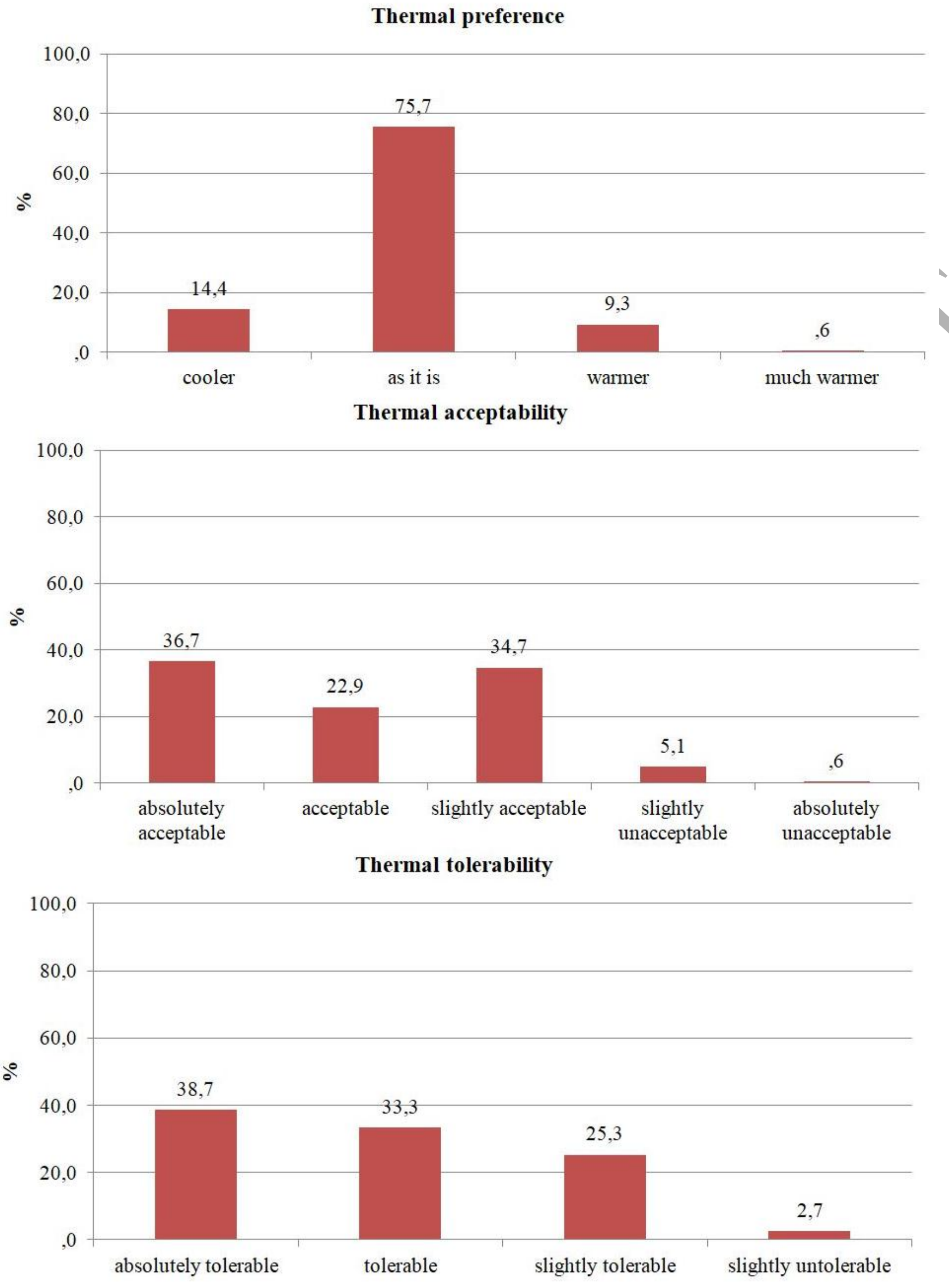

Fig. 17. Thermal preference, acceptability, tolerability; employees' perception.

5.9.1. **Comparison of the different seasons results**

Comparing the results of all the seasons, several statistically significant differences in terms of thermal comfort indicators could be detected (Fig. 18). In particular, the thermal sensation varies with seasonal changes: in autumn and winter it showed to be closer to thermal-warm neutrality, while in spring and especially in the summer it was closer to the neutral- cool condition. Thermal comfort also varied, with better conditions in autumn and winter and slightly worse conditions in spring and summer. In terms of thermal preference, participants showed a slightly higher preference for a cooler environment in autumn and winter. On the contrary, in summer they would have preferred a slightly warmer environment, while in the spring they liked it as it was.

