Thermal comfort conditions in airport terminals: Indoor or transition spaces?

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ABSTRACT

This paper reports on the investigation of the thermal comfort conditions in three airport terminals in the UK. In the course of seasonal field surveys, the indoor environmental conditions were monitored in different terminal areas and questionnaire-guided interviews were conducted with 3087 terminal users. The paper focuses on the thermal perception, preference and comfort requirements of passengers and terminal staff. The two groups presented different satisfaction levels with the indoor environment and significant differences in their thermal requirements, while both preferring a thermal environment different to the one experienced. The thermal conflict emerges throughout the terminal spaces. The neutral and preferred temperatures for passengers were lower than for employees and considerably lower than the mean indoor temperature. Passengers demonstrated higher tolerance of the thermal conditions and consistently a wider range of comfort temperatures, whereas the limited adaptive capacity for staff allowed for a narrower comfort zone.

1. Introduction

Airport terminals are subject to frequent internal change and external growth in response to the increasing passenger volumes and the evolving nature of aircraft design. The ensuing increase in energy demand has turned them to very energy-intensive environments and one of the greatest energy-consuming centres per square kilometre on our planet [1]. The energy use is de-facto comparable to that of small cities. The typical electrical energy used in a major airport lies between 100 and 300 GWh/year, which corresponds to the consumption of 30,000 to 100,000 households [2]. Terminal buildings use big amounts of energy for lighting, heating, ventilation, air conditioning, and conveyance systems. They are characteristic of the large volume of spaces, often with non-uniform heat gains and extensive glazing areas (e.g. glass curtain walls) aimed at providing natural light and aesthetically attractive facilities. The energy consumed by the HVAC systems can exceed 40% of the total electrical energy, while excluding smaller systems (e.g. domestic hot water) they consume nearly all the natural gas used at an airport [3].

Due to the large differences in energy demand among airports, there is a variety of low and high-cost energy efficiency approaches for this type of facility (periodical energy auditing, solar gain control, thermal energy storage, CHP and CHCP systems, renewable energy sources, etc.) [3,4]. Along with the respective energy strategy implemented, energy savings can be achieved and maximised through the fine-tuning of environmental controls for the provision of indoor comfort conditions, particularly adjustments to space temperature setting, as less energy would be required to maintain a broader range of indoor temperatures. Reducing the gap between outdoor temperature and indoor climate set-points, however, requires the consideration of the comfort requirements of the large and diverse population typically held in these buildings.

Decades of thermal comfort research in different operational contexts has revealed the complexity of field. Thermal comfort, 'that condition of mind which expresses satisfaction with the thermal environment' [5,6] is affected by a range of parameters both environmental (i.e. air and mean radiant temperature, relative humidity, air movement) and personal (i.e. clothing insulation and metabolic rate), maintaining a constant deep core temperature of around 37 °C, balancing heat losses and heat gains from the surrounding environment. This thermal exchange between the human body and the surrounding environment has formed the basis for current thermal standards [6,7].

Field studies, predominantly in offices and dwellings, have demonstrated that occupants can be thermally satisfied with

conditions falling outside the boundaries designated by the heat-balance approach [8–10], by undertaking a range of actions to maintain or restore their comfort. The adaptive approach to thermal comfort has highlighted that occupants can take various actions to improve their comfort state either through appropriate control, or taking personal actions. Individual control is critical to occupant comfort and satisfaction [11,12] and the impact of perceived control in the determination of thermal comfort assessments has been shown to be of equal importance to the thermal variables [13]. The personal actions include changes in clothing levels as well as posture and activity. Clothing adjustment is among the principal modes of adaptation, shown to moderate changes of thermal sensation with climate [14–16] while being significantly related to the indoor mean operative temperature [17]. Changes in posture are also an important modifier of thermal comfort; a shift from seated to standing/walking activity increases the metabolic rate by an average of 0.3 met, which ultimately results to a change in preferred temperature of about 2.4 °C [18]. By associating the adaptive actions to the subjective assessments of the thermal environment the adaptive theory links the comfort temperature to the conditions experienced [19,20]. Along with the physical actions, the adaptive approach has revealed that psychological parameters also influence thermal comfort conditions, allowing for a wider range of comfort temperatures [17,21].

Airport terminals are designed predominantly as indoor spaces, while the overwhelming majority is people in transient conditions. Thus they pose a particularly challenging environment, where the indoor microclimatic conditions are expected to provide a comfortable transient environment for passengers without compromising a comfortable working environment for the smaller number of terminal staff. A number of factors, however, including dressing code, activity levels, dwell time and overall expectations differentiate the adaptive capacity between the two groups and consequently their comfort requirements. The diversity of spaces and the heterogeneous functions across the different terminal zones are further contributing factors to potential thermal comfort conflicts.

There has been limited work, however, on the evaluation of the thermal environment in airport terminals and the investigation of the thermal comfort requirements for the different user groups. Balaras et al. took spot measurements of the thermal and visual conditions in three Greek airports for a week during summer. The study reported lack of proper humidity control and problems with temperature regulation in all three buildings, while through 285 questionnaires it highlighted the different satisfaction levels between passengers and staff with all IEQ parameters [22]. The satisfaction with IEQ was also evaluated in eight Chinese airports where subjective and objective data were collected over a year. The study highlighted thermal issues such as overcooling and overheating in several terminal spaces, however, the buildings were shown to underperform more in terms of acoustic environment and indoor air quality [23]. Environmental and subjective data were also collected from passengers in Terminal 1 at Chengdu Shuangliu International Airport, China, over a period of two weeks in summer and winter. Neutral temperature was 21.4 °C in winter and 25.6 °C in summer, with the respective comfort zones at 19.2–23.1 °C and 23.9–27.3 °C. Based on 569 questionnaires, the study reported that 78.3% of passengers were generally satisfied with the thermal environment and 95.8% considered the thermal conditions acceptable [24]. Another study surveyed 128 staff and passengers in the terminal of Ahmedabad airport, India, during the summer, and found a very high comfortable temperature range in the air-conditioned part of the building, 24–32 °C [25]. Ramis and dos Santos collected temperature and humidity data from three airports in Brazil. The temperature was found below the acceptable

levels, which could result in thermal discomfort particularly in occasions of prolonged dwell times [26]. In general, time of exposure is important to the context of thermal comfort [27], as discomfort is not viewed negatively if the exposure to it is short [28] or the individual anticipates that it is temporary [21].

Currently, thermal comfort criteria for airport terminal buildings are provided by ASHRAE and CIBSE. ASHRAE's design criteria suggest a temperature range of 23.0–26.0 °C and a RH range of 30–40% in winter and 40–55% in summer [29], with an 80% acceptability comfort zone. CIBSE [30] provides seasonal comfort criteria for five terminal areas, allowing for different temperature ranges in different facilities (Table 1).

The work presented in this paper focuses on evaluating thermal comfort conditions in airport terminals in the UK, while also identifying potential differences in the comfort requirements of the main user groups. Borrowing from the methods and procedures of thermal comfort studies in different operational contexts, it employs extensive field surveys with a large population sample in different areas, in three airport terminal buildings in the UK.

2. Methodology

The methodology included extensive on-site surveys in three airport terminals, London City Airport (LCY), Manchester Terminal 1 (MAN T1) and Manchester Terminal 2 (MAN T2). During the week-long surveys, the indoor environmental conditions were monitored across the different terminal spaces and questionnaire-guided interviews were simultaneously conducted with terminal users. Each terminal was surveyed in summer and winter in 2012 and 2013 to allow for the seasonal variations, daily from 5am to 9pm to obtain the peak and off-peak occupancy profiles.

2.1. Terminal buildings surveyed

The terminals surveyed were selected to represent buildings of different size and typology (described in detail in Ref. [31]). The small-scale terminal at LCY is a two-storey building of 10,000 m² built in 1987. The linear terminal has 15 gate lounges distributed predominantly across its two piers. In comparison with its peers, the main terminal building is relatively small; if all the internal walls were removed, a Boeing 747 (wingspan 64.4 m and length 70.7 m) would fit snugly nose to tail and wingtip to wingtip within the external walls. LCY presents the highest degree of uniformity compared to the interior of MAN T1 and MAN T2. Since 2012, it has been the 15th busiest airport in the UK handling annually about 3 million passengers [32].

Manchester airport has been in the 3rd place since 2012, serving around 20 million passengers a year [32]. The passenger-related facilities in the significantly bigger MAN T1 and MAN T2 are spread over a total floor area of 43,499 m² and 26,063 m²

Table 1
Recommended comfort criteria for airport terminal spaces (CIBSE [30]).

	Summer[a]	Winter[a]	Activity (met)
	Operative temperature (°C)		
Baggage reclaim	21–25[b]	12–19[b]	1.8
Check-in areas[c]	21–23	18–20	1.4
Concourse (no seats)	21–25[b]	19–24[b]	1.8
Customs area	21–23	18–20	1.4
Departure lounge	22–24	19–21	1.3

[a] For clothing insulation of 0.65 clo in summer and 1.15 clo in winter.
[b] Based on PMV of ±0.5. At other cases based on PMV of ±0.25.
[c] Based on comfort requirements of check-in staff.

respectively, excluding the car parks, conveyance systems and air bridges, with an annual capacity of 11 and 8 million passengers per year [33].

The five-storey MAN T1 is a large complex building that has undergone consecutive overhauls and various expansions over the years since its opening in 1962. As a result, the terminal comprises an assortment of different terminal design trends with heterogeneous architectural features, housing a variety of spaces ranging from the "boxed up" to modern styles. MAN T1 was the first terminal in Europe to incorporate the pier system and today it has 28 gate lounges along its finger and satellite piers. The newest among the terminals in Manchester airport (1993), MAN T2, features the most contemporary terminal design. Almost all the spaces are open-plan with high floor-to-ceiling heights and abundance of natural light through glazed curtain walls and rooflights. The four-storey terminal utilises 17 gate lounges distributed across the two diametrically opposed piers spanning from the central building.

Passenger dwell time is another principal differentiating factor between the terminals. As a result of its small size and the focus on business passengers, LCY provides short walking distances and fast passenger processing that result in significantly shorter dwell times, which can be down to 20 min from check-in to boarding.

All three terminals are mechanically ventilated. The indoor environment in MAN T1 and MAN T2 is controlled through variable refrigerant volume (VRV) and fan coil unit systems, with direct expansion (DX) systems employed in smaller areas. In both terminals, the temperature set-point was fixed at 21.0 °C throughout the year. The spaces in LCY were conditioned by 13 air handling units aiming for a temperature set-point of 20.0 °C for winter and 23.0 °C for summer.

