# THERMAL COMFORT CONDITIONS
# IN AIRPORT TERMINAL BUILDINGS

A thesis submitted for the degree of

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By

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ABSTRACT

Airport terminals are characteristic for the large and open spaces with diverse and transient population. They are designed predominantly as indoor spaces while the overwhelming majority is people in transient conditions. Dressing code and activity, along with dwell time and overall expectations are differentiating factors for variations in thermal requirements between passengers and staff. The diversity of spaces and the heterogeneous functions across the different terminal zones further contribute to this differentiation, which results in thermal comfort conflicts and often in energy wastage.

Understanding such conflicts and the comfort requirements can improve thermal comfort conditions while reducing the energy consumed for the conditioning of these energy-intensive buildings. Through extensive field surveys, the study investigated the thermal comfort conditions in three airport terminals of different size and typology. The seasonal surveys included extensive environmental monitoring across the different terminal areas and over 3,000 questionnaire-guided interviews with passengers, staff, well-wishers and other short stay visitors.

The findings demonstrate a preference for a different thermal environment than the one experienced and that thermal neutrality lies at lower temperatures. The comfort requirements for passengers and staff are evaluated and shown to differ significantly. Neutral temperature for passengers is lower by 0.6 - 3.9 °C. In accordance with the neutrality discrepancies, passengers prefer cooler temperatures than staff by 0.4 - 2.0 °C. Employees have limited adaptive capacity that leads in a narrower comfort zone, whereas passengers consistently demonstrate higher tolerance of the thermal environment and a wider range of comfort temperatures. Furthermore, the findings highlight the complex nature of thermal comfort in airport terminals, where the desired thermal state for more than half the occupants is other than neutral and a multitude of design and operational characteristics influence the indoor environment.

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To my son Alexandros

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# CHAPTER 1: INTRODUCTION TO THE PROJECT

The chapter introduces the reader into the broader research theme and provides an overview of the project's multi-aspect nature. It explains the particular research problem, outlines the research limitations, states the aims and objectives of the study and closes with a description of the thesis structure.

## 1.1 General background

Reflecting and facilitating globalization, the number of airports rose twentyfold between 1940 and 2002, with the air travel increasing tenfold in the past 40 years (Edwards, 2005). Despite the economic downturns and the recent recession in 2008-2009, global passenger traffic is constantly posting strong growth numbers. Expressed in revenue passenger kilometers, passenger traffic grew by 5.3% in 2012 (IATA, 2013), while preliminary data reveal an increase of 5% in 2013 when nearly three billion people were transported by air (ICAO, 2014). In the same year, passenger traffic in the UK increased by 3.5%, with nearly 3 million aircraft movements handling over 228 million passengers (CAA, 2013).

Under the current short and long term projections global passenger traffic is forecasted to grow by 5.9% in 2014 and by 6.3% in 2015 (ICAO 2013), while the number of passengers is expected to increase 2.3 times compared to 2012, reaching 6.7 billion in 2032 (AIRBUS, 2013). Following the upward trends, the latest unconstrained projection for the UK (figure1-1) suggests that, if airports expand as required to meet demand, growth in UK air passengers is likely to be within the range of 1% and 3% every year over the period between 2010 and 2050, reaching 480mppa by 2050 (DfT, 2013).

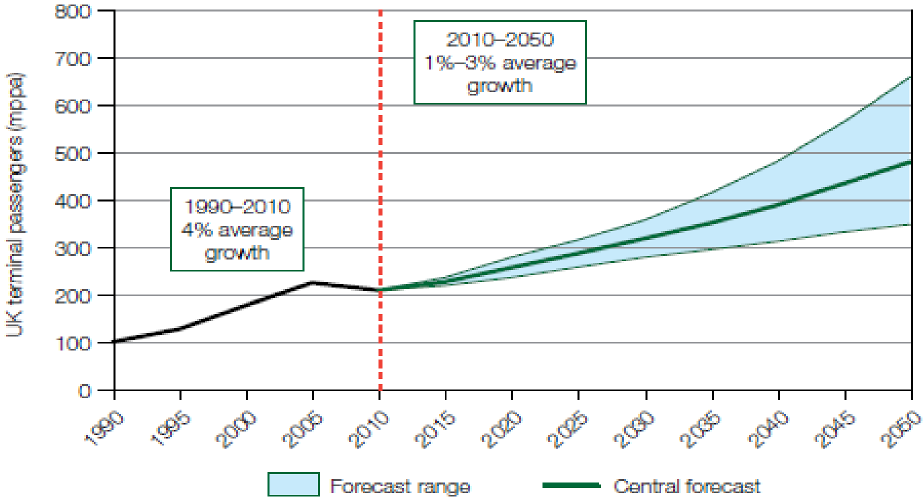



*Figure 1-1: Central forecast and projected range of high and low scenarios for air passenger traffic in the UK between 2010 and 2050 (Source: DfT UK Aviation Forecasts, January 2013).*

As airport terminals have grown larger and more complex over the years to meet passenger demand and the evolving nature of aircraft design, airport operators have been concerned with a number of environmental issues. Traditionally, these include noise mitigation, water quality and conservation, land use compatibility, waste management and local air pollution. Although not new concepts for airports, energy efficiency and climate change are well established among the major environmental concerns incorporated in airports' planning and management strategies in the last two decades.

At the global level, climate change is likely to drive important changes in the aviation industry over the next 10 to 20 years (Upham et al., 2003). In general, aviation is responsible for nearly 11% of greenhouse emissions (GHG) from transportation and about 3% of total emissions (ACRP, 2009). These are dominated by aircrafts in flight and are beyond the control of airport operators. Measurements have shown that the greatest relative contributor to the total GHG emissions by an airport are the aircraft operations (LTO cycles, about 60%), followed by ground aircraft servicing at the apron/gate complex (nearly 20%), the airport ground access systems/modes (15%), and electricity consumption in airport buildings (about 5%), (Janic, 2011). On the other hand, it is also true that there is still a great potential for decreasing GHG originated by the airport building and its services (Baumert et al., 2005). The share of aviation infrastructure is estimated as 3.2% of the total emissions per passenger-km, of which one third is associated to its construction and the remaining two thirds originate from the infrastructure operation (IEA, 2011).

Airport facilities are very energy-intensive environments and one of the greatest energy-consuming centres per square kilometer on our planet (Edwards, 2005). The energy use is de-facto comparable to that of small cities. The typical electrical energy used in a major airport lies between 100-300 GWh/year which corresponds to the consumption of 30,000 to 100,000 households (CASCADE, 2012a). Despite the lack of a standardised method for measuring and reporting energy consumption at airports, published data are representative of the magnitude of the energy use in such facilities (figure 1-2).

For instance, the total energy consumption in the two busiest airports in Italy – Roma Fiumicino (FCO) and Milan Malpensa (MXP) – was 244 GWh and 390 GWh in 2009. In the same year, the total energy use in Manchester airport was 235 GWh, while more recent data (2012) from Gatwick and Heathrow documented an annual energy consumption of 221 GWh and 701 GWh respectively (Gatwick, 2013; Heathrow, 2012).

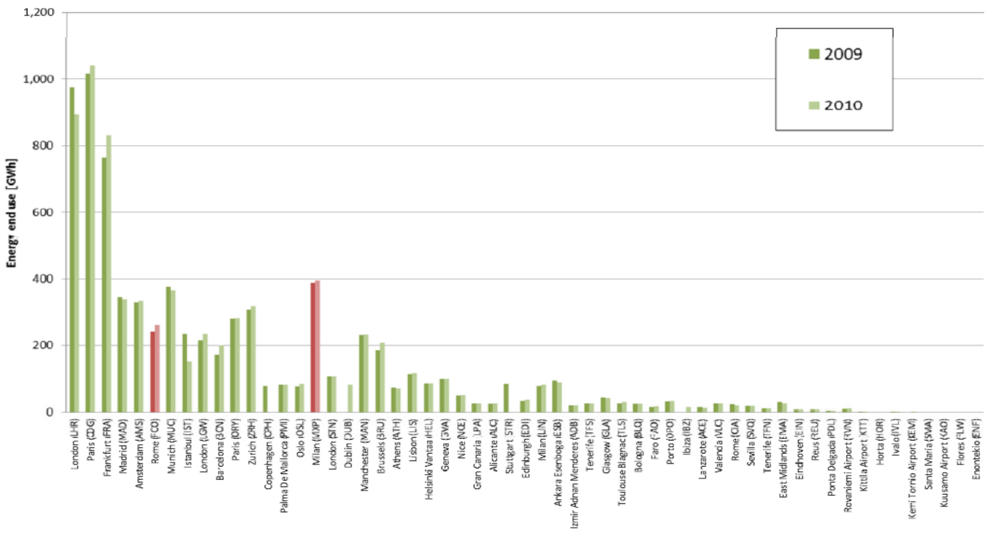



*Figure 1-2: Energy end use data from 55 airports in the period 2009-2010 (CASCADE, 2012b).*

The airport terminal building is one of the permanent features in the aviation infrastructure with a great potential for energy saving advancements. The common energy end-use categories are cooling and ventilation, heating, lighting, as well as baggage and people movers (conveyors). As a result of the variable occupancy in passenger terminal building, the HVAC systems experience transient loads. The indoor environment, on the other hand, plays an important role for the terminal's commercial success as it is expected to serve the many needs of different types of users, while also being crucial for the airport's operational cost.