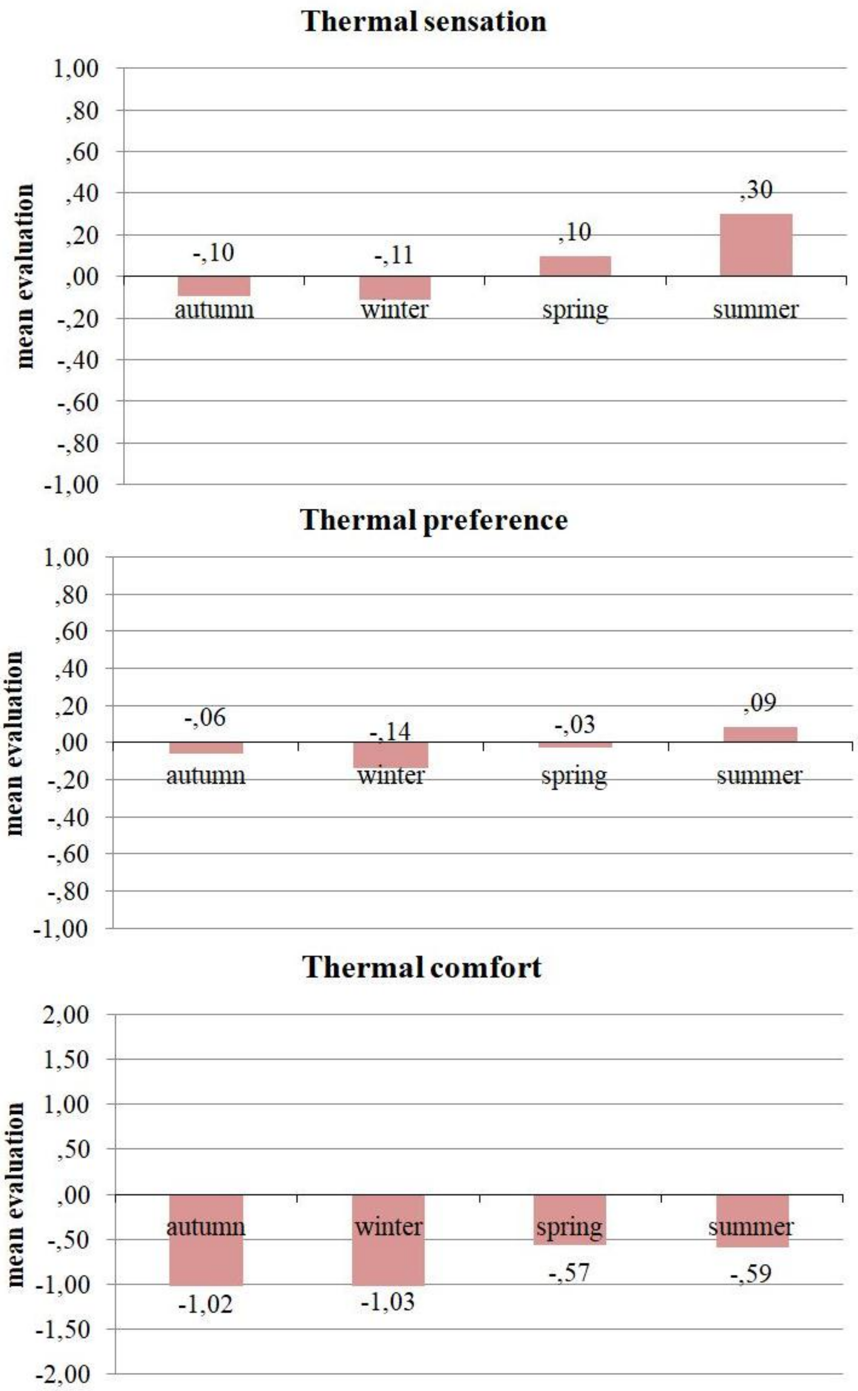

Fig. 18. Variation of thermal perception with varying season during the course of the year.

5.10. **Acoustic comfort survey analysis**

In this section, the acoustic comfort is analyzed according to workers' answers to the questionnaire (Figure 19). Even if no acoustic field measurements were carried out in this study, the survey answers were collected and analyzed in order to consistently assess the whole comfort perception of the workers. Give the large variability of their working attitudes and duties, acoustic behavior would have been too much influenced by specific conditions of each working area, and not only by the company policies aimed at improving working wellbeing. This additional information could also add interesting insights in the view of considering a global comfort sensation. The acoustic sensation, comfort, and preference of each work area and of the canteen is taken into account. According to the survey, 75.9% of the respondents believed that the sound level of their workstation was totally acceptable, while 20.0% had the feeling that there is too much noise and 2.8% absolutely too much noise. Only 0.7% thought that the work space is too much and too silent. Moreover, 86.2% of the workers believed that their workplace was acoustically comfortable, while 11.7% found it uncomfortable and 2.1% thought it was very dis-comfortable. As a result, while 61.4% of the participants wanted the acoustic level to remain as it was, 33.8% wanted it quieter and 4.8% much quieter. As for the company canteen, 71.1% believed that the sound level was adequate and 86.8% thinks it was comfortable, while only 13.2% defines it as "dis-comfortable".

By analyzing the acoustic perception, the effect of the different working environments is evident. However, results were always around neutrality, demonstrating that the work environment was generally seen as comfortable from the acoustic perspective. The worse areas in terms of acoustic perception were the ones where employees' concentration has to be guaranteed even in a mixture of working activities, i.e. the computer stations within the machinery area, the mending zone within the control area, etc. These results slightly differed with respect to the acoustic comfort in general, where the same zones were perceived as "neutral", while others are defined "comfortable" or "very comfortable". Likewise, about acoustic preference, such zones would have been better preferred with more silent conditions than the present state, in employees' opinion. Differently from visual and thermal comfort, in the case of acoustic comfort, the canteen area resulted to be noisier and less comfortable according to the opinion of the respondents (Fig.).

Like visual and thermal comfort analysis, the work environment may be considered as generally comfortable for workers from an acoustic point of view.