2.2. Environmental monitoring

For the population in transit, it was important to investigate the immediate microclimate people experience [28,34,35]. A microclimatic monitoring station was designed to be easily transported across the terminal spaces and dismounted for passing through security screening when moving from landside to airside. The equipment (Fig. 1a) consists of a data logging system, a shielded temperature and humidity probe, an ultrasonic anemometer, a black globe thermometer, a lux sensor and a CO_2 sensor, all conforming to ISO 7726 [36]. The environmental parameters monitored included dry bulb and black globe temperature, relative humidity, air movement, horizontal illuminance and carbon dioxide levels. The latter was used as an indicator of changes in occupancy. All parameters were measured at the average height of a standing person, 1.7 m, and recorded at 1-min intervals. The spaces

monitored include check-in areas, security search areas, circulation spaces, retail facilities, departures lounges, gates, baggage reclaim areas and arrivals halls. Measurements were taken in different locations within a space to ensure readings are representative of the conditions throughout the area under investigation, while interviews were carried out in close proximity to the equipment (1.0–1.5 m). Due to security concerns it was not possible to leave separate dataloggers to monitor temperatures in different spaces concurrently.

2.3. Subjective data – questionnaire

A standardised questionnaire was developed to collect subjective data for the evaluation of comfort conditions. The questionnaire consisted of 31 questions and used a combination of open-ended, partially closed-ended and predominantly closed-ended questions. Thermal sensation (TS) was assessed on the 7-point ASHRAE scale (Fig. 1b) while a 5-point scale was used for thermal preference (TP). Questions were also used for the evaluation of other environmental parameters including air movement, humidity and lighting. Additional data collected include the activity level during and 15 min prior to the questionnaire (15′ met), clothing insulation, time spent in the terminal, state of overall comfort and demographic data. Interviewees were selected randomly to ensure a representative sample of terminal users was achieved.

3. Data analysis

The datasets were analysed using the Statistical Package for Social Sciences (SPSS). A statistical analysis plan was developed to ensure uniformity in data analysis and validity of results. Data analysis was terminal and season specific.

3.1. Indoor environmental conditions

A summary of the environmental conditions in the three terminals is presented in Table 2, while the comparison of the mean operative temperature with the mean thermal sensation for passengers and staff across the different spaces for summer and winter is shown in Fig. 2.

LCY had a very narrow temperature range – 4.4 °C in summer and 3.6 °C in winter – indicative of its small size and uniform spaces. The thermal environment was homogeneous across the majority of terminal spaces (Fig. 2) where the mean temperature ranged between 22.7 and 23.9 °C in summer and between 22.9 and 23.9 °C in winter. The retail area in the summer was the exception, where the extensive spot lighting and the very low floor-to-ceiling

Fig. 1. (a) Portable microclimatic monitoring station designed for the surveys and (b) extract from the questionnaire related to the thermal environment.

Table 2
Indoor environmental conditions in the surveyed terminals.

		Summer				Winter			
		$T_{op.}$ (°C)	V_{air} (m/s)	RH (%)	CO_2 (ppm)	$T_{op.}$ (°C)	V_{air} (m/s)	RH (%)	CO_2 (ppm)
LCY	Mean	23.3	0.12	50.4	483	23.4	0.13	32.3	817
	SD	0.9	0.06	3.0	138	0.6	0.04	7.0	152
	Min	21.4	0.04	44.7	324	21.7	0.04	21.7	660
	Max	25.8	0.58	64.1	1095	25.3	0.26	53.3	1333
MAN T1	Mean	22.0	0.15	57.5	648	21.3	0.16	32.5	770
	SD	1.5	0.05	5.8	172	2.0	0.16	5.9	107
	Min	19.1	0.04	46.6	298	16.2	0.03	23.2	587
	Max	25.4	0.32	73.8	1059	25.6	1.04	53.1	1365
MAN T2	Mean	23.0	0.18	51.1	726	21.1	0.16	32.6	752
	SD	1.3	0.11	6.8	209	0.9	0.09	6.0	159
	Min	20.6	0.04	37.6	490	18.9	0.04	22.0	284
	Max	26.3	0.55	66.6	1380	24.5	0.49	44.5	1273

height often resulted in higher temperatures, while the temperature in the gate lounges was representative of free-running conditions.

Thermal uniformity also characterizes the thermal environment in MAN T2, which had a wider range of operative temperatures (Table 2) with the temperature in all spaces being 1.1–3.6 °C lower in winter (Fig. 2). More specifically, conditions in the airside spaces (i.e. beyond the security search area), were fairly uniform in the summer with the mean temperatures ranging between 21.9 °C and 23.0 °C. A higher temperature (23.7 °C) was found in the search area due to the ineffective conditioning of the space during the occupancy peaks in the busy summer period. The warmest space in the summer was the check-in area, 24.6 °C, which reflects the impact of external heat gains on the thermal environment, as a result of the extensive glazed façade and rooflights. In winter, the mean temperature was very similar between the spaces, close to 21.0 °C. This was associated with the terminal's operational profile at this time of the year. MAN T2 is serving mostly holiday destinations and as a result it was significantly busier during the summer monitoring period, whereas in winter the main occupancy peak in the morning was succeeded by sparse passenger traffic for the rest of the day. Consequently, there were prolonged periods of time with very low occupancy resulting in uniformly lower temperatures very close to the temperature set-point.

On the other hand, a variety of thermal environments existed within MAN T1 as a result of the diversity of internal spaces. The terminal exhibited the widest temperature range in both seasons (19.1–25.4 °C in summer and 16.2–25.6 °C in winter; Table 2) and the highest mean temperature differences between its spaces (Fig. 2). Characteristically, the arrivals hall was on average 4.7 °C cooler than the departures lounge 1 in summer and 6.2 °C cooler than the seating area in winter. The particularly cool conditions in the arrivals hall (19.8 °C in summer and 17.4 °C in winter) originated from its great exposure to outdoor conditions through a north-orientated unprotected doorway. Additionally, departures lounge 2 was constantly cooler than its extension, the nearby departures lounge 1, with the highest mean temperature difference between them (2.5 °C) in summer due to the extensive glazing in the latter. Other spaces of similar function but with different thermal conditions were the check-in halls 1 and 2. Check-in 2 was on average 1.1 °C warmer in winter due to the significantly smaller volume and very low floor-to-ceiling height.

The mean temperature in the majority of spaces surveyed in the three terminals was within or very close to the CIBSE comfort criteria (Table 1) for summer. In winter, however, the thermal conditions in nearly all spaces were beyond the respective range, with mean temperatures up to 4.2 °C higher than recommended [31,37].

The 24 h-mean outdoor temperature during the summer surveys fluctuated between 11.0 and 20.0 °C for LCY, 15.0–16.0 °C for MAN T1 and 10.0–16.0 °C for MAN T2. The corresponding range in winter was 3.9–12.0 °C, 0.9–6.6 °C and −1.6 to 6.3 °C respectively. Indoor and outdoor temperatures were weakly correlated for LCY and MAN T1 (Table 3). On the contrary, the (linear) relationship between the two was strong for MAN T2 associating nearly 50% of the temperature variance indoors to outdoor temperature. This is largely associated with the extensive glazing areas in the terminal and the use of indoor air quality controls.

The compact nature of LCY, although an advantage in terms of fast passenger processing, presented a major thermal disadvantage during busy times. The HVAC system could not cope efficiently with the large volume of passengers handled at peak times resulting in a largely occupancy-driven thermal environment. This was revealed in the similarity between the mean hourly profiles of temperature and CO_2 and was reflected in the correlation between the two variables (Table 3) (r = 0.44, p < 0.01). The correlation between operative temperature and CO_2 concentration was weaker for MAN T1 (r = 0.06, p < 0.05) and MAN T2 (r = 0.13, p < 0.01), while also implying the tendency for higher temperatures with increased occupancy levels. The effect was significant in the smaller spaces within LCY, where a highly variable traffic was handled within the day. Occupancy changes in LCY explain 40% of the temperature variance in summer and nearly 30% in winter (r = 0.62, p < 0.01 for summer, r = 0.55, p < 0.01 for winter). The overall effect was weaker for MAN T1 and MAN T2 due to the considerably larger volume of spaces and the use of air quality controls in the latter. Seasonally, the correlation was significant only for the busy summer period (r = 0.29 for MAN T1 and r = 0.37 for MAN T2, p < 0.01), as occupancy volumes did not vary much during the winter surveys; passenger traffic in MAN T2 was very low during winter, while in the busier MAN T1 traffic had very little variance within the day.

The mean CO_2 levels in all three buildings (Table 2) were well below the ASHRAE recommended maximum concentration range of 1000–1200 ppm and indicate sufficient ventilation rates [38]. The higher concentrations recorded during occupancy peaks remained close to the maximum recommended range. Although none of the buildings include (de)humidification in their control strategy, the mean RH (%) levels were within the ASHRAE recommended range. Draughts are the most common cause of local discomfort and one of the most common problems encountered in airport terminal buildings due to the large entranceways, high ceilings and long passageways which have openings to the outdoors [29]. In all three buildings, however, air movement was very low with average values within the range of 0.1–0.2 m/s. Readings beyond the upper comfort boundary of 0.3 m/s occurred

Fig. 2. Mean thermal sensation (lines) for passengers and staff plotted against mean operative temperature (bars) in the monitored terminal spaces. Line breaks indicate insignificant number of questionnaires from the respective population group in the corresponding space.

Table 3
Correlation coefficients for operative temperature, outdoor temperature and CO_2.

		LCY	MAN T1	MAN T2
Top. vs. Tout.	Overall	0.18	0.18	0.70
Top. vs. CO_2	Overall	0.44	0.06[a]	0.13
	Summer	0.62	0.29	0.37
	Winter	0.55	n/a	n/a

[a] Significant at $p < 0.05$, all other at $p < 0.01$.

sporadically in certain spaces exposed to outdoor wind through openings (e.g. the gate lounges at LCY and the arrivals hall at MAN T1).

3.2. The sample population

The total sample population from the three terminals consists of 3087 people, aged from less than 18 years to over 65 years and with a 50:50 male-female ratio. Interviewees were classified into (a) employees, (b) passengers and (c) well-wishers and other, consistent with the distinct nature of occupancy they represent (Fig. 3).

The 2333 passengers account for 74–80% of the survey participants at each terminal. They consist of arriving (3–9%) and predominantly departing passengers (91–97%). The former were interviewed exclusively in the baggage reclaim areas and arrivals halls and the latter across all other terminal spaces. Almost 80% of passengers in LCY had stayed maximum an hour airside, with 40% spending up to 30 min. The latter was comparable with only 19% and 14% of passengers flying from MAN T1 and MAN T2, where dwell time for the majority exceeded an hour. Over half the passengers departing from LCY (52%) were travelling on business, whereas this percentage was significantly lower in MAN T1 (14%) and MAN T2 (3%).