## 1.2 Research framework and limitations

With a focus on the indoor environment, the study investigates the breadth of thermal comfort conditions in airport terminal buildings with the view of employing wider temperature control set-points for cooling and heating. Beyond the mechanistic efficiency of HVAC systems and the incorporation of innovating technologies, reducing the gap between outdoor temperature and indoor temperature set-points can be a key energy conservation measure. However, should such a straightforward energy-saving action taken without compromising comfort levels, it is necessary to understand the thermal comfort requirements of the terminal population.

Characteristic for the highly dynamic conditions, airport terminals are a particularly complex building type aimed at meeting the comfort requirements of very different population groups. These include terminal staff and passengers, as well as meeters, greeters and other short-stay visitors. The indoor design criteria usually cater for terminal staff, whereas the vast majority is people under transient conditions. Dissimilarity in occupancy type and dwell time, but also in activity, dressing code and overall expectations are differentiating factors for variations in thermal requirements between the population groups. The diversity of spaces and the heterogeneous functions held across the different terminal areas further contribute to this complexity, by differentiating the comfort requirements from one space to another for a given user group while resulting in adaptive disparities between the groups.

Along with the highly fluctuating occupancy levels, such terminal attributes may give rise to thermal comfort conflicts and often to energy wastage for the conditioning of terminal buildings. Further to the energy standpoint, the (dis)satisfaction of terminal population with the indoor environment can also have significant implications for the design and refurbishment strategies of airport terminals, which are regularly modified to improve staff's working environment and passenger experience.

The study used three airport terminal buildings of different size and typology as case studies and a large sample population to secure the statistical significance of the findings. Yet, a greater number of terminals, located ideally in different climatic zones, would allow for a broader comparative analysis and further generalization of the results, especially of those associated with the outdoor weather conditions. Most of the research limitations, however, originated from the nature of the terminal buildings and particularly from the necessary security and safety measures that dictate their operation. Inevitably, all phases of the project – from planning to execution – were influenced and performed as to comply with these measures.

Along with certain particularities of each of the terminals surveyed, these factors limited the acquisition of supplementary data (such as type of HVAC system in every terminal space monitored and energy consumption) that would allow the investigation of the thermal conditions from a building services perspective. Nonetheless, the collection of data – by means of environmental monitoring and questionnaire-guided interviews – essential to the scope of the work was not hindered and the study's aims and objectives were met.

This work is a component of the project "Integration of active and passive indoor thermal environment control systems to minimize the carbon footprint of airport terminal buildings", which brought together research teams from five Universities: Brunel, Loughborough, City, De Montfort and University of Kent. The project was funded by the UK Engineering and Physical Sciences Research Council (EPSRC), with the overall aim being the minimisation of the energy consumption and carbon footprint of airport terminals.

### 1.3 Research aims and objectives

The study aimed at understanding the nature of thermal comfort conditions in airport terminal buildings. Indirectly, this can contribute towards the reduction of cooling and heating energy consumption in airport terminals and of the associated carbon footprint. In the service of this purpose, the following three objectives were set:

1) To investigate the thermal environment in airport terminals of different size and typology, thus allowing for a representative range of the indoor conditions usually experienced in mechanically conditioned terminal buildings.

2) To evaluate the thermal comfort conditions for the people using the terminal buildings and separately for the different population groups – with a focus on passengers and staff – while identifying thermal conflicts and their causes.

3) To investigate the prospect of increasing the cooling set-points in summer and decreasing the heating set-points in winter in consistency with the thermal requirements of terminal users.

The achievement of these objectives is intended to fill a gap in the literature, currently reflected in the absence of extensive field studies and comprehensive understanding of the thermal comfort conditions in airport terminals. Understanding occupant comfort requirements in terminals can improve thermal comfort while influencing the implementation of different energy conservation strategies to reduce energy consumption. Moreover, the outcomes of the study can be useful in the design of new terminal buildings and the refurbishment schemes for existing terminal facilities.

## 1.4 Structure of thesis

The thesis is organized into seven chapters. **Chapter 1** describes the general background of the project and sets the research framework, including the aims and objectives of the study. **Chapter 2** steps into the airport terminal environment. It outlines the evolution of terminals, reviews the configurations emerged over time and presents the up-to-date design considerations. In addition, the chapter identifies the common passenger stressors and addresses indoor environmental quality for terminal buildings. **Chapter 3** introduces the context of thermal comfort into the complex nature of airport terminals. It describes the parameters affecting thermal comfort, outlines the two dominant approaches and explores the adaptive capacity of occupants in terminals. The chapter extends to other aspects of the indoor environment, lighting and carbon dioxide levels, and reviews the existing comfort criteria and associated studies.

**Chapter 4** discusses the characteristics that convoyed the selection process of the case studies and provides a comprehensive description of the airport terminals surveyed. **Chapter 5** focuses on the methodology adopted. It discusses the design of the research tools, the pilot studies that followed their development, the nature of the work carried out in the case study terminal buildings, as well as the respective limitations in data collection that emerged during the project.

**Chapter 6** presents the results of the data analysis. The outline of the plan developed for the statistical analysis and the description of the sample population succeeds an overview of the environmental conditions and satisfaction, and the examination of the parameter “clothing”. Thermal sensation and preference are assessed and the determining factors are identified. Neutral and preferred temperatures specify the thermal comfort conditions for the terminal population and quantify the diverging thermal requirements of passengers and staff. The formative factors of the thermal environment are explored, along with the investigation of the thermal conditions and the evaluation of occupants’ comfort requirements in the different terminal spaces. The chapter also stresses the perception and preference over the lighting environment and the environmental conditions influencing overall comfort. Additionally, the perceived importance of the indoor environmental conditions and of the thermal conditions in particular, is assessed and juxtaposed with non-environmental parameters. **Chapter 7** discusses the findings of the study, concludes the research work and provides recommendations for further work in this field.

## CHAPTER 2: THE AIRPORT TERMINAL ENVIRONMENT

### 2.1 Introduction

Introducing the reader into the terminal environment, the chapter commences with an overview of the airport terminal evolution since aviation's infancy and defines the terminal complex as developed nowadays. Driven by aircraft and passenger trends, the terminal design holds a key role in the characteristics of the indoor environment which in turn influence occupants' comfort requirements. Accordingly, the different configurations implemented in airport terminals are highlighted along with the design considerations for such facilities. Also, the chapter discusses the common stressors in airport terminals which may influence passenger comfort and closes with a review of the research findings on indoor environmental quality that are important to the airport terminal environment.

### 2.2 Evolution of airport terminals

In the very early days of aviation there were no terminal facilities as we know them today. It was the introduction of the airmail operations in the early 1920s which stimulated the development of the first civil airport terminal facilities. These were small depots, usually single-room facilities, similar to those used in the rail transportation system. While very little was yet required in terms of passenger and cargo services, these facilities were mainly used for loading and uploading the mail, as well as for aircraft fueling and maintenance.

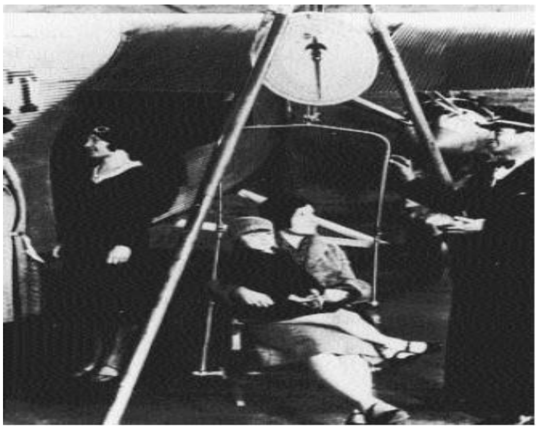


*Figure 2-1: Passengers weigh before departing from Chicago's Midway Airport in 1927 (Wells and Young, 2004).*

The earliest commercial passenger services were introduced in the late 1920s, leading to the development of the first passenger processing policies. Influenced from the rail transportation, tickets and boarding passes were introduced, while cargo transportation started being charged according to the weight. Sometimes, passengers were also weighed in order to ensure that the maximum takeoff weight of the airplane is not exceeded (figure 2-1).

The first terminal buildings known as "simple-unit" terminals sprang up during the 1930s and were centralised facilities accommodating all passenger processing facilities, airports' administrative offices and air traffic control facilities. As air transport became more popular in the 1940s and 1950s, airport terminals expanded to accommodate growing volumes of aircraft, passengers and cargo. The advent of fast monoplane aircrafts during World War II provided a huge impetus which transformed civil aviation. Jet-engined aircrafts were further developed in the 1960s, leading to the conversion of most fleets to jets which were faster, more comfortable and with larger capacities than their piston-engined counterparts. Air travel had begun to replace rail and ocean liner as the favoured transport means for long-distance journeys. The larger jet aircrafts triggered significant changes in the terminal buildings and airport planners started moving away from the single-design concept. Terminals had to move beyond the niche designs catering for few wealthy patrons, to alternative configurations capable of accommodating thousands of passengers and meeting traffic variations. As there were no guidelines to work on, experimentation was the rule.

The terminal typology was established in America, where new airport layouts (e.g. hub airports) and terminal configurations emerged in the 1950s and 1960s, including the standard two-level departures and arrivals concept adopted by many civic terminals nowadays. In the 1970s, the epicentre was shifted to Europe where airports integrated with other transportation modes were developed (Edwards, 2005). Deregulation and privatization in the 1970s and 1980s unfolded commercialization in passenger terminals, with the UK pioneering the notion of terminals as large retail malls and Europe leading the way (Edwards, 2005; Graham, 2008). In the 1980s, the emphasis in the Middle East and parts of the Far East was more upon the terminal architecture as an expression of national symbolism, resulting in the development of imposing terminal buildings (Edwards, 2005).