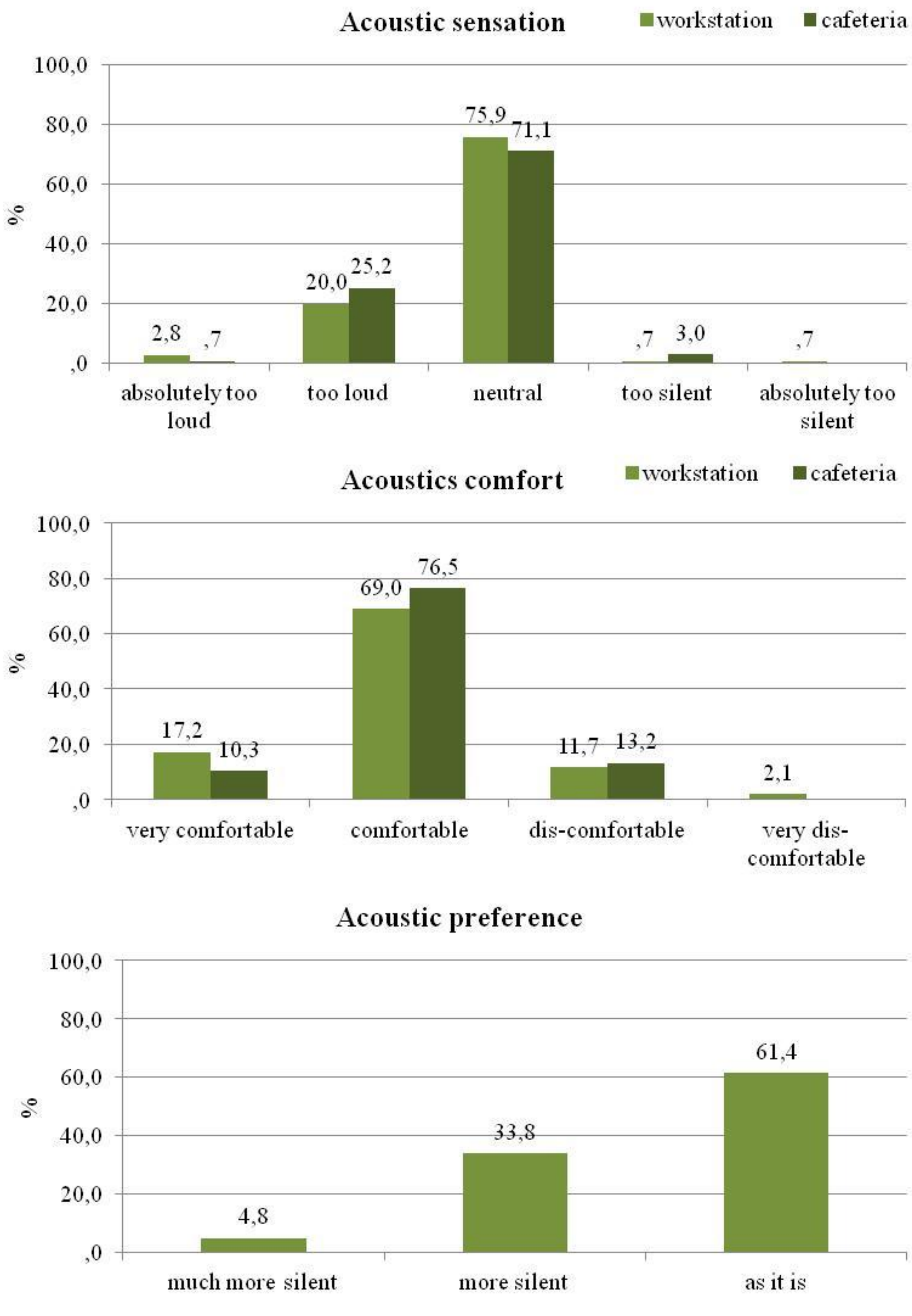

Fig. 19. Acoustic sensation, comfort, preference; employees' perception.

5.11. Impact of the working environment on the global comfort of the occupants

In this section, workers' responses are analyzed in terms of visual, thermal, acoustic and whole-comfort with respect to the (i) working environment, (ii) home environment, (iii) personal mood, (iv) health, and (v) efforts of the company to promote non-measurable strategies for improving the quality of the company working environment (Fig. 20).

According to 51.4% of respondents, visual comfort was influenced by the pleasant environment they work in, while according to the 24.0% of them, this is not true. Moreover, 24.6% did not know how to answer. Slightly different results were identified in terms of thermal comfort. In fact, in this case, 51.7% of the workers thought that thermal comfort is influenced by a pleasant surrounding environment, while the 35.7% thought that this had no effect, and 12.6% of them did not express their opinion about this.

When talking about general comfort conditions, the majority of the workers (i.e. 75.1%) believed that the work environment influenced their feeling and comfort perception, the 16.7% believed that this is not true, while the 8.2% did not know how to respond. The majority of the workers (i.e. 79.0%) also stated that the effect of the work environment on their global comfort perception was positive, while only the 4.0% declared to suffer negative effects from their working environment. The 17.0% did not know how to respond.

Likewise, 64.6% of the employees declared that the home environment can affect their overall comfort, while the 24.4% did not think that the home environment influenced their comfort condition at all. Finally, the 11.0% did not give any feedback about it. Therefore, according to the respondents, the home environment positively influenced their general comfort (82.5%), the 15.7% could not answer, and only the 1.8% declared that the home environment had a negative effect on their perception.

As for the health condition, most of the workers (71.8%) stated that this aspect affected the general comfort condition, while only the 16.8% believed that it had no effect. Finally, 11.4% of the participants did not give any feedback about this. The effect of health on workers' comfort is positively perceived by 58.4% of participants, while 28.5% of the workers did not know how to answer this question.

As concerning the influence of their personal mood, 62.2% of the respondents said that it was affected by the working environment, while 28.1% thought it had no impact. Moreover, the 9.7% did not know how to answer to this question. Therefore, the personal mood had a positive impact according to 46.6% of the respondents, while 41.8% of them did not know how to define such effect. Finally, the 11.0% thought that their personal mood negatively affects the working general comfort condition.

The vast majority of the respondents (i.e. 89%) also believed that the company had put in place effective strategies to ensure the overall well-being and comfort of its employees. The 9.6% did not know how to judge it, while only the 1.5% believed that the company had not put in place effective measures to ensure their comfort. According to the statistical analysis, these results in terms of general comfort are not significantly influenced by the type of office, building, or even season when the questionnaire was submitted.

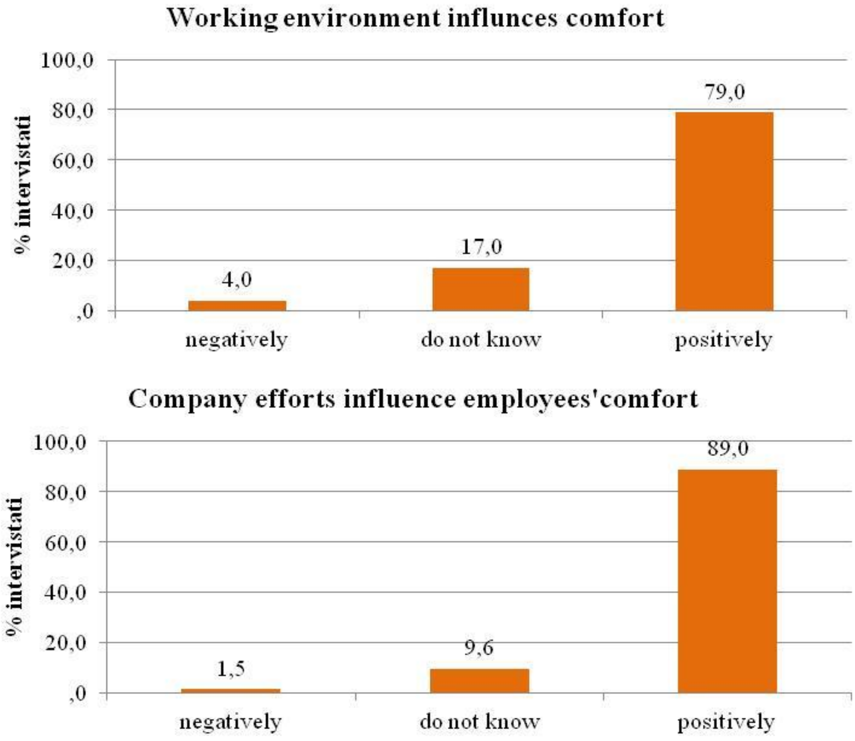

Fig. 20. Overall wellbeing conditions of employees with respect to the working environment.

From the further data analysis of questionnaires, a statistical evaluation was carried out to investigate the correlation between the different comfort perceptions: visual, thermal and acoustic one. Similar levels of comfort were assessed with respect to visual, thermal and acoustic comfort. More specifically, thermal comfort perception was significantly linked to visual comfort throughout a regression analysis ($p<0.01$). The regression model included also acoustic perception as a variable, but acoustic comfort did not significantly affect neither thermal nor visual comfort. Therefore, according to the regression model, as visual comfort increased, also thermal comfort increased consistently (Fig.).