A wide range of terminal personnel, 465 in total, were studied in their workspace and represent 14–17% of the terminals' sample population. Reflecting staff's dwell time, nearly 80% of interviewed employees were working full-time and 20% on a part-time basis. Well-wishers and other account for 3–12% of the terminals' sample population. This user group consists mainly of meters and greeters interviewed in the landside areas of the terminals (check-in and arrivals halls) and other short-stay visitors. The analysis focuses on the two main user groups, passengers and staff.

Clothing insulation was evaluated using the detailed clothing data collected from each interviewee during the questionnaire and the insulation values for separate garment pieces provided in ISO 9920 [39]. In summer the mean clothing insulation for passengers and staff was very similar at 0.56 and 0.60 clo (Table 4). This increased to 0.88–1.15 clo for passengers and 0.79–0.90 clo for staff, in winter, reflecting the greater impact of outdoor weather on passengers' outfits. In fact, outdoor temperature explained about 20–40% of the clothing variation for employees whose outfits were largely dependent on clothing policies, and 50% of the variance in passenger clothing (Fig. 4). Another factor influencing passengers' clothing was the destination. Passengers had the lowest mean clothing insulation at MAN T2, which serves mostly holiday destinations in warmer climates, in spite of the low mean daily outdoor temperatures during the surveys.

3.3. Satisfaction with the indoor environment and the link with overall comfort

The data analysis revealed a consistent satisfaction gap between the two groups in all terminals, with dissatisfaction being considerably higher among staff in both seasons (Fig. 5). The assessment of satisfaction with air movement and thermal comfort was based on the assumption that a person requiring no change (in the respective preference question) is satisfied with the prevailing conditions.

No change in the thermal environment was required by approximately half the passengers and by only a third of staff. In addition, a significant fraction of employees, 60–80%, preferred either higher or lower air movement in their workspace whereas such requirement was expressed by 40–50% of passengers in the three terminals. The assessment of the indoor air as "stuffy" was widespread among employees, 40–60% of staff, compared to only 20–40% of passengers. Similar levels of dissatisfaction were reported with respect to the lighting environment. The satisfaction gap was prevalent in all three terminals implying different comfort requirements for the two groups and reflected in the considerably different levels of discomfort; 23–49% among staff and 8–21% between passengers.

The study also collected data regarding the aspects of the terminals the interviewees liked and disliked the most, using two open-ended questions. Such data were used to assess the importance of the indoor conditions − and particularly of the thermal environment − compared to other common concerns in such facilities. For the analysis it was assumed that a person who reports to (dis)like a certain condition the most views that condition as important (not necessarily as the most important).

The primary classification of the responses into "environmental" (thermal, lighting, acoustic environment and air quality), "non-environmental" (all other issues) and "nothing particularly" showed that the environmental conditions get a higher rank among the "dislike" than the "like" statements of both groups. This implies that the negative impact of the indoor environment on overall comfort is stronger than the positive one, and consequently that the indoor conditions were not considered important unless expectations were not met. Focussing on the "dislike the most" responses, the percentage of employees raising an environmental issue (54–62%) was significantly higher than passengers (8–15%).
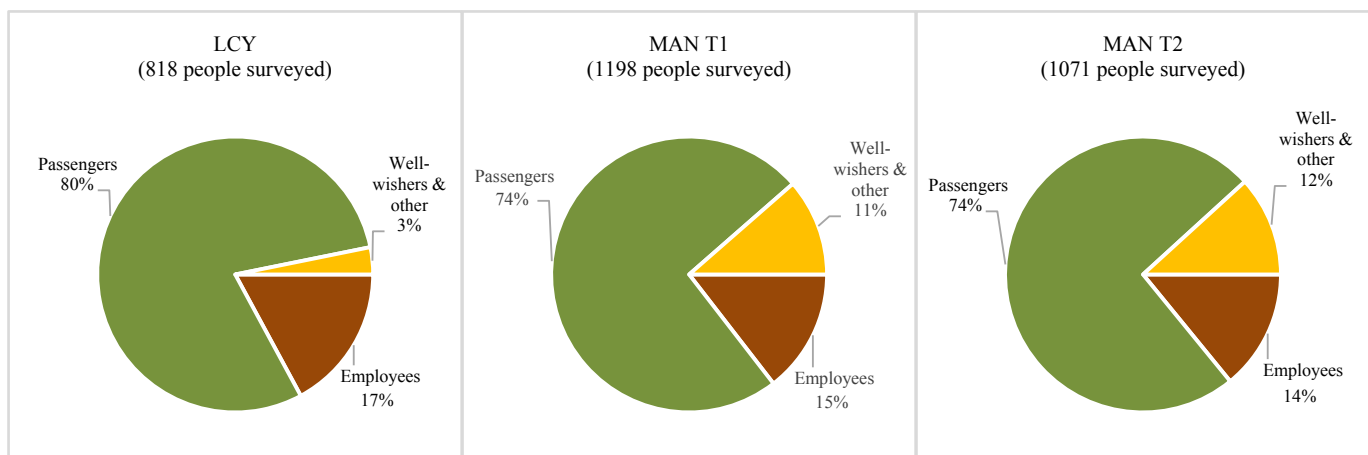

Fig. 3. Breakdown of the interviewees per category in the surveyed terminals.

Table 4
Mean value and standard deviation of clothing insulation (clo) for terminal users.

|		LCY		MAN T1		MAN T2	
		Summer	Winter	Summer	Winter	Summer	Winter
Clo Mean	Total population	0.64	1.11	0.55	0.99	0.51	0.89
	Employees	0.64	0.90	0.60	0.79	0.56	0.80
	Passengers	0.64	1.15	0.53	1.02	0.50	0.88
	Well-wishers & other	0.67	1.28	0.57	1.04	0.54	1.05
Clo SD	Total population	0.19	0.27	0.15	0.28	0.13	0.24
	Employees	0.13	0.16	0.16	0.20	0.13	0.17
	Passengers	0.20	0.27	0.15	0.28	0.13	0.23
	Well-wishers & other	0.17	0.15	0.16	0.21	0.12	0.29
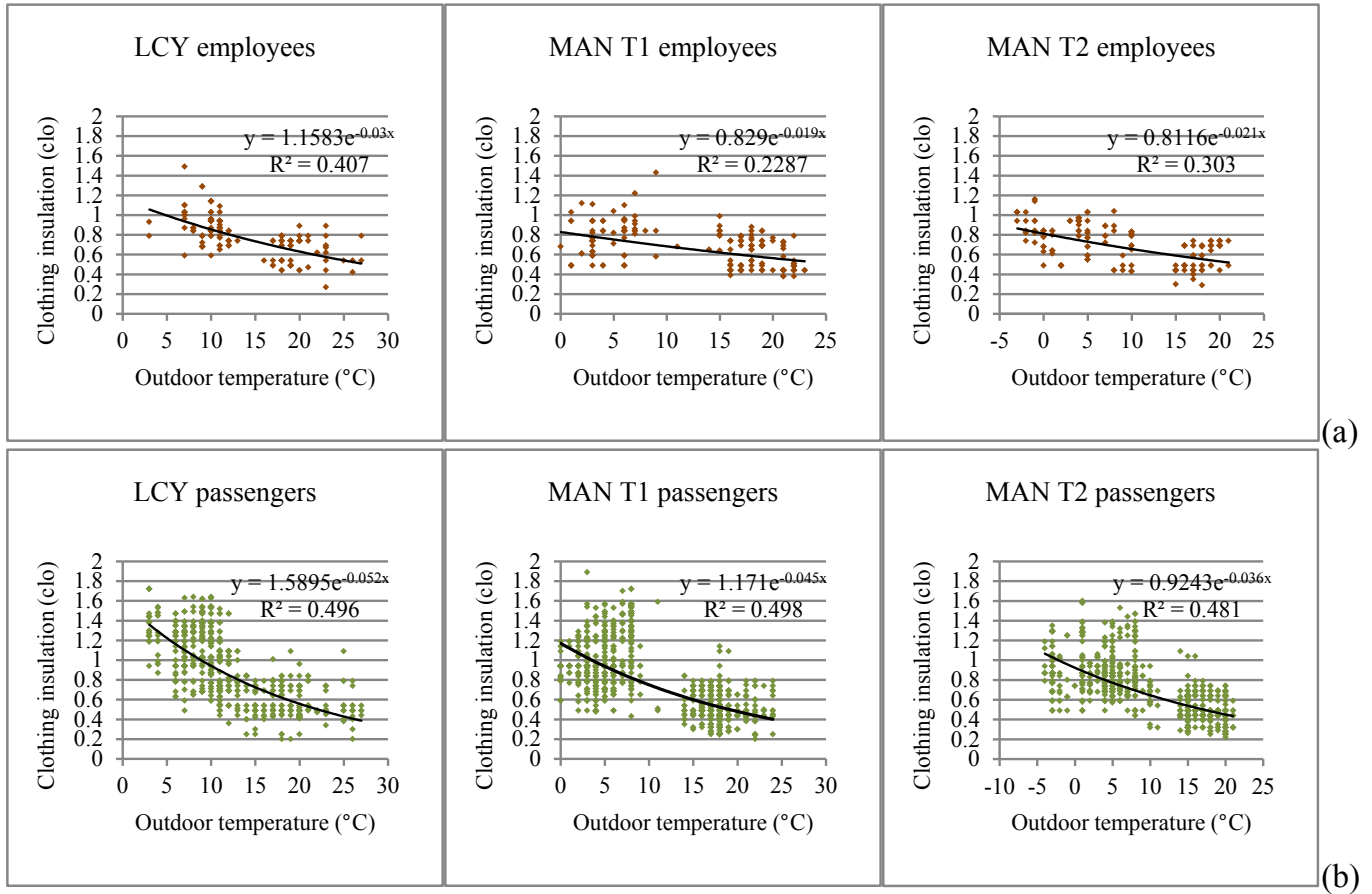
Fig. 4. Relationship between clothing insulation and outdoor temperature for (a) employees and (b) passengers.