With thousands of passengers cycling through every day, airport terminals nowadays have become complex buildings incorporating the fundamental – as perceived today – passenger and baggage processing services, as well as a wide spectrum of commercial and customer service facilities. Thus, today we are fortunate to be able to look back at the different terminal designs emerged over the years and understand the advantages and disadvantages of each configuration.

### 2.3 Defining the terminal complex

The passenger terminal constitutes the key element of the airport infrastructure, comprising the interface between the ground access system and the aircraft. The terminal building is designated to serve aircrafts and passengers, and as such its components may be thought of as falling into two primary categories: the apron and gate system, and the passenger and baggage handling system (Wells and Young, 2004). The apron and gates provide stands for aircrafts and serve the purposes of enplaning and deplaning passengers and cargo, preflight preparation and aircraft servicing. The passenger and baggage handling system is a series of links and functions that facilitate the transfer between ground access and aircrafts and can be subdivided to access/processing interface, passenger processing and flight interface (Wells and Young, 2004).

The access interface accomplishes the change of transport mode; it is a complex system of facilities that coordinates the transfers between ground transportation and the terminal building. These include parking facilities, automated conveyance systems to and from parking facilities, sidewalks, connecting roadways, terminal curb fronts, shuttle services, taxi stands and rail stations. The access interface involves activities such as circulation, parking, and curbside loading and unloading of passengers, all aimed to enable originating and terminating passengers, visitors and baggage to enter and exit the terminal (Horonjeff et al., 2010; Ashford et al., 2011).

Passenger processing facilities serve the major processing activities required for origination, termination, or continuation of an air transportation trip. They house a number of public and non-public facilities including baggage sorting and processing facilities for inbound and outbound flights, airport administration and service areas, operations and maintenance facilities, ticketing and baggage check-in counters, baggage and passenger security stations, information kiosks, customs facilities, car rental and other ground transportation desks. The primary activities taking place within this component are ticketing, baggage check-in, baggage claim, security, passport check, customs and immigration (Wells and Young, 2004; Horonjeff et al., 2010).

The flight interface provides the connection between the passenger processing facilities and the aircraft. A number of facilities are provided to perform the functions in the flight interface, including moving sidewalks, buses and mobile lounges, loading bridges and air stairs, holdrooms, service counters and gate lounges. The activities that occur here include assembly, conveyance to and from the aircraft, and aircraft loading and unloading. (Wells and Young, 2004; Horonjeff et al., 2010)

A more tangible demarcation of the terminal facilities than the apron-gate and the passenger-baggage handling systems is that between landside and airside, with the physical boundary between the two being marked by the passenger and baggage security screening. Landside is most often open access and extends from the locations where passengers are dropped off the ground transport to the security screen facility. In most terminals, the airside is subject to strict control of access, allowed only to passengers and authorised staff, though in airports where airlines operate their own terminals (e.g. in the U.S.), wavers are allowed to reach the aircraft gate.

Airport terminals encompass three principal stakeholders: passengers, airlines and the airport operator. Passengers' volume is most often significantly larger than airline and airport staff, and as the prime reason for terminals' existence, passengers are deemed as the major source of airport revenue during the time that they spend in the terminal. Accordingly, most of the current terminal designs emphasize on passenger requirements with the maximum accommodation of passenger needs being a key objective in terminal design. The latter is also important for the operational efficiency of airlines which comprise one of the main agents of the airport operations and constitute another prime source of airport income. In terminals owned by airlines or where they are shareholders of the investment capital, they have a substantial role in terminal design decision making. From the airport operator perspective, terminal design requires equilibrium between operating efficiency and provision for an acceptable working and transient environment for its employees and passengers respectively. The extent at which the terminal meets the requirements of all these constituencies determines the success of its design.

### 2.4 Configuration of airport terminals

Airport terminals come in many sizes, shapes and configurations. Terminal type matters because it influences the terminal layout, the volume of spaces and the types of HVAC systems, all of which greatly affect the indoor environment and influence people's comfort. Different terminal design concepts result in terminals of different size and capacity which determine the type, nature, and scale of the energy infrastructure.

In general, there are two prime categories of terminal concepts. The first is associated to the nature of terminal processing; centralised or decentralised. The underlying premise of a centralised terminal is that all baggage and passenger processing is taking place in a single facility. Decentralised processing, on the other hand, means that these functions are spread in multiple unit terminals, each one operating independently. The second category encompasses four basic terminal configurations: linear, pier, satellite and transporter as illustrated in figure 2-2 (FAA, 1988; Wells and Young, 2004; ACRP, 2010a; Horonjeff et al., 2010; Ashford et al., 2011).

In its simplest form, the linear or open-apron concept is the most straightforward among the four basic concept types. It is the outward expansion of the simple-unit terminal in a rectangular, linear or a curvilinear manner. It consists of a common waiting and ticketing area with exits leading to the aircraft parking apron. Aircrafts are arranged along the face of the terminal and passengers access them directly across the apron or by direct connection to the main terminal building. Consequently, this concept offers ease of access and relatively short walking distances. Nowadays, it is often adaptable to low activity airports and allows for future expansion of the terminal either by its linear extension or by developing two or more linear-terminal units with connectors.

Evolved during the 1950s in the U.S. and during the 1960s in Europe (opened in 1962, Terminal 1 at Manchester airport was the first terminal in Europe to have piers), the pier or finger concept provides interface with aircraft along piers extending from the main terminal. Aircrafts are parked on both sides of the pier and along its axis, which serves as departures lounge and circulation space for both enplaning and deplaning passengers. Access to the terminal area is provided at the base of the pier. The major advantage of this concept is the prospect of the pier's incremental expansion when additional aircraft stands are required, without necessitating the expansion of the central terminal facility. Pier terminals have been proven to be very efficient at airports handling up to 45 mppa, but at higher volumes the physical size of the terminal is likely to present considerable problems with respect to passenger walking distances and transfer times (Ashford et al., 2011).

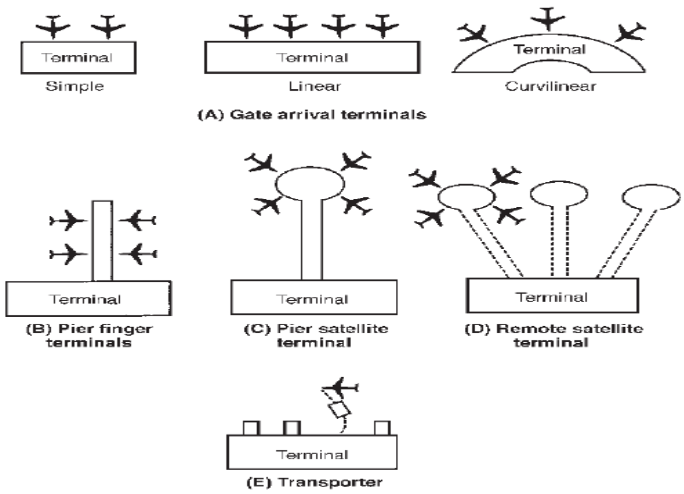



*Figure 2-2: Basic terminal design concepts (Source: FAA).*

The satellite concept evolved in the 1960s and 1970s, and similarly to the pier concept it consists of concourses extended from the main terminal building. At the end of the concourse, aircrafts are parked around the satellite in radial or parallel positions depending on the satellite's size and shape. Usually, circular satellites provide aircraft stands for 4 to 8 aircrafts, whereas the linear ones may well have 20 stands per side. Satellites are connected to the terminal by a surface, underground, or above-grade connector and can have common or separate departure lounges. Although the satellite structure can be compact, the walking distance from the terminal can be very lengthy. Thus, satellite terminals are often equipped with mechanized people-moving systems, such as automated passenger movement systems (APMs) and moving walkways to transport passengers between the satellite and the main-unit terminal. An additional disadvantage is that it lacks flexibility for expansion. On the other hand, among the chief advantages of this concept is the ease of aircraft maneuverability around the satellite and its adaptability to common departures lounge and check-in functions.

In the transporter or open apron concept, aircraft and aircraft-servicing functions are remotely located from the terminal. Deplaning and enplaning passengers are transported to and from the terminal by vehicular transport – buses or mobile lounges – thus walking distances are shorter in this configuration. Other important advantages are the flexibility in providing additional aircraft stands and the easy maneuvering of aircraft of under their own power. The main disadvantage, however, is the high initial, operational and maintenance cost associated with the transporter vehicles.

As a result of the volatile changes in civil aviation in the 1970s many airport terminals expanded in an ad hoc way. In the same period of time, issues related to passenger needs such as long walking distances, congestion and wayfinding became more popular. Nowadays, these have led to hybrid configurations adopted in many airport terminals worldwide, where two or more of the basic concepts have been incorporated in the terminal estate. It is often the case that hybrid terminals are the result of expansion over time and likely have different energy infrastructure and different heating/cooling strategies.

### 2.5 Design considerations for terminal facilities

The design of airport terminal buildings requires the consideration of an enormous number of variables due to the multitude of activities and stakeholders involved. First and foremost, terminal spaces are expected to provide a good level of service to all users, however, planning and design of the overall terminal facility is greatly influenced by the more rigid requirements of accommodating the aircrafts' needs. It is the latter that largely determines the size of the apron and gate system, and along with the nature of airport operation and forecasted passenger volume, it influences the overall terminal design to a great extent.

In an industry of little stability, airport terminals are subject to both internal changes and external expansions with the pace of change being the uncertain factor. The motive for change tends to be the aircraft design as it evolves, but airports also change to adapt to passenger loads growth and optimize operational efficiency. Therefore, flexibility is a major objective in the overall terminal design, allowing for the modification of spaces and activities during the terminal's lifetime at minimum cost and without disrupting operations.