Another interesting outcome was the relation between the perceived “wellbeing as affected by the workplace” and interviewees’ comfort sensations. In this case, throughout a regression model ($p<0.05$), visual comfort and acoustic comfort were directly related to interviewees’ wellbeing perception as positively/negatively affected by the work environment, while thermal comfort did not display significant effect on it. The model demonstrated that employees perceived that their workplace had a clear recognizable effect on their wellbeing (positive or negative effect) as acoustic and visual comfort increased or decreased. Similar results were found while asking the question related to the effect of company efforts towards employees’ wellbeing, which again resulted very well correlated ($p<0.05$) to acoustic and visual comfort, but not to thermal comfort.

These analyses could be integrated in future studies, aimed at assessing the specific correlations among sectorial comfort perceptions by interviewees.

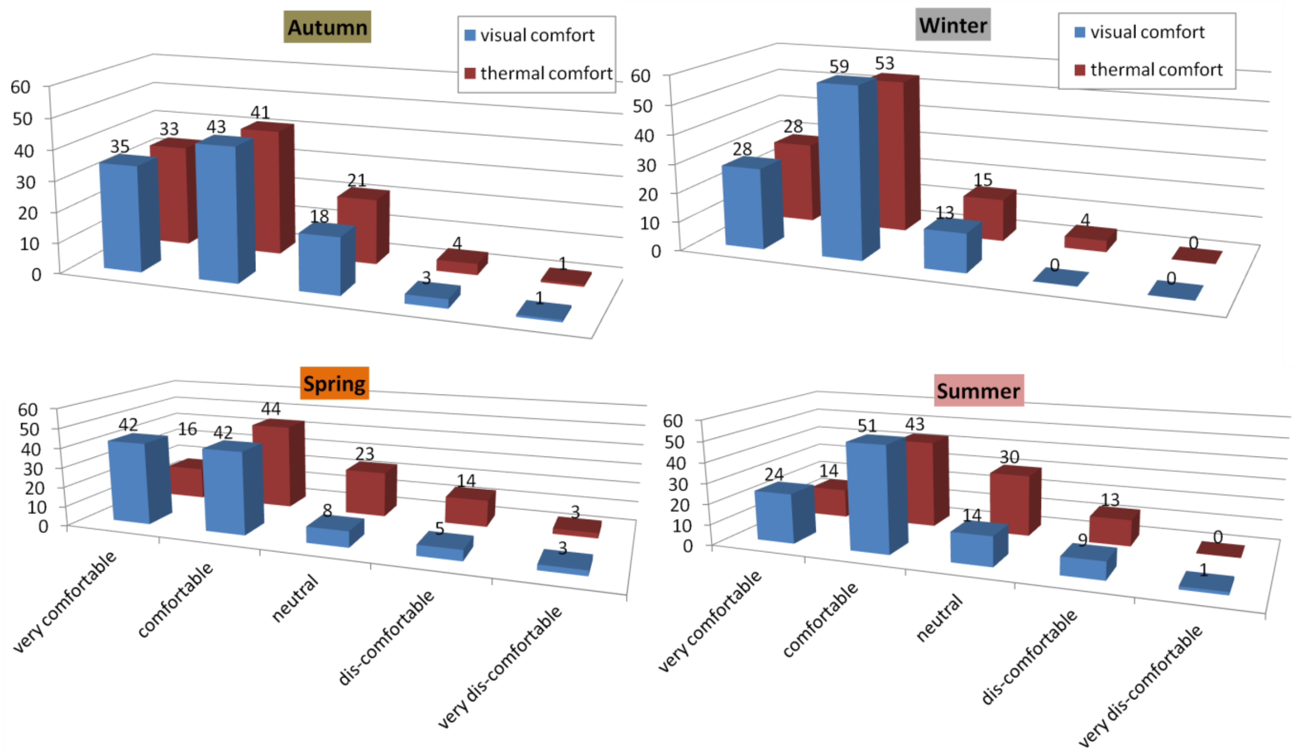

Fig. 21. Comfort levels comparison: visual and thermal comfort correlation with varying season.

5.11.1. Considerations on workplace, wellbeing and health

As highlighted in the introduction section, workplace played an important role in determining wellbeing and health of its employees. At the same time, employees' personal health conditions played an undeniable influence on their ideal comfort conditions. The influence of these personal conditions on comfort was relatively difficult to measure, but a clear role of personal variables was detected in the definition of the comfort sensation, underlining the need of a global assessment that considers not only physical, but also subjective parameters. Given this first assumption, a section about personal health conditions was included at the end of the questionnaire survey (Appendix A), after other personal information questions. Interviewees were asked about their personal health conditions, or the presence of potential dysfunctions, for example with respect to thyroid, which represents a very popular disease in the working area where the case study is located. Thyroid dysfunctions can indeed cause higher sensitivity to hot and cold microclimate conditions, since the production of the thyroid hormone T3 is important in the thermo-regulation and adaptation to cold or warm environmental conditions. Individuals affected by hypothyroidism are less tolerant within cold environments, while on the other hand people affected by hyperthyroidism are more sensitive to hot conditions. On the considered sample, 10% of the participants, i.e. around 30 interviewees, declared to experience thyroid issues. The statistical analyses however did not demonstrate any significant correlation between thermal comfort and thyroid dysfunctions. Further analyses could be conducted with a larger sample.

A similar percentage (8%) of participants declared to suffer of cervical pain. In this case, employees suffering of cervical pain were significantly more inclined to declare that the workplace environment had an effect on health and wellbeing conditions. The same comparison was not significant when the same question was asked with reference to their domestic environment.

Moreover, regression analyses on visual and thermal comfort considered as dependent variables demonstrated that each comfort sensation was influenced by the presence of migraine in the respondents, with a confidence interval of 90% (for visual comfort) and 95% (for thermal comfort). Therefore, health conditions played an important role in affecting people comfort sensations, and represented an important, additional, subjective factor to consider. Additionally, workplace was considered by many participants as an environment able to influence both health and comfort conditions, more than the domestic environment.

6. Discussion of the results

Based on the above described results, the monitoring campaign showed a generally acceptable quality of the selected working areas, consistently with the currently available standards. Therefore, a good indoor air quality was registered within all the monitored workspaces and acceptable lighting levels were observed even if relatively low values compared to suggested standards were detected in winter within the control area of building B. Nevertheless, such results were not mirrored by the questionnaire survey results, where there was no statistical significance in the visual perception evaluation between the different buildings, and a general comfortable and well perceived visual perception was assessed. With particular reference to the canteen, the monitoring campaign measured illuminance levels generally below the suggested threshold all along the year. However, by analyzing the questionnaire, the canteen achieved higher scores in visual perception with respect to workplaces and it resulted in the most visually preferred environment compared to all the others. This non-consistent observation may be imputable to the company policy of creating green, healthy and sustainable lunch breaks in the company canteen, positively affecting employees' perception.