Fig. 6 presents the parameters disliked the most, highlighting that the thermal environment was the highest ranked issue among staff in all terminals for a significant fraction of employees (34–40%). For passengers, however, it was only ranked 5th in LCY and MAN T2 and 6th in MAN T1, with only 4–6% of passengers at each terminal addressing thermal conditions and even then only mentioned by those who had reported unacceptable TS. Even in this case the percentage of passengers who considered the thermal environment as the worst aspect of their in-terminal experience was low (15–21%), suggesting a great extent of passengers' tolerance of thermal conditions. In fact, these percentages are comparable to common passenger-concerns such as the "amount of space/crowding" in LCY, "seating" in MAN T1 and "speed of processing/queues" in MAN T2.

The importance of the thermal environment for the employees was further highlighted in their assessment of the impact of the environmental conditions on their productivity (on a 3-point scale) and the explanations among those reporting "negative". A significant fraction of staff in all terminals (40–46%) reported a negative effect, with a slightly higher percentage (47–56%) reporting "neither positive nor negative". For the vast majority (69–91%) among those who reported a negative effect, this was attributed to thermal conditions.

3.4. Perception and preference over the thermal environment

3.4.1. Thermal sensation

Correlation analysis between the physical variables and TS shows that TS correlates better with operative temperature (Table 5). A positive correlation was also found with CO_2 levels;
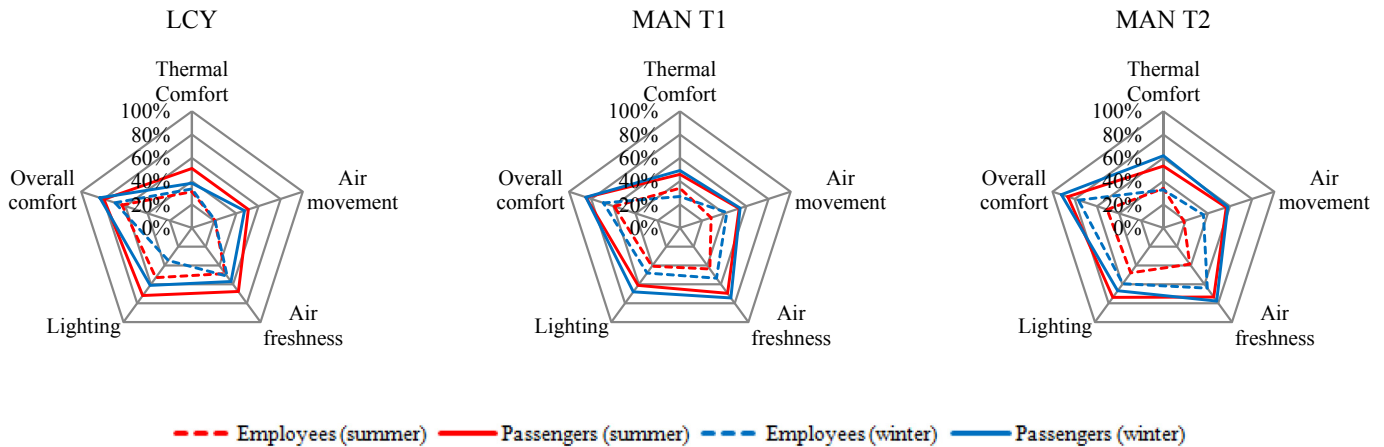
Fig. 5. Satisfaction levels of passengers and staff with the indoor conditions in summer and winter.

higher concentrations were normally the result of overcrowded spaces where TS had an increasing trend. Moreover, the correlation with 15′ met suggests that having performed lighter activities people reported cooler sensation. Conversely, this demonstrates a tendency towards warmer sensations experienced by people with higher metabolic heat generation, associated with higher activity levels such as walking or walking while carrying luggage.

Other variables that did not vary sufficiently to produce a statistically significant correlation with TS may still have a significant impact through their interrelationship with other variables. To investigate this point, but also the relative importance of the variables involved (i.e. operative temperature, air movement, RH, clothing insulation and the activity levels during and 15 min prior to the questionnaire) multiple (stepwise) regression analysis was performed. All models are significant at p < 0.005.

The results (Table 6) highlighted operative temperature, clothing and 15′ met as the set of variables explaining best TS in LCY, supplemented with the square root of air movement in the case of MAN T1 and MAN T2. The unstandardised coefficients, measured in the unit of the variable they accompany, indicate the amount of change expected in TS for every one-unit change in the value of the variable they correspond, provided that all other quantities in the model are held constant. Thus, controlling for the variables "clo" and "15′ met", a temperature rise of 1.0 °C in LCY would result in nearly 0.4 units change in the thermal sensation of the terminal population. In other words, the temperature change required to shift TS by one unit was 2.7 °C. Similarly, the temperature change required to increase people's TS by a unit in MAN T1 and MAN T2 was higher at 3.3 °C and 4.1 °C respectively.

On the other hand, the standardised coefficients, measured in standard deviations, enable the comparison of the relative strength of the various predictors within the models [40]. Although clothing correlated with TS only in LCY (r = 0.21, p < 0.01), the results indicate that it provides the second strongest unique contribution (behind operative temperature) in explaining TS in all cases. Similarly, controlling for the other variables, air movement makes a significant contribution into explaining TS in MAN T1 and MAN T2.

The percentage distribution of TS for passengers and staff is illustrated in Fig. 7. The overwhelming majority (90%) of passengers handled in LCY were within the three central categories of the ASHRAE scale (−1 ≤ TS ≤ +1) in summer, when "neutral" (41%) and "slightly warm" (35%) were the most frequently experienced sensations. In winter, the same percentage shifted towards warmer votes, with only 20% of passengers feeling "neutral" and the bulk of sensations referring to "slightly warm" (42%) and "warm" (28%).

These three categories also represent the majority of passengers in MAN T1 and MAN T2 (nearly 80%) in both summer and winter, with "slightly warm" being the highest in most cases, representing the thermal state of at least one out of three passengers.

Employees, however, experienced more unacceptable sensations (±2, ±3) than passengers in summer and winter. This is demonstrated from their wider TS distribution and validated statistically from the higher standard deviation of staff's mean TS in all cases (Table 7). More specifically, unacceptable TS expressed at least one out of three employees in each terminal, reaching almost half (47%) in LCY during summer. On the contrary, such sensation was experienced from 10 to 31% of passengers with the highest percentages found in winter, predominantly from "warm" votes.

Differentiating per season, the mean TS for staff is lower in winter than summer in all cases, with the most significant seasonal difference − 1 unit on the ASHRAE scale − found in MAN T2. Conversely, and despite the lower temperatures, the mean TS for passengers increased in winter (with the exception of T2) due to the higher clothing insulation worn, particularly at LCY and MAN T1 (Table 4).

3.4.2. Thermal preference

Similarly to TS, TP correlates better with operative temperature (Table 5). The distribution of TP for the two groups is illustrated in Fig. 8, where TP has been transformed to a 3-point variable. "Prefer cooler" corresponds to the "much cooler" and "a bit cooler" votes and "prefer warmer" represents the preference for a "much warmer" and "a bit warmer" environment.

About 70% of the employees in all terminals required a change in the thermal environment, with the majority preferring to be cooler. Although this is true for both seasons, the votes for warmer conditions were greatly increased in winter. Passengers' TP profile was consistent among the terminals in summer − nearly 50% found the temperature just right and the preference for a cooler environment was dominant among those requiring a change − and varied in winter.

The large fraction of passengers (60%) preferring cooler conditions in LCY, coupled with the significantly increased votes on the warm side of the ASHRAE scale in winter, indicates a problem with overheating. Yet, cooler conditions were preferred by only a third of employees. This suggests that overheating in winter was an issue predominantly for passengers, whilst the respective figures for summer suggest an overheating issue for staff. In MAN T1, almost half the passengers found the thermal environment 'just right' in winter and the majority among those requiring a change preferred
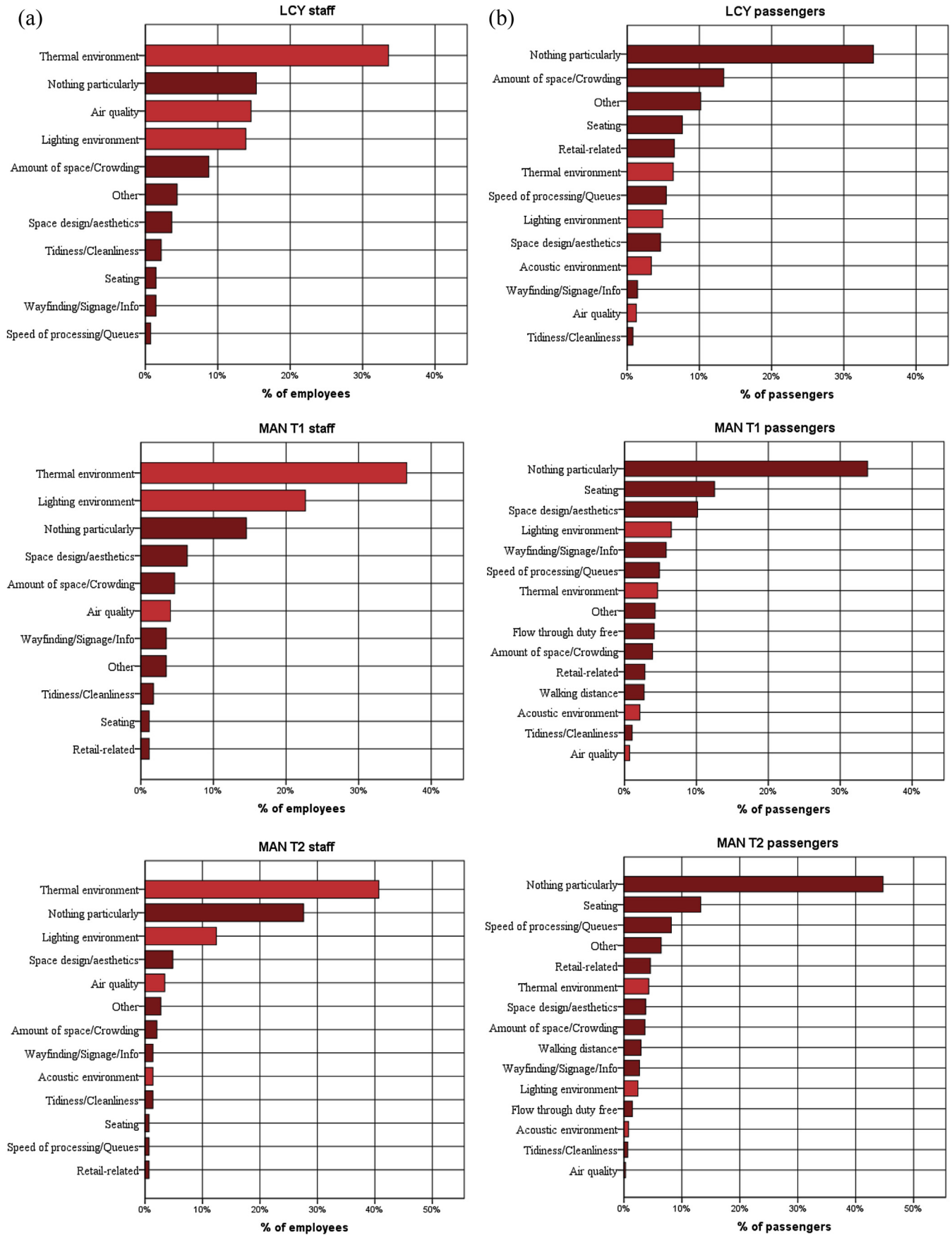
(a)

(b)

Fig. 6. Aspects of the terminal buildings that (a) employees and (b) passengers disliked the most in the surveyed terminals.