Various guidelines and standards provide design requirements for terminal spaces. One of the most widely used, the "level of service" (LOS) framework was originally developed by Transport Canada (TC) in the 1970s, as the definitions of "capacity" at this period of time were considered inadequate. In the context of airport terminal planning, LOS is a general term that describes, either qualitatively or quantitatively, the service provided to passengers at various points within the airport terminal building. LOS measure ranges from "A" to "F", where level

“A” is excellent and level “F” is the point of system breakdown (table 2-1). The standard assumption is that airport planners should design for LOS “C” for ordinary use (Neufville and Odoni, 2003).

*Table 2-1: Level of service framework (IATA, 2004).*

| | |
|---|---|
| A | An Excellent level of service. Conditions of free flow, no delays and excellent levels of comfort |
| B | High level of service. Conditions of stable flow, very few delays and high levels of comfort. |
| C | Good level of service. Conditions of stable flow, acceptable delays and good levels of comfort. |
| D | Adequate level of service. Conditions of unstable flow, acceptable delays for short periods of time and adequate levels of comfort. |
| E | Inadequate level of service. Conditions of unstable flow, unacceptable delays and inadequate levels of comfort. |
| F | Unacceptable level of service. Conditions of cross-flows, system breakdowns and unacceptable delays; an unacceptable level of comfort. |

Most often, LOS denotes the degree of congestion or crowding experienced at the passenger and baggage processing facilities (figure 2-3), while it may also relate to length of queues, passenger walking distances and dwell time at these facilities (Horonjeff et al., 2010; ACRP, 2011). Most of these parameters are evaluated in a terminal design with the aid of mathematical modeling.

| Check-in area for single queue ($m^2$/occupant) LOS | A | B | C | D | E |
|---|---|---|---|---|---|
| Few carts, little luggage, row width 1.2 m | 1.7 | 1.4 | 1.2 | 1.1 | 0.9 |
| Few carts 1 or 2 pieces of luggage, row width 1.2 m | 1.8 | 1.5 | 1.3 | 1.2 | 1.1 |
| High % passengers using carts. Row width 1.4 m | 2.3 | 1.9 | 1.7 | 1.6 | 1.5 |
| Heavy flights with 2 or more items per passenger high cart usage, row width 1.4 m | 2.6 | 2.3 | 2.0 | 1.9 | 1.8 |

| Circulation Space and Speeds Location | Carts | Space $m^2$ per passenger | Speed m/sec |
|---|---|---|---|
| Airside | None | 1.5 | 1.3 |
| After check-in | Few | 1.8 | 1.1 |
| Departure area | Many | 2.3 | 0.9 |

| Single-Queue Passport control LOS | A | B | C | D | E |
|---|---|---|---|---|---|
| $m^2$ per passenger in passport control | 1.4 | 1.2 | 1.0 | 0.8 | 0.6 |

| Passenger Holding Areas LOS | A | B | C | D | E |
|---|---|---|---|---|---|
| Max. occupancy rate, % capacity | 40 | 50 | 65 | 80 | 95 |

| Bag Claim Area IATA Standard Assumes that 40% of passengers use carts LOS | A | B | C | D | E |
|---|---|---|---|---|---|
| $m^2$ per passenger | 2.6 | 2.0 | 1.7 | 1.3 | 1.0 |

*Figure 2-3: IATA Level of Service (LOS) Standards, 2004 (IATA, 2004; Ashford et al., 2011).*

There is a number of design standards used for the design of specific terminal facilities. As the design context differs substantially between airports, no single set of standards can be applicable to all airports. These standards express subjective judgments rather than scientific facts. As such, they differ between countries while they may also differ within the same culture. For instance, a privately managed airport may prioritize economy and efficiency, whereas a public owned airport may be concerned with other issues, such as to represent a national or regional impressive gateway. Table 2-2 illustrates the diversity between design standards from different organizations. They all provide seating for about 50% of passengers and may allow more space for seated passengers. In practice, however, the standards imply different sizes for departure lounges for identical aircraft (Neufville and Odoni, 2003).

*Table 2-2: Illustrative differences in design standards for departures lounges (Neufville and Odoni, 2003).*

| | Standard for | | |
|---|---|---|---|
| Source of Standard | Seated Passengers ($m^2$/passenger) | Standing Passengers ($m^2$/passenger) | Mix, percent seated |
| Aéroports de Paris | 1.5 | 1.0 | 50 to 75 |
| Amsterdam/Schiphol | 1.0 | 1.0 | 50 |
| BAA | 1.0 | 1.0 | 60 |
| IATA | 1.0 to 1.5 | 1.0 to 1.2 | 50 |

Security is an extremely important function within the terminal spaces and inevitably influences terminal design. Since the early 1960s, terrorism threats to civil aviation have become commonplace. At first, these were associated with aerial hijackings but nowadays the threat has extended to airport facilities. Although security considerations are of operational nature, their implementation has extensively penetrated terminal design, such that security countermeasures have become a fundamental component in the layout of terminal buildings. The demarcation of terminals into airside and landside is a major by-product of security measures. Furthermore, security considerations are often the motor of ad hoc modifications in airport terminals. This is the case of many terminals designed prior to the provision for aviation security schemes, especially at the levels required since 2001 (Ashford et al., 2011).

The need for concessions and retail revenues in terminal buildings pose additional considerations in terminal design. In short, airport operators have five main revenue sources: landing fees, concessions in terminals, leasing with air carrier operators, leasing of non-airline services (e.g. car parks) and equipment rental (Edwards, 2005; Graham, 2008). Contrary to expectations, it is not the airlines that commonly generate the bulk of the airport revenues. For typical airports, landing fees represent nearly 20% of total earnings, whereas revenues made out of commercial activities can approach 50% of total income (Edwards, 2005). For example, car parks at Stansted yield higher revenues than the landing fees, while at Heathrow revenues generated from the lease or sale of concessions is one of the principal sources of income, again exceeding the landing fees. Consequently, the implications of commercial facilities to terminal design are reflected in the maximization of the available space allocated for such activities in the terminal and the creation of a conducive to loitering environment aimed at maximising dwell time (Edwards, 2005).

Airport reputation is largely determined by the quality of the terminal buildings, not just as architectural entities but in terms of meeting customer needs. Successfully designed terminals enhance the status of airports and the air carriers using them while ensuring a comfortable and stress-free journey for passengers. Therefore, there is a trend towards designing out stress by creating calm places for contemplation (Edwards, 2005).

### 2.6 Common stressors and passenger behaviour

While the design of certain terminal spaces is constrained by the needs of staff, passengers and visitors, passengers are considered the most important out of all the terminal users. For many airports non-aeronautical revenues are a substantial proportion of the overall revenue, with the commercial ones accounting on average for nearly half of all revenues (Graham, 2009). Therefore, providing a comfortable environment to passengers is an important objective for airport operators. The terminal environment, however, can be very stressful and various factors may influence passenger comfort and behaviour.

Crowding is a common phenomenon in airport terminals during peak-hours or out-of-peak hours due to adverse weather conditions or operational issues causing delays. When airports experience congestion, passengers experience stress. Airport terminals are stressful places with periodic bottlenecks at check-in, security control, customs, and departure gates. The areas where stress occurs are often the most physically confined (Edwards, 2005). Regardless of the specific environmental and personal factors which may be involved, all situations of crowding involve manifestations of stress. The so called “crowding stress” can be expressed in the form of psychological or physiological strain. Psychological stress can be the result of the realization that one’s demand for space exceeds the available supply or from emotional imbalance resulting from feelings like lack of privacy. Physiological stress involves disequilibrium in one’s internal response system (e.g. increased blood pressure, temperature) and can be triggered by purely spatial variables, as evidenced in the discomfort of feeling cramped (Loo, 1974).

Other stress factors in the terminal environment originate from passenger activities associated to terminal functions. In general, passenger activities in terminal buildings can be classified into processing and discretionary (Kirk, 2013). Processing activities are the necessary activities to be completed, such as check-in, security screening and passport control. Discretionary activities include all activities performed while passengers move between processing points. Although the proportion of time spent for these activities varies greatly from one terminal to another depending on size and speed of processing, data collected from three airports in Australia show that passengers spend on average 36% of their dwell time in processing and 64% for discretionary activities (Kirk, 2013). Throughout their time at the airport, passenger stress levels fluctuate depending on where they are within the airport processes (Scholvinck, 2000; Graham, 2008). Elevated levels of negative emotions, including stress and anxiety are experienced in the periods immediately before and during the completion of processing activities (Thomas, 1997; Scholvinck, 2000; Livingstone et al., 2012). According to the “travel stress curve”, higher levels of stress are expected in the check-in, security screening and boarding (figure 2-4).