These results showed a gap between (i) the interpretation of simply measured physical parameters, and (ii) the related index calculated based on such parameters, and (iii) the visual comfort as perceived and declared by the interviewees, by means of questionnaire surveys. This gap can be justified by hypothesizing the influence of non-physical parameters on interviewee's visual perception, such as, for example, the pleasant outside view, and the fresh, variegated, local food in the canteen. Moreover, in terms of visual comfort, other factors such as luminance, glare and the colors of the surrounding environment could influence the visual sensation of the participants.

From the thermal comfort perspective, according to the standards, the case study buildings were analyzed first by means of the Fanger model, since the areas were mechanically conditioned. However, the adaptive model was also used afterwards to have a better understanding of the impact of non-physical and non-measurable parameters, i.e. people adaptability, on the final comfort perception of the occupants, together with a dedicated questionnaire survey for comparison purposes. Therefore, comfort indexes calculated by means of both approaches were compared.

Consistently with the expectations, Fanger results were detected to be much more severe than the ones from the adaptive model. Moreover, the dis-comfort conditions highlighted by using the Fanger approach is always related to slightly warm perception (i.e. PMV > 0.5), while dis-comfort estimated through the adaptive model during the fall and summer monitored periods is due to the relatively cold operative temperature.

Such results confirm that, especially when no strong dis-comfort trends are detected as in this case (low values of OptOT_DI and PMV_DI), the analysis and interpretation of thermal comfort perception has to be carefully examined by means of methods taking into account the impact of both physical monitored parameters, people adaptation capability of people and how they are affected by other non-negligible variables. Furthermore, the submitted surveys allowed to gather data about (i) the percentage of dissatisfied people in terms of thermal sensation (PD, percentage of interviewed who judged its thermal environment very uncomfortable or uncomfortable) and (ii) the mean thermal sensation vote for each season (TSV, average of thermal sensation vote considering the five points sensation scale elaborated accordingly to ISO 10551). Such parameters were therefore compared to the PPD and PMV calculated by means of the Fanger model and averaged over all the monitored spaces. The observed gap confirms the strictness of the Fanger method already highlighted by the comparison with the adaptive approach. In particular, Fanger approach leads always to higher levels of thermal dis-comfort and the biggest discrepancy was observed in autumn when +5.9% and +0.34 of dissatisfied and mean thermal vote were detected with respect to the survey results.

6.1. **Comparative analysis of the results of the monitoring and the questionnaires**

In order to further demonstrate the validity of the data collected through (i) experimental monitoring and (ii) questionnaires, the results of both experimental campaigns were compared (Figure 22). The data obtained from the monitoring showed how the main environmental parameters generally fall within the comfort range indicated by the regulations during the whole year. However, some values outside the range were detected in Building A, B, and C during fall, winter and spring seasons, especially in terms of operating temperatures slightly above the suggested upper limit. Specifically, the Performance Index (PI) indicated that general comfort condition in Building C, and D while in Building A and B were not always detected especially during spring and summer.

As concerning the seasonal visual and thermal comfort variation, generally there was a good correlation between the monitored parameters and the results of the questionnaire. In fact, in the case of Building A, both the monitoring and the survey show a PPD (i.e. unsatisfied percentages) > 10%.

In general, the less comfortable seasons according to the questionnaire were spring and summer that showed 16.4% unsatisfied people in spring and 12.9% in summer (by considering all the evaluated work areas). Table 5 confirmed such trend, especially for Building A. These data were consistent to the results of the monitoring, as shown in Figure 22, where unsatisfied percentages exceeded 13-15%, approaching 16-13% provided by the questionnaire.

A discrepancy between the results of the monitoring campaign and the questionnaire was detected in terms of thermal comfort in Building C; therefore, according to the monitoring, this working area was characterized by comfort conditions and low PPD whereas, according to the questionnaire, a high PPD (i.e. 16.4%) is registered in all the seasons. However, in this peculiar case, a relatively minor number of participants to the questionnaire was registered, so the results may not be entirely representative.

In general, by considering all the buildings, the percentage of dissatisfied throughout the year was less than 10% according to the questionnaire, while it was slightly higher (i.e. 12%) according to the field monitoring. Moreover, by examining the trend in terms of visual comfort, the experimental monitoring measures illuminance levels below the indicated threshold defined by the regulations for the specific activities carried out in Building B both in Autumn and Spring, and in Building D during both Spring and Summer season (Fig.). Consistently, the results of the questionnaire confirmed that the most stressful conditions in terms of visual comfort were spring and summer, where the percentage of dissatisfied people, meaning those respondents that found the environment dis-comfortable or slightly dis-comfortable, was 8.1% and 10, respectively.