Table 5
Correlation coefficients for TS, TP and physical variables.

		LCY	MAN T1	MAN T2
Thermal sensation	Operative temperature	0.25	0.40	0.20
vs.	CO_2 levels	0.23	0.06[a]	0.25
	15′ met	0.18	0.09	0.14
Thermal preference	Operative temperature	0.27	0.41	0.31
vs.	CO_2 levels	0.16	n/a	0.23
	15′ met	0.12	0.10	0.14

[a] Significant at $p < 0.05$, all other at $p < 0.01$.

Table 6
Standardised and unstandardised coefficients for the TS predictors.

		Unstandardized coefficients		Standardized coefficients	
		B	Std. error	Beta	Significance level
LCY	(Constant)	−9.240	0.996		
	Top (°C)	0.369	0.042	0.284	0.000
	Clothing (clo)	0.613	0.103	0.196	0.000
	15′ activity (met)	0.556	0.096	0.190	0.000
MAN T1	(Constant)	−6.492	0.436		
	Top (°C)	0.305	0.018	0.448	0.000
	Clothing (clo)	0.512	0.102	0.133	0.000
	15′ Activity (met)	0.251	0.091	0.072	0.006
	Sqrt Vair	−0.958	0.305	−0.083	0.002
MAN T2	(Constant)	−5.760	0.658		
	Top (°C)	0.246	0.027	0.315	0.000
	Clothing (clo)	0.803	0.145	0.188	0.000
	15′ Activity (met)	0.588	0.105	0.173	0.000
	Sqrt Vair	−1.257	0.319	−0.122	0.000

to be cooler. MAN T2 presented the highest thermal satisfaction rate for passengers in winter as well as in summer with over 60% of passengers preferring "no change".

Further scrutiny of the TS and TP votes found that neutral ("neither cold nor hot") was not the desired thermal state for the over half the passengers and staff. Assuming that preference for no change denotes thermal satisfaction, the results showed that 51%, 64% and 62% of passengers and 53%, 57% and 61% of the employees satisfied with the thermal environment in LCY, MAN T1 and MAN T2 had reported TS other than neutral.

3.4.3. The space-to-space thermal conflict

The thermal conditions in the terminal spaces were often evaluated differently by passengers and staff (Fig. 2), with the respective mean TS difference reaching up to 2.1 units. As indicated by the spatial profiles of mean TS in all terminals, employees' TS profile fluctuates significantly between the spaces whereas for passengers it is considerably more stable. This demonstrates passengers' wider adaptive capacity as opposed to the rigid working conditions for the vast majority of staff.

Interestingly, employees' TS profile did not always fluctuate in accordance with the temperature changes between the spaces, but reflected the diverse activity levels between the various types of staff associated to the nature of work they perform. For instance, security staff working in the search area of LCY in summer (0.74 clo) experienced a mean temperature of 23.4 °C and reported a mean TS of 1.7. In the nearby seating area (0.70 clo), with just 0.2 °C higher temperature staff's mean TS was −0.5, while inside the warmer retail facilities (24.6 °C, 0.64 clo) staff reported neutral TS. The comparison between staff in the check-in hall, search area and arrivals hall of MAN T2 in winter is also representative. The mean temperature in these spaces was nearly identical at 21.0 °C and employees had a very similar mean clothing insulation (0.84–0.92 clo). Nevertheless, three distinct mean sensations were

reported; −1.1 in the check-in area, −0.4 in the arrivals and 1.1 in the search area. Similarly, staff in the check-in 2 (0.74 clo) and search area (0.66 clo) at MAN T1 experienced a mean temperature of 22.4 °C in summer and reported a mean TS of 0.2 and 1.1 respectively. The figures for the search areas are fairly consistent between the three terminals. In most cases, the mean TS for both groups was among the highest reported while overall comfort was lower than in other spaces. This suggests that the particular function has an increasing effect on TS and decreasing effect on comfort due to staff's mental concentration leading to increased metabolic rate and passengers' stress in a confined space.

3.5. Quantifying the thermal conflict

3.5.1. Neutral temperatures

Neutral temperatures, i.e. the temperature where people are neither warm nor cool but are in a state of thermal neutrality [8,41,42], were calculated using weighted linear regressions [43]. Working with half-degree (°C) increments of operative temperature, the mean TS of the two groups was determined for each bin. The mean TS was regressed against operative temperature (Fig. 9) and neutral temperatures were subsequently obtained by solving the regression equations for TS = 0. All models were significant at the 99% level.

The gradient of the regression models, representing thermal sensitivity [43], demonstrates that employees were on average 1.6 times more sensitive to temperature changes than passengers in both seasons. This means that the rate of TS change differs significantly. For example, in summer, a unit increase in staff's TS would require 2.5 °C temperature rise in LCY, 2.2 °C in MAN T1 and 2.4 °C in MAN T2, whilst passengers' TS would not be altered with temperature changes below 4.1 °C, 3.5 °C and 3.7 °C respectively.

The results demonstrate the discrete thermal requirements of the two groups, who consistently achieved neutrality at different temperatures (Table 8). Neutral temperature for staff was 0.6–3.9 °C higher than for passengers, with the highest differences met in winter. For both groups, neutrality was found at temperatures cooler than the mean indoor temperature (except from the winter case of staff in MAN T2), with employees' neutral temperature being closer to it in all cases. More specifically, the difference between mean and neutral temperature was only 0.6–1.2 °C for staff and 1.5–2.7 °C for passengers.

3.5.2. Preferred temperatures

Weighted linear regression models were generated to associate the thermal preference votes with temperature[1] [44,45]. Using the sample size of each temperature bin as weighting factor, the percentages of "prefer cooler" and "prefer warmer" votes were

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[1] Probit analysis confirmed the results obtained from linear regression in some cases but was ineffectual where the temperature range was very narrow. The alternative method of linear regression was used to retain uniformity in data analysis (Personal communication with Humphreys M.A. [46]).
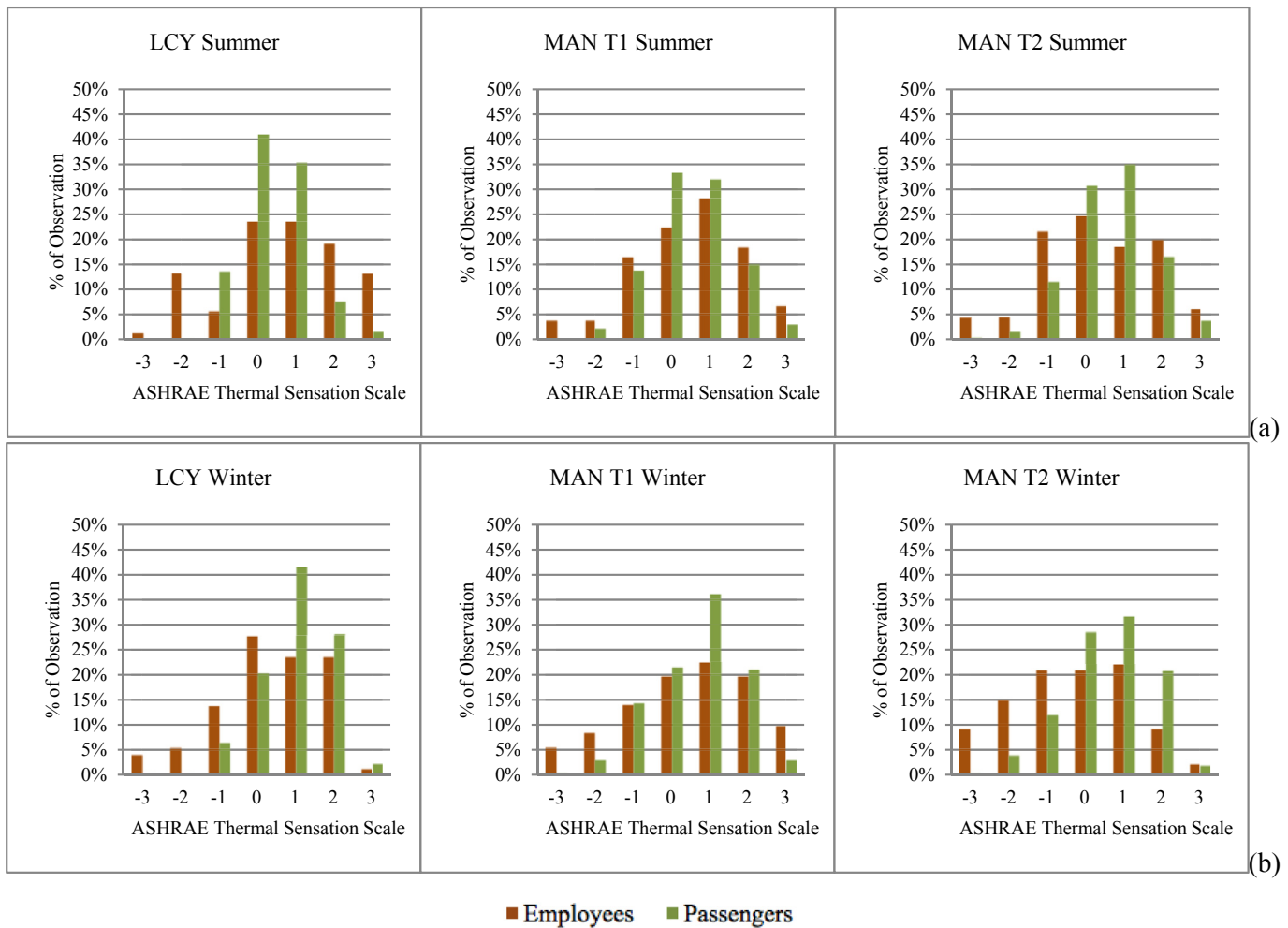
Fig. 7. Percentage distribution of thermal sensation for passengers and staff in summer and winter.