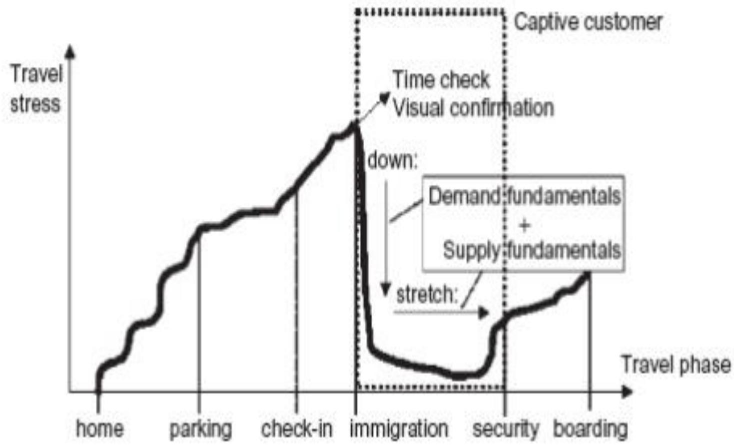



*Figure 2-4: Travel stress curve (Scholvinck, 2000).*

However, these are partly supported from a survey conducted in six major international airports. Based on 2,526 passengers (40% of who were in transit), the results showed that 31% of passengers considered security checks as the most stressful, nearly twice as much as a flight transfer (16%), while check-in and bag drop was rated most stressful by 12% of the interviewees. The same survey also reported that “loss of time” and particularly the fear of missing a flight due to long wait times and queues is by far the greatest cause of stress, as reported by 44% of interviewees. Other top stress origins were “unexpected changes”, according to 11% of passengers, followed by “lack of control” (8%) and “lack of information” (7%), (SITA, 2013).

Such differences are reasonable due to the uniqueness of each airport terminal. For example, check-in and security screening may be functionally the same in most terminals, but factors including terminal capacity, nature of traffic and speed of passenger processing differentiate passenger perception and behaviour. In addition, passenger behaviour itself varies according to the purpose of trip, the flight logistics and the type of flight (Ashford et al., 1976; Weston, 2004;

Ashford et al., 2011). For instance, with respect to the purpose of travelling, business passengers tend to spend less time in the terminals, and as revealed by a study conducted in four airports in the UK, they are also less willing than leisure passengers to wait at passport control (84% vs. 63%), security (57% vs. 38%) and check-in/fast bag drop (58% vs. 30%). Moreover, the same survey reported that those who were flying with a no-frills air carrier were no more willing to accept longer waiting times than those flying with a full-service airline (CAA, 2008).

## 2.7 Indoor environmental quality in airport terminals

Beyond the functions and common stressors associated to the nature of airport terminals, the indoor conditions are an integral element of passenger experience and a key component for the satisfaction of terminal employees with their workspace. Indoor air quality (IAQ) is often the most popular among the different aspects of indoor environmental quality (IEQ) addressed in airports' master plans and sustainability reports. It encompasses issues related to microbial contaminants, gases such as carbon monoxide (CO), carbon dioxide ($CO_2$) and volatile organic compounds (VOCs) and particulates that can induce adverse health conditions. At this type of facility, most issues relating to IAQ arise as a result of fumes and odour from kerosene-based products entering the terminal building through air intake systems and air handling units.

Research on the indoor environmental quality (IEQ) in airport terminals is very limited. Nevertheless, certain conclusions that have been drawn from studies conducted systematically in a number of other building types can be of high importance for the airport terminal environment. Thermal, visual and acoustic environment along with indoor air quality have been well documented to impact occupant satisfaction (Humphreys, 2005; Astolfi and Pellerey, 2008; Lai et al., 2009; Wong et al., 2008). Yet, satisfaction with one or more environmental aspects of the building performance does not necessarily yield satisfaction with the entire environment, while the individual IEQ factors do not contribute equally to the subjective assessment of the indoor environment (Humphreys, 2005; Bluyssen et al., 2011). Along with the environmental parameters, a number of non-environmental factors can influence occupant satisfaction; among others the space layout and size, view, aesthetics and occupant control over the indoor environment (Veitch et al., 2007; Choi et al., 2009; Bluyssen et al., 2011).

Studies conducted in a number of different building types have reported diverging results in respect to the IEQ attributes that impact overall satisfaction the most. This suggests, among others, the plethora of factors involved in the subjective judgment of ranking the important IEQ factors. Frontczak et al. investigated which subjectively evaluated IEQ factors affect occupant satisfaction the most in office buildings while taking into consideration the effect of building features. The results revealed that the three most important parameters were the amount of space, noise level and visual privacy. Among the environmental factors noise level and sound privacy were the most significant, followed by temperature, amount of light and air quality (Frontczak et al., 2012). A comprehensive literature survey conducted by Frontczak and Wargocki addressed studies conducted in different building types including schools, residences and office buildings. The study reported that thermal comfort is ranked to have slightly higher importance compared to acoustic comfort and satisfaction with air quality, and considerably higher importance than visual comfort (Frontczak and Wargocki, 2011), though this finding is not universal among all the studies examined (figure 2-5).

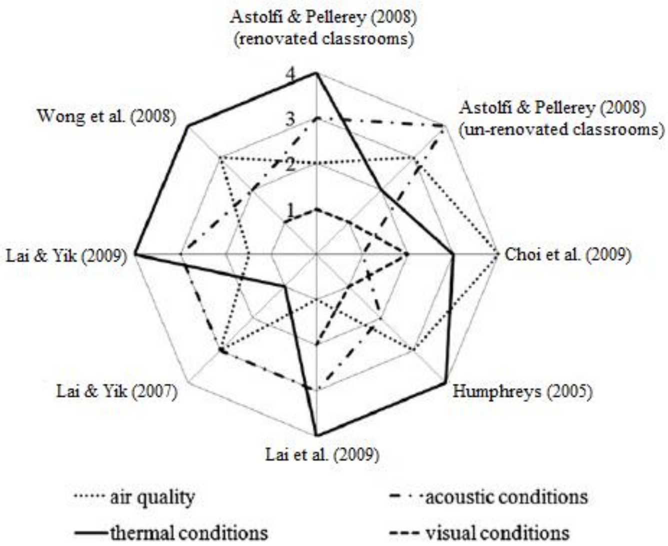



*Figure 2-5: Ranking of importance of IEQ attributes for overall satisfaction, higher number indicates higher ranking (Frontczak and Wargocki, 2011).*

Other researchers have demonstrated that the perceived significance of IEQ attributes varies upon different psychophysical factors such as gender and time spent in the building (Lai and Yik, 2007), as well as between buildings of the same type in different countries (Humphreys, 2005). Additional influencing factors have been seen in the distance between workplace and window, country of origin, level of education, type of job, psychosocial atmosphere at work, time pressure, type of building and whether a person is an occupant or a visitor (Lai and Yik, 2009; Frontczak and Wargocki, 2011).

Moreover, studies have revealed that when occupants are more dissatisfied with a given condition, the latter is considered to be of higher importance (Wong et al., 2008; Lai et al., 2009), though this finding is not supported by other studies (Astolfi and Pellerey, 2008; Choi et al., 2009; Frontczak and Wargocki, 2011). Further to this point, Kim and de Dear used Kano's model (Kano, 1984), developed formerly in the marketing domain, to analyse a large dataset from 351 different office buildings with different ventilation types across various climate zones and countries. The study categorized 15 IEQ parameters in question into basic, bonus and proportional factors. Basic factors are those expected by occupants, thus are regarded as minimum requirements whose absolute magnitude of the impact resulting from underperformance is greater than the impact resulting from positive performance. Bonus factors are not normally expected by occupants, so the absolute value of the impact on overall satisfaction resulting from positive performance is greater than that resulting from underperformance. Proportional factors impact occupants' satisfaction or dissatisfaction proportionally depending on their performance level.

The study demonstrated that the influence of an individual IEQ factor depends on whether the factor in question is delivered at a satisfactory level or not (Kim and de Dear, 2012b). Subsequently, Kim and de Dear distinguished between the buildings with different ventilation types and showed the different expectations on IEQ factors between occupants in naturally ventilated, mixed mode and air-conditioned buildings. In naturally ventilated buildings temperature was found to be among the bonus factors. On the contrary, the negative impact of thermal performance in AC buildings (regression coefficient r = -0.22) was two times greater than its positive impact (regression coefficient r = 0.11) as shown in figure 2-6, suggesting that temperature is among the basic factors, and thus a minimum requirement in AC buildings (Kim and de Dear, 2012a).

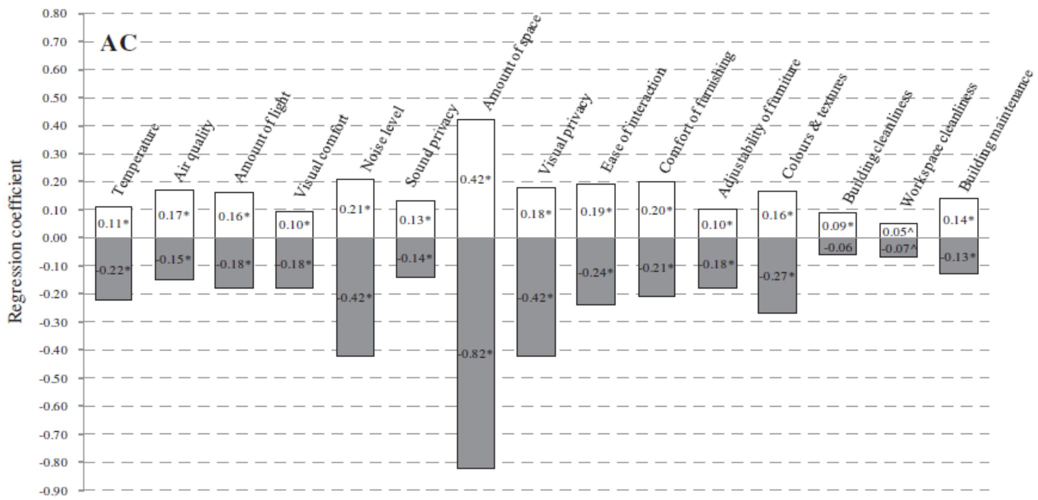



*Figure 2-6: Positive (unshaded) and negative (shaded) impact of IEQ factors on overall workspace satisfaction in AC buildings (Kim and de Dear, 2012a).*

IEQ in airport terminals has been addressed by a single study. It was conducted in three Greek airports where a standardised questionnaire was used to collect subjective data on IEQ from a total of 97 employees and 188 departing passengers. The results highlighted the different aspects of IEQ concerning the users of the three terminal buildings and revealed highly different satisfaction levels with all IEQ parameters between the two population groups in all three airports (figure 2-7).