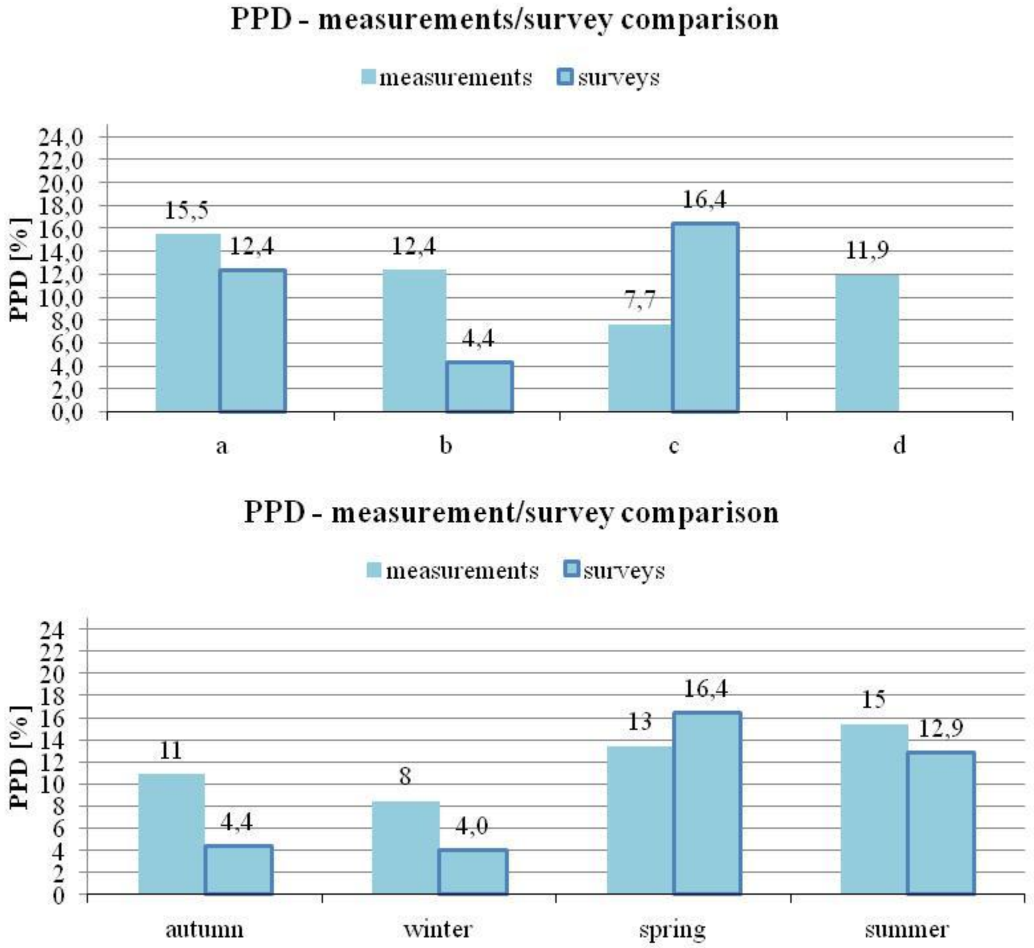

Fig. 22. Percentage of dissatisfied employees with respect to thermal sensation: monitoring and survey results comparison.

7. Conclusions

The purpose of the present research study was to investigate the indoor comfort conditions perceived by employees by means of a novel multi-physics and multi-domain approach aimed at investigating thermal, hygrometric, visual, acoustic, and air quality conditions together with a variety of personal variables such as psychological-to-social, physiological and health disease perception. The novel proposed method is implemented in a working area where a variety of tailored strategies are applied by the company management in order to make the whole environment more pleasant and to qualitatively improve the working conditions. In particular, the role of non-physical variables, which cannot be classically monitored, was investigated assuming that they played a key role in determining occupants' wellbeing perception, globally affected by personal attitudes, habits, personal behavior, health and psychological mood condition, social drivers, etc. To this aim, a combined experimental analysis integrating (i) a continuous microclimate monitoring and (ii) a dedicated questionnaire to the workers, was performed over a year in the company selected as case study. In particular, the continuous monitoring was aimed at classically assessing the physical measurable indoor microclimate conditions by gathering data regarding indoor air temperature, relative humidity, air velocity, mean radiant temperature, illuminance level, and air quality to verify the compliance of such parameters with the comfort ranges suggested by acknowledged regulations (i.e. UNI EN ISO 7726-7730). Moreover, the evaluation of the indoor thermal environment was carried out by means of both (i) the Fanger and (ii) the adaptive methodology, to identify which one of them better fits occupants' perception, which was investigated also by means of questionnaires surveys.

The questionnaires submission to the workers was useful to understand their perception, preferences, and tolerance level with respect to the different local environmental parameters and to investigate how their final and general comfort was affected by their personal attitudes, behavioral habits, personal feelings, mood and health condition, and environment policy implemented by the company management. Moreover, the survey allowed to understand how the workers perceived the strategies put in place by the company to make the environment more pleasant from an aesthetic, health and architectural point of view.

The results of such experimental campaigns were post-processed in order to understand the correlation between such different parameters, i.e. physical and personal ones, and to understand their impact on the final perceived comfort of the occupants. Based on such premises, the main results of the study can be summarized as follows:

- the classic year-long continuous monitoring showed good thermal-hygrometric, visual and air quality conditions in each of the working environment assessed according to the regulations. Therefore, no local discomfort phenomena of the occupants were detected. Nevertheless, slightly lower values of relative humidity (i.e. -10% with respect to the regulation limit) were registered in winter in every area due to the inadequate HVAC control. Additionally, a slight overheating was registered in the machinery area in summer and spring due to the major heat gain compared to the other working environments. As for the visual comfort, only in 2 buildings (Building B and D) slightly lower lighting values were detected over the work plan in fall and spring. Finally, by focusing on the air quality, CO_2 e VOC values were always within the regulation ranges except for the canteen, where peaks up to 1000 ppm were detected. This is due to the huge occupancy level and reduced volume of this area compared to the other monitored ones.
- the evaluation of the indoor thermal environment by means of both the Fanger and the adaptive methodology was summarized through the calculation of three indexes, i.e. PI, SI, and DI. A general comfort condition is detected by means of both the approaches. Nevertheless, the adaptive methodology depicted a more comfortable environment with a calculated maximum DI of 0.17 with respect to the maximum DI obtained through the Fanger methodology equal to 0.81.
- responses of the workers to the questionnaires highlighted that most of the occupants work in open spaces, therefore they cannot manage the indoor microclimate controls. However, workers declared to be more than satisfied within their working environment from a thermal, visual, acoustic point of view. Moreover, 79% of them thought that the pleasant working environment designed by the company has a positive impact on their

final and overall comfort perception. Additionally, 89% of them thought also that the strategies put in place by the company to make the workers feeling better at work have a positive influence on their comfort perception.

- the global perception of the working environment is more than positive from the thermal, visual, acoustic, and air quality perspective, and a consistent correlation between the monitoring and the survey can be detected. In particular, the PPD (unsatisfied people percentage) resulted to be ~10% according to the monitoring and 12.4% from the survey. Finally, the lower comfortable seasons were found to be spring and summer from both the methods. The only discrepancy between the results of the monitoring and questionnaire was detected in the case of Building C, which is the one occupied by people who are more sensitive with respect to the local environmental conditions since they perform the most stationary activity, i.e. the administrative role of the company.

Therefore, this research demonstrated that non-measurable factors such as the psychological ones arisen from company policy implementation, are able to positively influence occupants' general comfort perception even if the majority of workers do not have the opportunity to control their working environment from the thermal point of view and do not have the possibility to manage the opening/closing of windows/doors which are generally considered conditions influencing the perception in a negative way. Therefore, the discrepancy detected between the comfort level obtained from the monitoring campaign and from the surveys could be attributable to the company policy to realize a pleasant aesthetics of the workplace, to keep the outdoors visible from all the work spaces, to implement green policies and healthy diet, as it was recognized by more than the 80% of the interviewed. This demonstrates that a pleasant and likable architectural working environment and other personal-social forcing can contribute to the increase workers satisfactions and, potentially, their productivity.

This paper opened the doors to further possible energy saving strategies based on non-physical solutions that may positively influence employees to better adapt their thermal expectation in a pleasant working environment, which potentially motivates their increase in satisfaction and tolerability.