Table 7
Mean score and standard deviation of TS for staff and passengers and percentage of unacceptable TS.

		Employees			Passengers		
		Mean TS	SD	% of unacceptable TS	Mean TS	SD	% of unacceptable TS
Summer	LCY	0.65	1.59	47%	0.42	0.90	10%
	MAN T1	0.50	1.44	33%	0.53	1.08	21%
	MAN T2	0.32	1.51	35%	0.63	1.09	23%
Winter	LCY	0.38	1.39	35%	0.97	0.96	31%
	MAN T1	0.44	1.65	44%	0.66	1.17	28%
	MAN T2	−0.31	1.54	36%	0.58	1.16	28%

calculated for each half-degree (°C) increment and regressed separately against operative temperature. Preferred temperature was obtained from the intersection of the two regression lines as shown in Fig. 10.

The results demonstrate that both groups preferred a cooler environment than the one experienced (Table 8). Passengers, however, preferred constantly lower temperatures than employees, by as little as 0.4 °C (in MAN T1 in summer) to 2.0 °C (in MAN T2 in winter). In accordance with the profile of neutral temperatures, the greatest differences were encountered in winter while in both seasons staff's preferred temperature was closer to the mean temperature experienced.

The exception was the winter of MAN T1 and MAN T2, where the lowest temperatures were observed and employees' preferred

temperature was slightly higher than the mean temperature. These cases provide evidence of tolerance to cool conditions, which appears to be considerably higher among passengers. With the mean temperature at 21.3 °C in MAN T1, employees preferred 21.7 °C but were still comfortable at 20.6 °C demonstrating limited adaptation to the cooler conditions. On the other hand, passengers preferred 20.6 °C, yet they were still comfortable at 19.2 °C. Similarly, with the mean temperature at 21.1 °C in MAN T2, employees preferred a slightly warmer temperature, 21.9 °C, and achieved neutrality at 22.3 °C, while passengers preferred 19.9 °C but were also comfortable at 18.4 °C, demonstrating higher adaptation to cooler temperatures.
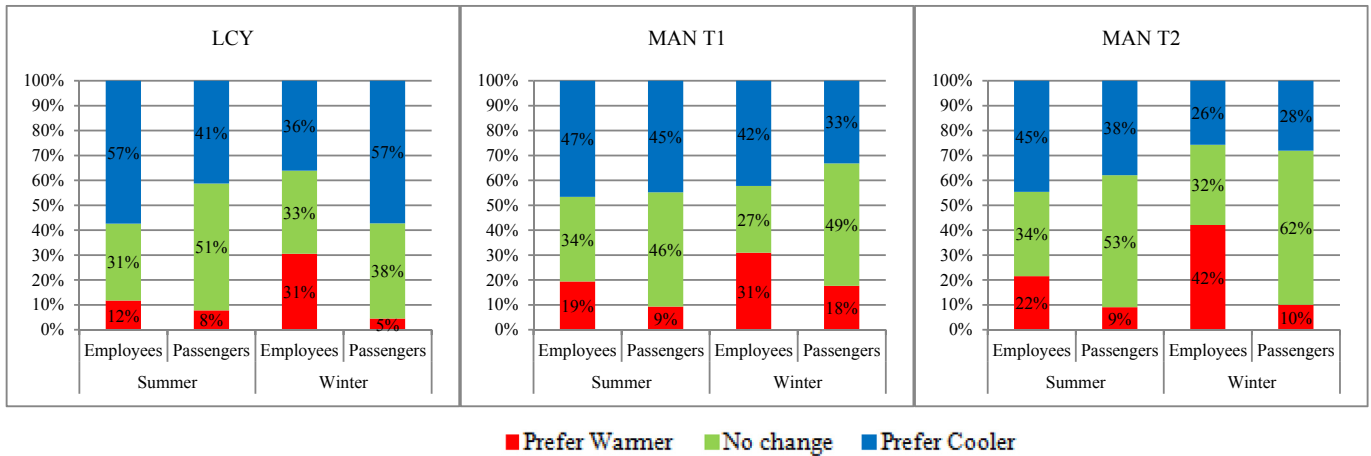
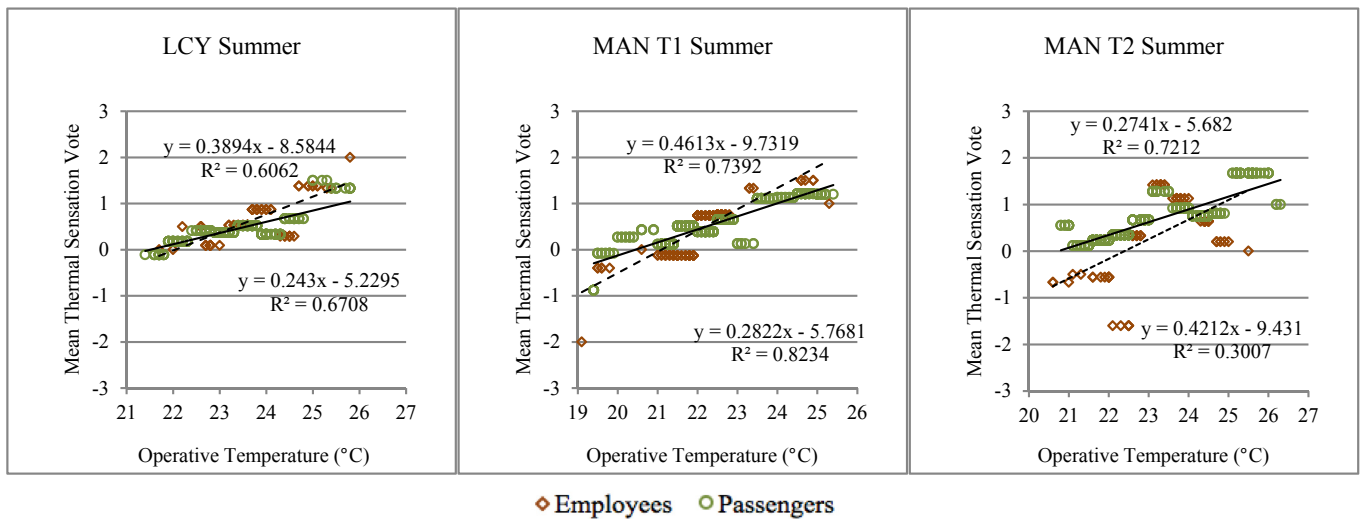**Fig. 8.** Percentage distribution of binned thermal preference votes for passengers and staff.

Fig. 9. Relationship between thermal sensation and operative temperature for passengers and staff at in summer.

Table 8
Summary of mean, neutral and preferred temperatures and acceptable temperature ranges for passengers and staff (within brackets is the % of time the respective range was met).

			Mean $T_{op.}$ (°C)	Gradient	R^2	$T_{neutral}$ (°C)	T_{pref} (°C)	80% Accept. (°C)	90% Accept. (°C)
Summer	Employees	LCY	23.3	0.389	0.61	22.1	22.1	19.9–24.3 (86%)	20.8–23.4 (57%)
		MAN T1	22.0	0.461	0.74	21.1	21.3	19.3–23.0 (79%)	20.0–22.2 (49%)
		MAN T2	23.0	0.421	0.3	22.4	22.5	20.4–24.4 (83%)	21.2–23.6 (61%)
	Passengers	LCY	23.3	0.243	0.67	21.5	21.4	18.0–25.0 (95%)	19.5–23.6 (66%)
		MAN T1	22.0	0.282	0.82	20.5	20.9	17.4–23.5 (83%)	18.7–22.2 (63%)
		MAN T2	23.0	0.274	0.72	20.7	21.1	17.6–23.8 (68%)	18.9–22.6 (52%)
Winter	Employees	LCY	23.4	0.756	0.38	22.5	22.8	21.4–23.6 (66%)	21.9–23.2 (38%)
		MAN T1	21.3	0.342	0.46	20.6	21.7	18.1–23.1 (70%)	19.2–22.1 (47%)
		MAN T2	21.1	0.362	0.21	22.3	21.9	19.9–24.6 (92%)	20.9–23.7 (69%)
	Passengers	LCY	23.4	0.407	0.86	21.1	21.5	19.1–23.2 (39%)	19.9–22.4 (5%)
		MAN T1	21.3	0.304	0.77	19.2	20.6	16.4–22.0 (60%)	17.6–20.9 (28%)
		MAN T2	21.1	0.219	0.75	18.4	19.9	14.5–22.3 (93%)	16.1–20.7 (28%)

3.5.3. Acceptable temperature ranges

Based on the acceptance of the statistical assumptions underlying PMV/PPD heat-balance model [6], the TS regression models were used for the calculation of the operative temperature ranges in which 80% and 90% of passengers and staff find the thermal environment acceptable. Accordingly, it was assumed that a mean

TS of ±0.85 and ± 0.50 corresponds to 80% and 90% general acceptability respectively.