For instance, in one of the airports (airport A), thermal dissatisfaction in summer was the most significant issue among employees due to low temperatures prevailing in most air-conditioned spaces, whereas for passengers that was the non-uniform and insufficient lighting in certain areas, and the excessive lighting with glare issues in other. This finding underscores the importance of dwell time in the way the two population groups perceive the indoor conditions. Towards the same conclusion are the results reported for airport B. The percentage of employees dissatisfied with the thermal and acoustic environment was double than that of passengers', and three times higher in respect to the lighting environment. Similar are the findings from airport C, where nearly half the passengers were dissatisfied with the lighting and acoustic environment, while for employees the overall IEQ was problematic (Balaras et al., 2003).

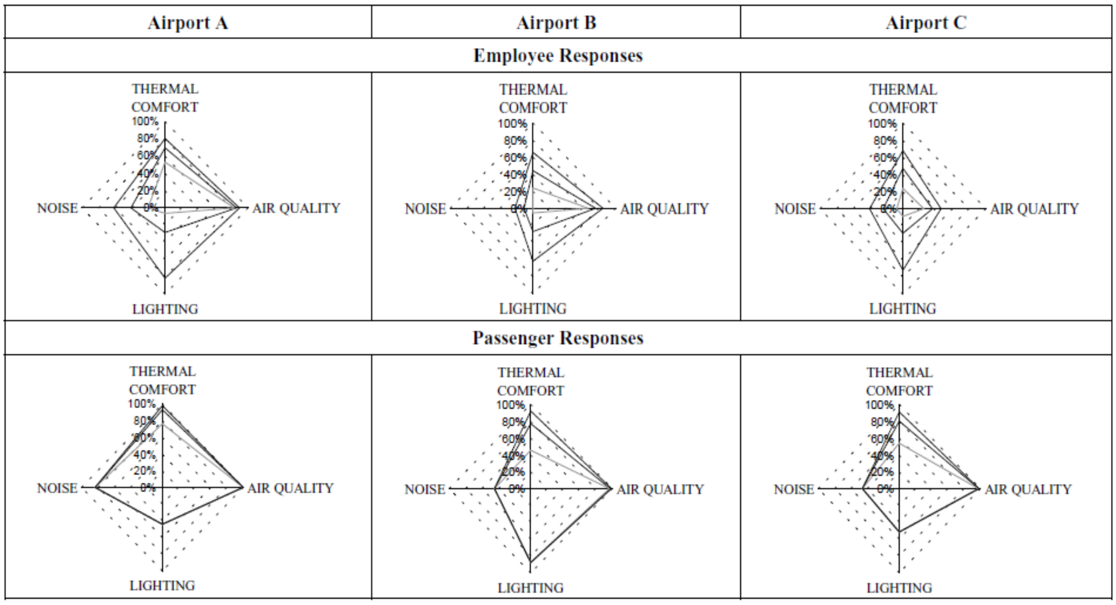



*Figure 2-7: Percentage of employees and passengers satisfied with the indoor environmental quality at three Greek airports (bold line is the average value, light grey is the minimum and light black is the maximum value), (Balaras et al., 2003).*

Different voluntary assessment schemes have emerged in different countries to enhance building environmental performance. Representative examples include the Building Research Establishment's Environmental Assessment Method (BREEAM) developed by the Building Research Establishment (BRE) in the UK and the Leadership in Energy and Environmental Design (LEED) developed in the U.S. by the Green Building Council (USGBC). IEQ is among the five categories of the LEED assessment system and included in the category 'Health and

Wellbeing' in BREEAM. Several airports nowadays have achieved relevant certification, while more have incorporated actions aimed to improve building performance in their environmental agenda. Notable example is the Logan International airport in Boston which was the first U.S. airport to receive LEED certification after an extensive redesign of Terminal A in 2006. The redesign included a roofing membrane and paving that reflect solar radiation and systems for daylighting, water conservation and waste recycling (AGG, 2009). Also, Terminal B at Mineta San Jose International Airport earned LEED silver in 2010 for its focus on water conservation and smart heating, cooling and lighting systems (SJC, 2011). In the UK, Heathrow's Terminal 2 was the first airport terminal awarded with a BREEAM rating for its sustainable building design (Heathrow, 2014).

## 2.8 Conclusions

As a result of the aviation's rapid development in the 20th century, airport terminal buildings expanded in various forms driven primarily from the evolution of aircraft design and the need to accommodate the increased number of passengers. Four basic terminal configurations were developed over the years: the linear, pier, satellite and transporter, each with its own advantages and disadvantages. Nowadays, most airport terminals adopt hybrid concepts and have become complex structures. This complexity is reflected in the interactive and dynamic environment aimed at accommodating the needs of the different stakeholders while influenced by security and commercial considerations.

As every terminal building is unique, the parameters affecting passenger behaviour are found in the most common feature between terminal buildings; the functions. Passengers often experience stress which fluctuates during their dwell time and is usually elevated immediately before and during the processing activities. Potentially stressful spaces and stress factors such as time, queuing and security screening are taken into account in this study as they may influence people's perception and preference over the indoor environmental conditions. The latter have been shown to have a significant impact on occupant comfort and satisfaction in a number of studies conducted in other building types. Therefore, the indoor environment in airport terminals plays a key role in passenger experience and in employees' satisfaction with workspace, while the two groups present different satisfaction levels with the IEQ parameters.

# CHAPTER 3: COMFORT CONDITIONS IN AIRPORT TERMINAL BUILDINGS

## 3.1 Introduction

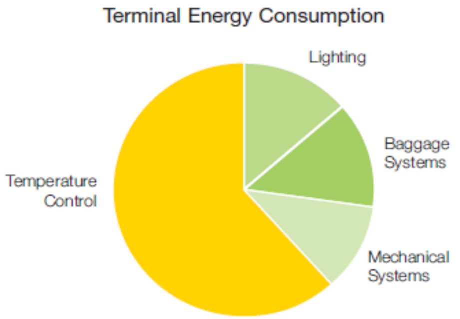
This chapter sets up the link between the indoor environment in terminal buildings and the concept of thermal comfort. The importance of a thermally comfortable environment and its multi-aspect nature in terminal buildings are addressed at the beginning of the chapter. Thermal and non-thermal parameters affecting comfort are presented, followed by an overview of the two dominant approaches in the field of thermal comfort. Lighting and indoor $CO_2$ levels are discussed and the chapter closes with a discussion on the existing comfort criteria for airport terminal buildings and the related studies conducted to date.

## 3.2 The context of thermal comfort in airport terminals

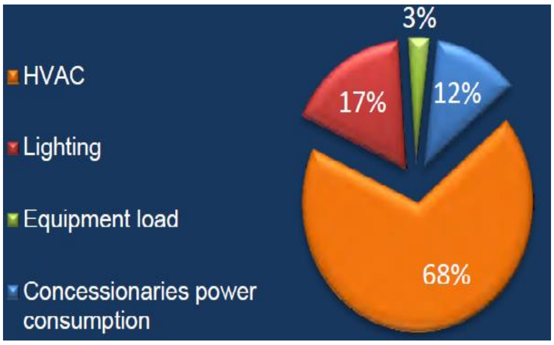
Experiencing the “right temperature” is among the most important considerations for occupants (Griffiths, 1990). Whether the reference building is residential, health care, educational, office or airport terminal, the objectives of field thermal comfort studies lie in the identification of the indoor conditions that are sufficiently acceptable for occupants, and extend to the associated energy use in the case of mechanically conditioned buildings. Airport terminals, however, possess a unique combination of characteristics which elevate the provision for thermal comfort to a particularly complex challenge.

With the exception of some small regional airports, most airports today rely exclusively on mechanical systems for the conditioning of terminal buildings. Terminal spaces are of large volume and open, with non-uniform heat gains and often with extensive glazing areas (e.g. glass curtain walls) aimed at providing natural light and aesthetically attractive facilities. From an operational perspective, airport terminals experience transient occupancy and feature long operational hours which can reach 24/7 all year round. They are unique in that there will be times of very low occupancy and times of peak occupancy which can alternate several times a day. The occupancy volumes and transient use of terminals are also weather-dependent; adverse weather conditions can result in delays in departing flights which in turn increase rapidly occupancy loads.

As a result, HVAC systems consume large amounts of energy that can exceed 40% of the total electrical energy. Excluding smaller systems such as those providing domestic hot water, HVAC systems consume also nearly all the natural gas used at an airport (ACRP, 2010b). Representative of the energy scale required for the conditioning of terminal buildings are the figures from Manchester and Bangalore airports (figure 3-1), where HVAC accounts for more than half of the total energy use.



*(a)*



*(b)*

*Figure 3-1: Energy end use breakdown at (a) Manchester airport, UK (Manchester, 2007), and (b) Bangalore International airport, India (Reddy, 2014).*

Beyond the energy standpoint, and unlike other building types, airport terminals are unique for the large and diverse population handled on a daily basis. They are also characteristic for the diversity of spaces which is most often a result of successive refurbishments and expansion schemes over the years. Moreover, the unique nature of terminals is reflected in the broad assortment of heterogeneous functions performed across the different terminal zones, ranging from check-in and security to retail and baggage reclaim.