Future work will focus on the analysis of the effect of a pleasant and high-quality working environment in terms of employees' productivity, by quantifying also the potential economic benefits achievable by the company by means of this strategy implementation. The idea would be to identify the correlation between the comfort perceived by the workers and the quality of their work, and to understand to what extent the strategies put in place by the company for improving the indoor environmental quality can influence it.

Appendix A

Questionnaire survey

Section	#	Questions*
Working habits, workplace	1	How long do you stay at work, on a typical working day?
	2	Do you go to work every day? If not, how many days do you go to work?
	4	Which are your working hours in a typical working day?
	5	Where do you have your meals? And how long is it your meal-time?
	7	How many working positions are in your office/workplace?
	8	In which building are you working?
	13	Which is your office exposition with respect to the cardinal points?
	14	Do you usually work with the desk light turned on?
	15	Do you usually turn off the light when you leave the office?
	16	Do you usually work with your door open?
	17	Do you usually work with your window open?
	18	Do you usually open the window when you arrive at work?
	19	Do you usually close the window when you leave?
	20	Do you usually turn off the computer when you leave?
	21	Do you usually control the temperature of your workplace/office with respect to cooling or heating?
	22	If yes, which are the set-point temperatures that you use?
	23	If not, would you like to control the temperature in your office/workplace?
	24	Do you usually control the mechanical ventilation of your office/workplace?
	25	If not, would you like to control the ventilation in your office/workplace?
	26	Do you usually turn on the cooling during summer? Which is the set-point?
	28	If not, would you like to turn on the cooling according to your preferences?
Visual comfort	29	Which is your ideal lighting level on your desk?
	30	Which is your visual sensation now?
	31	Which is your visual comfort now?
	32	How would you prefer this environment now, in terms of visual preference?
	33	In your opinion, this environment is visually… (adaptability)
	34	In your opinion, this environment is visually… (tolerability)
	35	Which is your visual sensation in the company canteen?
	36	Which is your visual comfort in the company canteen?
Acoustic comfort	37	Which is your ideal value of noise in your office/workplace?
	38	Which is your acoustic sensation now?
	39	Which is your acoustic comfort now?
	40	How would you prefer this environment now, in terms of acoustic preference?
	41	Which is your acoustic sensation in the company canteen?

	42	Which is your acoustic comfort in the company canteen?
Thermal comfort	43	Which is your summer ideal comfort temperature?
	44	Which is your winter ideal comfort temperature?
	45	Which is your thermal sensation now?
	46	Which is your thermal comfort now?
	47	How would you prefer this environment now, in terms of thermal preference?
	48	In your opinion, this environment is thermally… (adaptability)
	49	In your opinion, this environment is thermally… (tolerability)
	50	Which is your thermal sensation in the company canteen?
	51	Which is your thermal comfort in the company canteen?
General comfort	52	Do you think that your visual sensation is influenced by your surroundings at work?
	53	Do you think that your acoustic sensation is influenced by your surroundings at work?
	54	Do you think that your thermal sensation is influenced by your surroundings at work?
	55	Do you think that your general comfort sensation is influenced by your surroundings at work?
	56	If yes, how do you think your workplace influences it?
	57	Do you think that your general comfort sensation is influenced by your surroundings at home?
	58	If yes, how do you think your home environment influences it?
	59	Do you think that your general comfort sensation is influenced by your general/specific health conditions?
	60	If yes, how do you think your health conditions influences it?
	61	Do you think that your general comfort sensation is influenced by your mood?
	62	If yes, how do you think your mood influences it?
	63	Do you think that the company adopted effective strategies to improve your general comfort sensation?
Personal information	65	Did you have previous working experiences in other companies?
	66	How long have you been working in the present company?
	67	Which is your age?
	68	Which is your gender?
	69	Which is your education level?
	70	Which is your role in the company?
	71	Do you use contact lenses?
	73	Do you use eye-glasses?
	75	What is your eyes color?
	76	Do you have any health issue with your eyes?
	78	Do you have any health issue?
	80	How are you dressed now?
	81	Do you have any thyroid dysfunction? If yes, which one?
	82	Do you have any rachis dysfunction? If yes, which one?
	83	Did you have cervical pain? If yes, how often and how long?

	84	Do you often have migraine? If yes, how often and how long?
	85	Did you have dorsal pain? If yes, how often and how long?
	86	Did you have lumbosacral pain? If yes, how often and how long?