The results reveal a considerable difference in the adaptive capacity of the two groups, with passengers demonstrating consistently wider ranges of acceptable temperatures (Table 8). The 80% acceptability range was on average 4.0 °C wide for staff and 6.0 °C
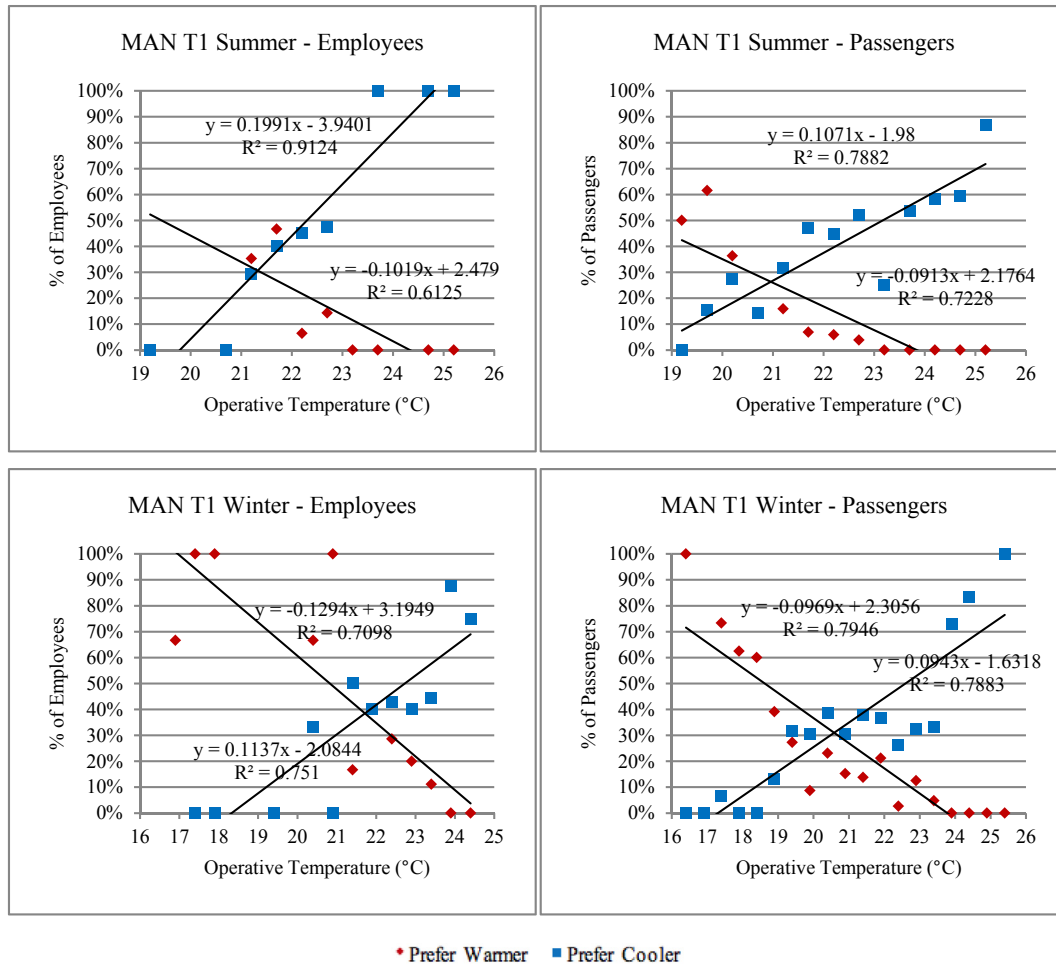
Fig. 10. Preferred operative temperatures for passengers and staff at MAN T1 in summer and winter.

wide for passengers, reducing to 2.4 °C and 3.5 °C respectively for the 90% acceptability range. This difference is predominantly due to the higher acceptance of cooler conditions that passengers demonstrated in all terminals (Fig. 11). On the contrary, it was employees' comfort zone that stretched to higher temperatures in some cases (at MAN T2 in summer and at all terminals in winter) and passengers' in others (at LCY and MAN T1 in summer).

4. Discussion

The data analysis showed that thermal discomfort was common in the three terminals, as demonstrated by the high percentages of unacceptable TS (passengers 10–31%, staff 33–47%; Table 7) and the percentage of people requiring changes in the thermal environment (50% of passengers in summer and 38–62% in winter, 70% of staff in both seasons; Fig. 8). In all terminals the thermal profile was close to the upper boundary of the acceptable temperature ranges, occasionally falling outside the comfort zone (Fig. 11). The mean TS for the two user groups was predominantly on the warm side of the ASHRAE scale (Table 7) and preference for cooler conditions was dominant among those requiring a change (Fig. 8). These results demonstrate that warm rather than cool conditions can be an issue in both summer and winter in such facilities, where neutral is not the desired thermal state for over half the passengers and staff.

Furthermore, the findings revealed a consistent discrepancy

between the thermal comfort conditions for passengers and staff. The thermal requirements of the two groups were shown to vary considerably (Table 8) resulting in thermal conflict across the terminal spaces. Passengers achieved neutrality at lower temperatures than staff by 0.6–3.9 °C, which was lower by an average of 1.0 °C in summer and 2.2 °C in winter. The respective difference in preferred temperature further highlights the thermal conflict between the two groups, with passengers preferring constantly lower temperatures by 0.4–2.0 °C. On average, passengers' preferred temperature was lower than staff's by 0.8 °C in summer and by 1.5 °C in winter. The differences in comfort temperatures were smaller in summer when clothing insulation values were similar and greater in winter when clothing was higher for passengers (Table 4).

The comfort temperatures for employees were in all cases closer to the indoor mean temperature, reflecting their long-term acclimatisation to the terminals' thermal environment that results from the long dwell times and the continuous experience with it. However, despite staff's familiarity with the indoor thermal environment, it was passengers that demonstrated greater adaptation to the thermal conditions. Employees were on average 1.6 times more sensitive to temperature changes than passengers (Table 8), whose TS profile was more stable across the terminal spaces demonstrating a greater adaptive capacity (Fig. 2). In this context, the 80% and 90% acceptability temperature ranges were significantly wider for passengers in all cases. Considering the 80% acceptability range, this was on average 6.4 °C wide in summer and
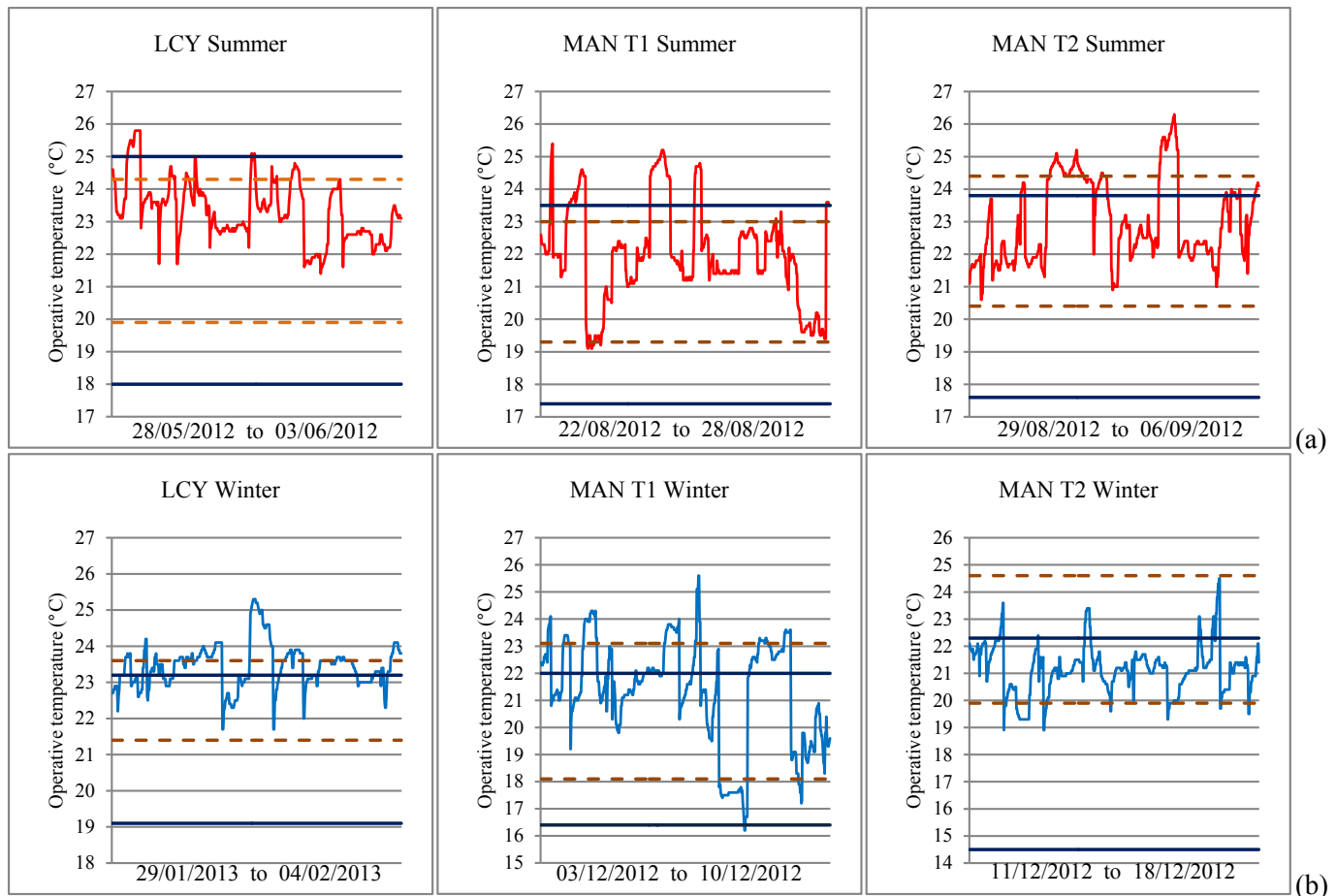
Fig. 11. Continuous operative temperature monitored across the terminal over the survey periods and 80% acceptability temperature ranges of passengers (continuous lines) and staff (dashed lines) in (a) summer and (b) winter surveys.

5.8 °C wide in winter for passengers, reduced to 4.0 °C for staff in both seasons (Table 8). Even when the operative temperature was within the acceptable range for both groups, the percentage of unacceptable TS was consistently higher among employees, while also indicating difficulties in coping with thermal discomfort. Characteristically, 30—40% of employees at each terminal rated the clothing policy as inflexible (on a 3-point scale) in maintaining their thermal comfort, while the vast majority (86—94%) reported no control over the indoor environmental conditions.

The different perspective of the two groups towards the thermal environment was also expressed in the significantly different weighting of the thermal conditions as the worst aspect of their in-terminal experience (4—6% of passengers and 34—40% of employees; Fig. 6). This implies a difference in the perceived importance of the thermal conditions and consequently a different impact on overall comfort. In fact, the highest discomfort levels among staff emerged in the terminal spaces identified as the most thermally-problematic (e.g. arrivals halls in MAN T1 and security search area in MAN T2). On the other hand, the highest discomfort levels among passengers were associated with processing activities including security screening and flight boarding; discomfort was increasing in the search areas, dropping in the departures lounge and slightly rising again in the gate lounges while boarding.

Comparing the results with the relevant guidelines for designers, the comfort zone for passengers is considerably wider than the range recommended by CIBSE for the majority of terminal spaces. Alongside the 80% acceptability ranges, preferred temperatures suggest that lowering the heating set-points in winter − when overheating was more apparent − would improve thermal comfort while leading to energy savings. To ensure, however, that employees' comfort is not compromised, appropriate control strategies, perhaps with localised control, for terminal staff could be considered. On the contrary, the results for summer suggest that increasing the cooling set-points would deteriorate thermal comfort conditions. As shown in Fig. 11, the thermal profile of all terminals was close to the upper limit of the 80% acceptability range with preferred temperatures implying that more cooling was required (Table 8). To provide energy savings for cooling without compromising thermal comfort different strategies can be investigated, from increasing air movement, to reducing peak temperatures, e.g. with the use of phase change materials (PCM). The application of PCM was modelled in an airport terminal in the UK and it was shown to prevent overheating in the summer months reducing peak temperatures up to 3.0 °C [47,48]. Additionally, thermal comfort could also be improved by increasing staff's adaptive capacity, e.g. through more flexible dress codes.