As a result, a variety of indoor thermal environments exists within the terminal areas, where thermal requirements may vary from space to space depending on the nature of activities undertaken, the number and type of people involved and the available adaptive opportunities. Yet, the indoor microclimatic conditions are expected to provide a comfortable environment to short-stay visitors (e.g. well-wishers), a comfortable working environment to the terminal staff, and at the same time a comfortable transient environment to passengers. A number of factors, such as variation in adaptive capacity, clothing and activity levels, time spent in the terminal and expectations on the indoor environment differentiate the thermal requirements between the population groups, often leading to energy wastage and thermal comfort conflicts.

While short-stay visitors may be disregarded as a target group due to their limited dwell time in the landside facilities, a thermally comfortable environment is of high importance for passengers and staff. For the latter, this is directly linked to well-being and productivity. An extensive literature review exists on the relationship between the thermal environment and productivity (Wyon et al., 1973; Clements-Croome, 2006). Studies have demonstrated that moderate heat stress can influence negatively thermal performance (Wyon, 1996), while other have reported a temperature threshold above which productivity was shown to drop (Niemelä et al., 2002). Moreover, optimal performance levels for office employees have been identified as a function of indoor temperature and thermal sensation vote (figure 3-2). McCartney and Humphreys found that perceived productivity of office employees is not influenced by the actual temperature itself, but by the 'perception' of temperature, i.e. thermal comfort, as it was shown that perceived productivity drops when thermal preference moves away from "no change" (McCartney and Humphreys, 2002).

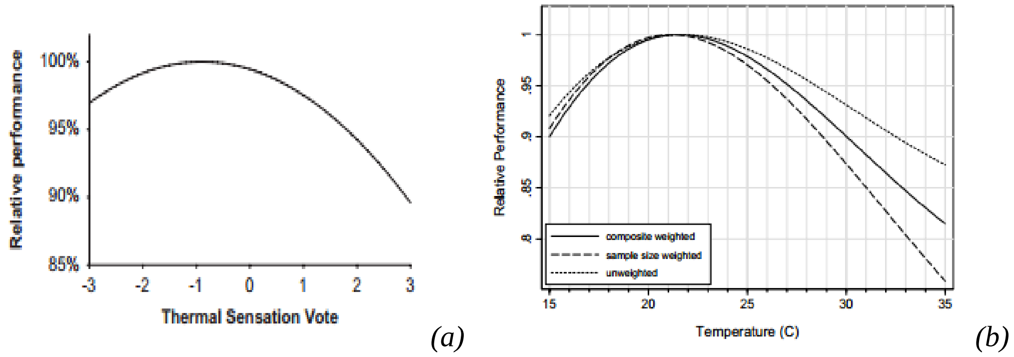



*Figure 3-2: Relationship between relative performance of office employees and (a) thermal sensation vote (reproduced by Jensen et al., 2009) and (b) temperature (Seppänen and Fisk, 2005).*

The indoor thermal environment is among the subjective criteria for the evaluation of the overall quality of an airport (Correia et al., 2008) and one of the non-processing variables determining passengers' in-terminal experience. As a result of airports' transformation from public utilities to businesses, passengers are considered as the major source of airport revenues during their stay in the terminal and thus the maximum accommodation of their needs, including the provision of a comfortable indoor thermal environment, is a key objective of the terminal operator.

## 3.3 Thermal comfort parameters

The key variables affecting the subjective sensation of warmth are classified into environmental and personal. Constituting the thermal environment, the environmental parameters include the air temperature, radiant temperature, air movement and humidity while the personal factors refer to metabolic heat production and clothing (figure 3-3).

All six factors may be independent of each other and may vary with time but it is their combination that contributes to thermal comfort in the built environment. The environmental variables affect the human body simultaneously and the extent of one's influence depends on the levels of the other parameters.

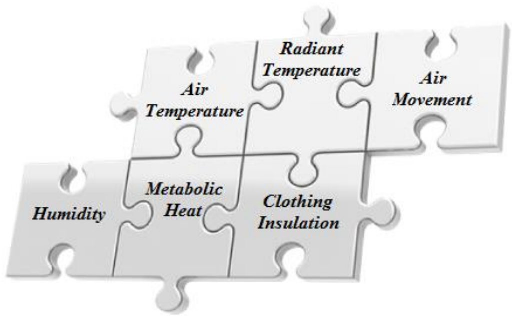



*Figure 3-3: Six basic factors that impact thermal comfort.*

### 3.3.1 Environmental

Air temperature, or more precisely the dry bulb temperature, determines the convective heat dissipation together with the presence of air movement. Radiant temperature, however, has a greater influence on the heat exchange between the human body and the environment. The radiant exchange depends on the mean temperature of the surrounding surfaces, weighted by the solid angle subtended by each surface. The expression most frequently used for the calculation of the mean radiant temperature is that for a standard globe by forced convection (ISO 7726, 1998):

$$\overline{T}_r = \left[(T_g + 273)^4 + 2.5 \times 10^8 \times V^{0.6}(T_g - T_a)\right]^{1/4} - 273 \qquad (1)$$

where $T_g$ and $T_a$ the globe and air temperature. The dry-bulb and mean radiant temperatures may be combined into the operative temperature defined as:

$$T_{op} = a \times T_a + (1 - a) \times \overline{T}_r \qquad (2)$$

where the constant "a" is the ratio $h_c$ / ($h_c$ + $h_r$) with $h_c$ and $h_r$ being the surface heat transfer coefficients by convection and by radiation respectively ($W \cdot m^{-2} \cdot K^{-1}$), and equals to 0.5 if V < 0.2 m/s, to 0.6 if 0.2 < V < 0.6 m/s and to 0.7 if 0.6 < V < 1.0 m/s. Operative temperature combines the effects of air and mean radiant temperature and is the metric most commonly used to define comfort zones in the built environment.

Air movement is expected to be well controlled in mechanically ventilated buildings. It is an important variable as it reduces the body's surface resistance and influences the convective heat exchange between a person and the environment. In warm or humid environments, the presence of air movement can increase convective heat loss without any change in the air temperature, whereas in cool environments may be perceived as draught. In general, the maximum air velocity to ensure indoor thermal comfort is 0.2 m/s as per ASHRAE (ANSI/ASHRAE, 2004) and 0.3 m/s according to CIBSE (CIBSE, 2006). On the other hand, very low or absence of air movement may cause the sense of stuffiness in mechanically heated spaces.

Humidity can be expressed as relative or absolute. However, it is the absolute humidity – expressed as water vapour pressure in the air – that influences the body's evaporative heat loss. At moderate temperatures (< 26 °C) and moderate activity levels (< 2 met) this influence is rather limited. In moderate environments humidity has only a modest impact on thermal sensation. Typically a 10% higher relative humidity is felt to be as warm as a 0.3 °C rise in the operative temperature (ISO 7730, 2005). For higher temperatures and activities, the influence is greater. Humidity can also have a significant influence in transient conditions (ISO 7730, 2005). Levels within the range of 40-70% are typically acceptable (CIBSE, 2006) but this varies between different building types.

### 3.3.2 Personal

Metabolic heat production depends to a great extent on the activity level. Most of the energy generated in the body is measurable as heat while some is used in performing mechanical work. Accordingly, the metabolic heat production (H) is expressed as:

$$H = M - W \quad (3)$$

where M is the metabolic rate and W the mechanical efficiency of muscular work (useful work) which usually ranges between 0 and 20% of M (Havenith et al., 2002). For the low activities performed in most types of industrial work W is very small and regarded as nil, thus the metabolic rate is typically assumed equal to the rate of heat production.

The metabolic rate is a key determinant of the comfort or the strain resulting from exposure to a thermal environment. In the airport terminal environment it is of significant importance, as the indoor conditions are expected to cater for people engaged in different activities. Representing the conversion of chemical into thermal and mechanical energy, the metabolic rate measures the cost of muscular load and gives a numerical index of activity (ISO 8996, 2004) described in terms of "met"; 1 met = 58 $W/m^2$ (Gagge et al., 1941). Metabolic rates of different activities are provided in table 3-1. As metabolic rate increases above 1.0 met, the evaporation of sweat becomes an increasingly important factor for thermal comfort (ANSI/ASHRAE, 2004). Based on steady-state models, studies have shown that shifting 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 (Olesen, 2000).

*Table 3-1: Metabolic rates of different activities (source: ISO 7730, 2005).*

| Activity | Metabolic rate | |
|---|---|---|
| | $W/m^2$ | met |
| Reclining | 46 | 0.8 |
| Seated, relaxed | 58 | 1.0 |
| Sedentary activity | 70 | 1.2 |
| Standing, light activity | 93 | 1.6 |
| Standing, medium activity | 116 | 2.0 |
| Walking on level ground: | | |
| 2 km/h | 110 | 1.9 |
| 3 km/h | 140 | 2.4 |
| 4 km/h | 165 | 2.8 |
| 5 km/h | 200 | 3.4 |

Metabolic rate is most accurately determined through laboratory studies, by measuring oxygen or heat production while participants perform specific activities. It can also be determined by measuring participants' heart rate and comparing it to previously developed tables of heart rate for specific activities (Havenith et al., 2002; Olesen and Parsons, 2002; ISO 8996, 2004). However, these methods are time-consuming and impractical to use in field studies. Therefore, metabolic rate is commonly estimated from tables of met rates for specific activities that have been developed in laboratory studies (ANSI/ASHRAE, 2004; ISO 8996, 2004).