*translated from Italian

References

1. Salata, F.; Golasi, I.; Proietti, R.; de Lieto Vollaro, A. Implications of climate and outdoor thermal comfort on tourism: the case of Italy. *Int. J. Biometeorol.* **2017**, doi:10.1007/s00484-017-1430-1.
2. Nikolopoulou, M.; Lykoudis, S. Thermal comfort in outdoor urban spaces: Analysis across different European countries. *Build. Environ.* **2006**, *41*, 1455–1470, doi:10.1016/j.buildenv.2005.05.031.
3. Rosso, F.; Pisello, A. L.; Cotana, F.; Ferrero, M. On the thermal and visual pedestrians' perception about cool natural stones for urban paving: A field survey in summer conditions. *Build. Environ.* **2016**, *107*, doi:10.1016/j.buildenv.2016.07.028.
4. Allesina, G.; Mussatti, E.; Ferrari, F.; Muscio, A. A calibration methodology for building dynamic models based on data collected through survey and billings. *Energy Build.* **2018**, *158*, 406–416, doi:10.1016/j.enbuild.2017.09.089.
5. Healy, J. D.; Clinch, J. P. Fuel poverty, thermal comfort and occupancy: results of a national household-survey in Ireland. *Appl. Energy* **2002**, *73*, 329–343, doi:10.1016/S0306-2619(02)00115-0.
6. Haghighat, F.; Donnini, G. Impact of psycho-social factors on perception of the indoor air environment studies in 12 office buildings. *Build. Environ.* **1999**, *34*, 479–503, doi:10.1016/S0360-1323(98)00034-1.
7. Al horr, Y.; Arif, M.; Katafygiotou, M.; Mazroei, A.; Kaushik, A.; Elsarrag, E. Impact of indoor environmental quality on occupant well-being and comfort: A review of the literature. *Int. J. Sustain. Built Environ.* **2016**, *5*, 1–11, doi:10.1016/j.ijsbe.2016.03.006.
8. Pisello, A. L.; Rosso, F.; Castaldo, V. L.; Piselli, C.; Fabiani, C.; Ferrero, M.; Cotana, F. The Role of People Educational Background on their Vulnerability to Urban Overheating. In *4th International Conference on Countermeasures to Urban Heat Island, 30-31 May and 1 June 2016, National University of Singapore, Singapore*; National University of Singapore, Singapore, 2016.
9. Salata, F.; Golasi, I.; Petitti, D.; de Lieto Vollaro, E.; Coppi, M.; de Lieto Vollaro, A. Relating microclimate, human thermal comfort and health during heat waves: An analysis of heat island mitigation strategies through a case study in an urban outdoor environment. *Sustain. Cities Soc.* **2017**, *30*, doi:10.1016/j.scs.2017.01.006.
10. Ward, K.; Lauf, S.; Kleinschmit, B.; Endlicher, W. Heat waves and urban heat islands in Europe: A review of relevant drivers. *Sci. Total Environ.* **2016**, *569–570*, 527–539, doi:10.1016/j.scitotenv.2016.06.119.
11. Al Horr, Y.; Arif, M.; Kaushik, A.; Mazroei, A.; Katafygiotou, M.; Elsarrag, E. Occupant productivity and office indoor environment quality: A review of the literature. *Build. Environ.* **2016**, *105*, 369–389, doi:10.1016/j.buildenv.2016.06.001.
12. Lan, L.; Wargocki, P.; Lian, Z. Quantitative measurement of productivity loss due to thermal discomfort. *Energy Build.* **2011**, *43*, 1057–1062, doi:10.1016/j.enbuild.2010.09.001.
13. Akimoto, T.; Tanabe, S. ichi; Yanai, T.; Sasaki, M. Thermal comfort and productivity - Evaluation of workplace environment in a task conditioned office. *Build. Environ.* **2010**, *45*, 45–50, doi:10.1016/j.buildenv.2009.06.022.
14. Fisk, W. J.; Rosenfeld, A. H. Estimates of Improved Productivity and Health from Better Indoor Environments. *Indoor Air* **1997**, *7*, 158–172, doi:10.1111/j.1600-0668.1997.t01-1-00002.x.
15. Mendell, M. J. Non- Specific Symptoms In Office Workers: A Review And Summary Of The Epidemiologic Literature. *Indoor Air* **1993**, *3*, 227–236, doi:10.1111/j.1600-0668.1993.00003.x.
16. Cappa, F.; Del Sette, F.; Hayes, D.; Rosso, F. How to deliver open sustainable innovation: An integrated approach for a sustainable marketable product. *Sustain.* **2016**, *8*, doi:10.3390/su8121341.
17. Chen, J.; Leung, W. S.; Evans, K. P. Are employee-friendly workplaces conducive to innovation? *J. Corp. Financ.* **2016**, *40*, 61–79, doi:10.1016/j.jcorpfin.2016.07.011.
18. Gupta, S.; Kumar, V. Sustainability as corporate culture of a brand for superior performance. *J. World Bus.* **2013**, *48*, 311–320, doi:10.1016/j.jwb.2012.07.015.
19. Saffari, M.; Gracia, A. De; Ushak, S.; Cabeza, L. F. Economic impact of integrating PCM as passive system in buildings using Fanger comfort model. *Energy Build.* **2016**, *112*, 159–172, doi:10.1016/j.enbuild.2015.12.006.
20. ASHRAE ASHRAE Standard 55 - Thermal Environmental Conditions for Human Occupancy 2010.
21. International Organization for Standardization ISO 7730:2005 - Ergonomics of the Thermal Environment – Analytical Determination and Interpretation of Thermal Comfort using Calculation of the PMV and PPD Indices and Local Thermal Comfort Criteria 2005.

22. Morgan, C.; de Dear, R. Weather, clothing and thermal adaptation to indoor climate. *Clim. Res.* **2003**, *24*, 267–284, doi:10.3354/cr024267.
23. Havenith, G.; Holmér, I.; Parsons, K. Personal factors in thermal comfort assessment: Clothing properties and metabolic heat production. In *Energy and Buildings*; 2002; Vol. 34, pp. 581–591.
24. Marino, C.; Nucara, A.; Pietrafesa, M. Mapping of the indoor comfort conditions considering the effect of solar radiation. *Sol. Energy* **2015**, *113*, 63–77, doi:10.1016/J.SOLENER.2014.12.020.
25. Atmaca, I.; Kaynakli, O.; Yigit, A. Effects of radiant temperature on thermal comfort. *Build. Environ.* **2007**, *42*, 3210–3220, doi:10.1016/j.buildenv.2006.08.009.
26. Enescu, D. A review of thermal comfort models and indicators for indoor environments. *Renew. Sustain. Energy Rev.* 2017, *79*, 1353–1379.
27. Brager, G. S.; de Dear, R. J. Thermal adaptation in the built environment: a literature review. *Energy Build.* **1998**, *27*, 83–96, doi:10.1016/S0378-7788(97)00053-4.
28. Humphreys, M. A.; Fergus Nicol, J. The validity of ISO-PMV for predicting comfort votes in every-day thermal environments. *Energy Build.* **2002**, *34*, 667–684, doi:10.1016/S0378-7788(02)00018-X.
29. Yao, R.; Li, B.; Liu, J. A theoretical adaptive model of thermal comfort – Adaptive Predicted Mean Vote (aPMV). *Build. Environ.* **2009**, *44*, 2089–2096, doi:10.1016/J.BUILDENV.2009.02.014.
30. Schweiker, M.; Wagner, A. A framework for an adaptive thermal heat balance model (ATHB). *Build. Environ.* **2015**, *94*, 252–262, doi:10.1016/j.buildenv.2015.08.018.
31. Ole Fanger, P.; Toftum, J. Extension of the PMV model to non-air-conditioned buildings in warm climates. *Energy Build.* **2002**, *34*, 533–536, doi:10.1016/S0378-7788(02)00003-8.
32. CEN Ventilation for non-residential buildings - Performance requirements for ventilation and room-conditioning systems.
33. International Organization for Standardization ISO 10551:1995 - Ergonomics of the Thermal Environment - Assessment of the Influence of the Thermal Environment Using Subjective Judgement Scales 1995.
34. Nakano, J.; Tanabe, S.; Kimura, K. Differences in perception of indoor environment between Japanese and non-Japanese workers. *Energy Build.* **2002**, *34*, 615–621, doi:10.1016/S0378-7788(02)00012-9.
35. Yamtraipat, N.; Khedari, J.; Hirunlabh, J. Thermal comfort standards for air conditioned buildings in hot and humid Thailand considering additional factors of acclimatization and education level. *Sol. Energy* **2005**, *78*, 504–517, doi:10.1016/j.solener.2004.07.006.
36. Pisello, A. L.; Asdrubali, F. Human-based energy retrofits in residential buildings: A cost-effective alternative to traditional physical strategies. *Appl. Energy* **2014**, doi:10.1016/j.apenergy.2014.07.049.
37. ISO 10551:1995(en), Ergonomics of the thermal environment — Assessment of the influence of the thermal environment using subjective judgement scales.