Overall, the findings highlight the perceived difference of the terminal as transition vs. indoor workspace, which is also reflected in the considerably different overall discomfort levels reported by the two groups (8—21% of passengers and 23—49% of employees; Fig. 5). The results are consistent with the broader context of adaptation to the thermal environment, where expectations, time of exposure and perceived control increase thermal tolerance and therefore adaptive capacity [30]. Employees have a limited adaptive

capacity originating from the rigid working conditions associated to the terminals' functions. On the contrary, when and where required in the terminal, passengers can take adjustment actions (e.g. moving to another space, altering clothing levels, etc.) that allow them to cope effectively preventing thermal discomfort.

5. Conclusions

This work investigated the nature of thermal comfort conditions in three airport terminal buildings of different size and typology. The indoor environmental conditions were extensively monitored in different terminal areas along with questionnaire-guided interviews with 3087 people across different seasons. Thermal sensation was predominantly determined by the combination of temperature, clothing insulation and activity levels. The latter two are among the parameters differentiating the comfort conditions of passengers and staff along with the variation in dwell time and overall expectations.

The two user groups presented different satisfaction levels with the indoor conditions, both preferring a different thermal environment to the one experienced. Warm rather cold conditions were most commonly the cause of discomfort, although this was affected by the particularities of each terminal. Passengers' neutral and preferred temperatures were lower than staff's and significantly lower than the mean indoor temperature in all cases, which has significant implications for energy conservation. Viewing the terminal as a transition space, passengers consistently demonstrated a wider adaptation potential through the wide range of acceptable temperatures. On the other hand, employees were more sensitive to temperature changes and their limited adaptive capacity resulted in a narrower comfort zone. From the energy conservation perspective, the results indicate little scope for increasing the cooling systems set-points in summer and alternative methods should be sought. In winter, however, there is a greater potential for energy savings by lowering the heating set-points, provided that more control over the thermal environment is provided to terminal staff. Soft policies such as more flexible dressing codes would also improve thermal comfort for staff.

Ultimately, understanding the differing comfort requirements of the key population groups in airport terminals is important to improve thermal comfort conditions and identify appropriate strategies for reducing energy consumption. Such knowledge can influence the design and potential refurbishment of this energy-intensive sector to maintain occupants' well-being without jeopardising the terminals' environmental performance.

Acknowledgements

References

[1] B. Edwards, The Modern Airport Terminal-new Approaches to Airport Architecture, Taylor & Francis, New York, 2005.

[2] CASCADE, Cascade in Energy-efficient Buildings (EeB PPP) Project Review, 2012.

[3] ACRP. Airport Energy Efficiency and Cost Reduction: A Synthesis of Airport Practice. ACRP Synthesis 21. Washington, D.C.: Transportation Research Board.

[4] E. Cardona, A. Piacentino, F. Cardona, Energy saving in airports by trigeneration. Part I: assessing economic and technical potential, Appl. Therm. Eng. 26 (2006) 1427–1436.

[5] ANSI/ASHRAE Standard 55-2004. Thermal Environmental Conditions for Human Occupancy.

[6] ISO 7730, 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.

[7] P.O. Fanger, Thermal comfort, Analysis and Application in Environmental Engineering, Danish Technical Press, Copenhagen, 1970.

[8] M.A. Humphreys, Field studies of thermal comfort compared and applied, Build. Serv. Eng. 44 (1976) 5–27.

[9] D. McIntyre, Indoor Climate, Applied Science Publishers, London, 1980, p. 154.

[10] N. Baker, M. Standeven, Thermal comfort for free-running buildings, Energy Build. 23 (1996) 175–182.

[11] M. Fountain, G. Brager, R. de Dear, Expectations of indoor climate control, Energy Build. 24 (1996) 179–182.

[12] A. Mahdavi, S. Kumar, Implications of indoor climate control for comfort, energy and environment, Energy Build. 24 (1996) 167–177.

[13] M. Paciuk, The role of personal control of the environment in thermal comfort and satisfaction at the workplace, in: Coming of Age, 21st Annual Conference of the Environmental Design Research Association, 1990 (Champaign-Urbana).

[14] M.A. Humphreys, Classroom temperature, clothing and thermal comfort-a study of secondary school children in summertime, Build. Serv. Eng. 41 (1973) 191–202.

[15] G. Schiller, E.A. Arens, F. Bauman, C. Benton, M. Fountain, T. Doherty, A field study of thermal environments and comfort in office buildings, ASHRAE Trans. 94 (2) (1988) 280–308.

[16] N. Oseland, A comparison of the predicted and reported thermal sensation vote in homes during winter and summer, Energy Build. 21 (1995) 45–54.

[17] G.S. Brager, R.J. de Dear, Thermal adaptation in the built environment: a literature review, Energy Build. 27 (1998) 83–96.

[18] B. Olesen, Guidelines for comfort, ASHRAE J. (August 2000) 41–46.

[19] J.F. Nicol, M.A. Humphreys, Adaptive thermal comfort and sustainable thermal standards for buildings, Energy Build. 34 (2002) 563–572.

[20] M. Humphreys, F. Nicol, S. Roaf, Adaptive Thermal Comfort: Foundations and Analysis, Taylor & Francis, 2015.

[21] M. Nikolopoulou, K. Steemers, Thermal comfort and psychological adaptation as a guide for designing urban spaces, Energy Build. 35 (2003) 95–101.

[22] C.A. Balaras, E. Dascalaki, A. Gaglia, K. Droutsa, Energy conservation potential, HVAC installations and operational issues in Hellenic airports, Energy Build. 35 (2003) 1105–1120.

[23] Z. Wang, H. Zhao, B. Lin, Y. Zhu, Q. Ouyang, J. Yu, Investigation of indoor environment quality of Chinese large-hub airport terminal buildings through longitudinal field measurement and subjective survey, Build. Environ. 94 (2015) 593–605.

[24] J. Liu, N. Yu, B. Lei, X. Rong, L. Yang, Research on indoor environment for the terminal 1 of Chengdu Shuangliu International Airport, in: Eleventh International IBPSA Conference, Building Simulation, Glasgow, Scotland, 2009.

[25] A.D. Babu, A Low Energy Passenger Terminal Building for Ahmedabad Airport, India, in: 'Building Envelope as an Environment Regulator'. PLEA 2008 – 25th Conference on Passive and Low Energy Architecture, 2008 (Dublin).

[26] J.E. Ramis, E.A. dos Santos, The impact of thermal comfort in the perceived level of service and energy costs of three Brazilian airports, J. Transp. Lit. 7 (2012) 192–206.

[27] F. Nicol, Adaptive thermal comfort standards in the hot–humid tropics, Energy Build. 36 (2004) 628–637.

[28] M. Nikolopoulou, N. Baker, K. Steemers, Thermal comfort in outdoor urban spaces: understanding the human parameter, Sol. Energy 70 (2001) 227–235.

[29] ASHRAE, HVAC Applications Handbook (Chapter 3): Commercial and Public Buildings, American Society of Heating, Refrigerating and Air-Conditioning Engineers Inc., Atlanta, GA, 2003.

[30] M. Humphreys, F. Nicol, M. Nikolopoulou, Chapter 1: environmental criteria for design, in: Guide a: Environmental Design, Chartered Institute of Building Services Engineers, CIBSE, London, 2015.

[31] A. Kotopouleas, Thermal comfort Conditions in Airport Terminal Buildings, PhD Thesis, University of Kent, 2015.

[32] Civil Aviation Authority, UK Airport Statistics, July 2015, http://www.caa.co.uk.

[33] Manchester Airport Master Plan to 2030, p.55–56.

[34] M. Nikolopoulou, J. Kleissl, P.F. Linden, S. Lykoudis, Pedestrians' perception of environmental stimuli through field surveys: focus on particulate pollution, Sci. Total Environ. 409 (2011) 2493–2502.

[35] M. Nikolopoulou, Outdoor thermal comfort. Front. Biosci. a Special Issue "Current Issues Therm. Physiology" S3, 1st June 2011;1552–1568.

[36] ISO 7726, Ergonomics of the Thermal Environment – Instruments for Measuring Physical Quantities, 1998.

[37] A. Kotopouleas, M. Nikolopoulou, Understanding thermal comfort conditions in airport terminal buildings, in: Proceedings of 8th Windsor Conference: Counting the Cost of Comfort in a Changing World, 2014 (Windsor).

[38] ANSI/ASHRAE Standard 62.1-2007. Ventilation for Acceptable Indoor Air Quality. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

[39] ISO 9920, Ergonomics of the Thermal Environment – Estimation of Thermal Insulation and Water Vapour Resistance of a Clothing Ensemble, 2007.

[40] B.G. Tabachnick, L.S. Fidell, Using Multivariate Statistics, fifth ed., Pearson Education, Boston, 2007.

[41] M.A. Humphreys, Outdoor temperatures and comfort indoors, Build. Res. Pract. 6 (2) (1978) 92–105.

[42] K.J. McCartney, J.F. Nicol, Developing an adaptive control algorithm for Europe, Energy Build. 34 (2002) 623–635.

[43] R.J. de Dear, G.S. Brager, D. Cooper, Developing an Adaptive Model of Thermal Comfort and Preference, Final Report on ASHRAE RP-884, Macquarie University, Sydney, 1997.

[44] J. Han, G. Zhang, Q. Zhang, J. Zhang, J. Liu, L. Tian, C. Zheng, J. Hao, J. Lin, Y. Liu, D.J. Moschandreas, Field study on occupants' thermal comfort and residential thermal environment in a hot-humid climate of China, Build. Environ. 42 (2007) 4043–4050.

[45] M.A. Humphreys, H.B. Rijal, J.F. Nicol, Examining and developing the adaptive relation between climate and thermal comfort indoors, in: Proceedings of Windsor Conference: Adapting to Change: New Thinking on Comfort, 2010 (Windsor).

[46] Personal communication with Humphreys MA, in: Proceedings of 8th Windsor Conference: Counting the Cost of Comfort in a Changing World, 2014 (Windsor).

[47] B.L. Gowreesunker, S.A. Tassou, Effectiveness of CFD simulation for the performance prediction of phase change building boards in the thermal environment control of indoor spaces, Build. Environ. 59 (2013) 612–625.

[48] B.L. Gowreesunker, S.A. Tassou, M. Kolokotroni, Coupled TRNSYS-CFD simulations evaluating the performance of PCM plate heat exchangers in an airport terminal building displacement conditioning system, Build. Environ. 65 (2013) 132–145.