Clothing is an important modifier of heat and moisture loss from the skin surface. The principle behind all clothing is that of trapped air within the layers of fabric; the insulation properties of clothing are due to the presence of a large number of small air pockets between interlacements of warp and weft yarns preventing air from migrating through the material (Song, 2011). However, the thermal insulation depends on a number of factors including thickness and number of layers, fibre density, drape, flexibility of layers and adequacy of closures. The thermal resistance of heat transfer from the body to the environment is the sum of three parameters: the thermal resistance to transfer heat from the surface of the body, the thermal resistance of the clothing material and the thermal resistance of the air interlayer (Huang, 2006; Song, 2011).

Clothing insulation is expressed in terms of "clo" units, which is equivalent to an insulating cover over the whole body with a transmittance (U-value) of 6.45 $W/m^2K$ (i.e. a resistance of 0.155 $m^2K/W$). The unit is based on the insulating value of the typical American man's business suit in 1941 and corresponds to a person wearing a typical business suit – shirt, undershirt, trousers and suit jacket (Gagge et al., 1941). A clo value of 1 is defined as the amount of clothing required to maintain comfort and mean skin temperature of 33 °C in a room temperature of 21 °C, with air movement up to 0.1 m/s, humidity not over 50% and activity level of 1 met. The addition of another 1 clo allows a reduction in air temperature of about approximately 7.2 °C without changing the thermal sensation (Song, 2011).

Table 3-2 provides clothing insulation values of various clothing ensembles. Such insulation tables are based on laboratory studies, usually using thermal manikins in conditions of still air. Some studies assume an average clo value depending on the season and climate of the study location, while more detailed ones make use of a garment checklist to estimate it separately for each participant. Existing guidelines and standards address clothing predominantly for design conditions. In most cases, the recommended temperature ranges assume clothing insulation of 0.5 clo for summer and 1.0 clo for winter (ANSI/ASHRAE, 2004; ISO 7730, 2005).

*Table 3-2: Thermal insulation for typical combinations of garments (source: ISO 7730, 2005).*

| Work clothing | $I_{cl}$ clo | $I_{cl}$ $m^2 \cdot K/W$ | Daily wear clothing | $I_{cl}$ clo | $I_{cl}$ $m^2 \cdot K/W$ |
|---|---|---|---|---|---|
| Underpants, boiler suit, socks, shoes | 0,70 | 0,110 | Panties, T-shirt, shorts, light socks, sandals | 0,30 | 0,050 |
| Underpants, shirt, boiler suit, socks, shoes | 0,80 | 0,125 | Underpants, shirt with short sleeves, light trousers, light socks, shoes | 0,50 | 0,080 |
| Underpants, shirt, trousers, smock, socks, shoes | 0,90 | 0,140 | Panties, petticoat, stockings, dress, shoes | 0,70 | 0,105 |
| Underwear with short sleeves and legs, shirt, trousers, jacket, socks, shoes | 1,00 | 0,155 | Underwear, shirt, trousers, socks, shoes | 0,70 | 0,110 |
| Underwear with long legs and sleeves, thermo-jacket, socks, shoes | 1,20 | 0,185 | Panties, shirt, trousers, jacket, socks, shoes | 1,00 | 0,155 |
| Underwear with short sleeves and legs, shirt, trousers, jacket, heavy quilted outer jacket and overalls, socks, shoes, cap, gloves | 1,40 | 0,220 | Panties, stockings, blouse, long skirt, jacket, shoes | 1,10 | 0,170 |
| Underwear with short sleeves and legs, shirt, trousers, jacket, heavy quilted outer jacket and overalls, socks, shoes | 2,00 | 0,310 | Underwear with long sleeves and legs, shirt, trousers, V-neck sweater, jacket, socks, shoes | 1,30 | 0,200 |
| Underwear with long sleeves and legs, thermo-jacket and trousers, Parka with heavy quitting, overalls with heave quilting, socks, shoes, cap, gloves | 2,55 | 0,395 | Underwear with short sleeves and legs, shirt, trousers, vest, jacket, coat, socks, shoes | 1,50 | 0,230 |

### 3.3.3 Other contributing factors

In addition to the independent environmental and personal factors influencing thermal comfort, other variables may also have some effect. These are generally considered secondary factors and include the state of health, body shape, consumption of food and drinks (influences the metabolic rate), age and gender and degree of acclimatisation (Auliciems and Szokolay, 2007).

Short-term physiological adjustment to altered conditions can be achieved in 20 - 30 minutes, but there are also long-term, endocrine adjustments which may extend beyond six months which constitute the acclimatisation process. From a physiological point of view, different body shapes present different surface-to-volume ratios and therefore allow for different heat exchange with the environment. A more rounded person would prefer a cooler temperature, partly because of the lower surface-to-volume ratio, but also because subcutaneous fat is a good insulator (Auliciems and Szokolay, 2007).

With respect to age and gender and their effect in thermal sensation and preference, results from different studies are contradictory. According to Auliciems and Szokolay, "older people tend to have a narrower comfort range and women usually prefer a temperature 1 K higher than men (although some authors contend that this is due only to clothing differences)" (Auliciems and Szokolay, 2007). Other studies have found that at standard clothing and activity levels, age is not a significant differentiating factor (Rohles and Johnson, 1972; de Dear et al., 1997) and that the lower metabolism in older people is compensated by a lower evaporative loss (Collins and Hoinville, 1980; CIBSE, 2006).

The skin temperature and evaporative loss of females are slightly lower than in males and this balances the marginally lower metabolic rate of females. The explanation for the higher temperatures preferred by females, as shown in some studies, may be the lower thermal insulation provided by some clothing ensembles worn by women (CIBSE, 2006). In his climate chamber studies, Fanger reported that females were more sensitive to a deviation from the optimum temperature but found no significant difference in the preferred temperature between males and females (Fanger, 1970). Another laboratory-based study found few gender differences in thermal comfort responses for neutral and slightly warm conditions but females tended to be cooler than males in cool conditions (Parsons, 2002).

Thermal comfort as a function of gender has been also investigated in several field studies. In an office study, Cena and de Dear reported that there were significantly more expressions of thermal dissatisfaction from females, however, there was a little difference found (particularly in summer) in thermal sensation (Cena and de Dear, 2001). A study conducted in homes and offices found that females were less satisfied with the indoor temperature in both summer and winter (Karjalainen, 2007), and similar was the conclusion of another study in office buildings where significant gender differences were found only in summer (Choi et al., 2010).

### 3.3.4 Local discomfort

Further to the environmental factors affecting thermal comfort, thermal dissatisfaction in the built environment may be caused from local discomfort as a result of vertical temperature differences, warm or cold floors, asymmetric thermal radiation and draughts. Warm or cold floors are a concern only in applications where occupants are barefoot. Vertical temperature differences can be an issue when they exceed 3 °C between the ankle and head levels.

Asymmetric thermal radiation may lead to local cooling or heating when the body exchanges radiation with adjacent cool surfaces (e.g. cool windows) or hot surfaces (e.g. overhead lighting) respectively. Intrusion of short-wavelength radiation such as solar radiation through glazing may also result in local discomfort. 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 (ASHRAE, 1999). Studies have shown that dissatisfaction from draughts is not only a function of mean air speed and local air temperature, but also of fluctuations of air speed in which people are particularly sensitive when the fluctuation frequency is 0.3-0.6 Hz (CIBSE, 2006).

### 3.4 Thermal comfort approaches – an overview

A large number of experiments have been conducted on human response to thermal stimuli. Research on thermal comfort began early in the twentieth century when Haldane (1920) studied the relation of high temperatures and work to sweating (Moss, 1923). In 1923, Houghten and Yagloglou investigated the impact of weather on employee behaviour and attempted to define the 'comfort zone' (Houghton and Yagloglou, 1923). Few years later, Vernon and Warner substituted the dry-bulb with the black-globe temperature introducing the "corrected effective temperature" (Vernon, 1930; Vernon and Warner, 1932), and similarly to Bedford (Bedford, 1936), they carried out empirical studies on factory employees. Winslow, Herrington and Gagge studied the physiological reactions of the human body to varying temperature levels (Winslow et al., 1937). These and other early studies underpinned the research pathways on thermal comfort in the following decades.

The scientific community has developed knowledge on indoor thermal comfort for decades and the most important outcomes stand nowadays as the basis of national and international standards. In such standards, thermal comfort is defined as ''that condition of mind which expresses satisfaction with the thermal environment" (ANSI/ASHRAE, 2004; ISO 7730, 2005). As the definition implies, thermal comfort is a cognitive process that involves a number of inputs influenced by physical, physiological, psychological and other factors. These factors have been the theme of controversy between the two different approaches dominating the development of thermal comfort research; the heat-balance and the adaptive.

#### 3.4.1 The heat balance approach

The heat-balance approach lies on the combination of the heat transfer theory and the physiology of thermoregulation to determine the range of comfortable indoor temperatures. The underlying premise is that the effects of the thermal environment are explained exclusively by the physics of heat exchanges between the body and its surroundings and therefore the person is viewed as a passive recipient of the thermal stimuli. The human body exchanges heat with its environment via convection, conduction, radiation and evaporation and it is in a state of thermal equilibrium with its environment when it loses and gains heat with exactly the same rate. Mathematically, the relationship between the body's heat production and all other heat gains and losses is given in the basic formula (4) below, where M is the metabolic rate, E the evaporative heat gain or loss, R the radiant heat exchange, C the conduction and convection rate and S the body heat storage rate.

$$\text{Heat production} = \text{heat loss or } M = E \pm R \pm C \pm S \qquad (4)$$

This approach is based on extensive experimental research conducted in controlled climatic chambers, primarily from the pioneering work of Fanger in the 1960s. Under the premise that heat balance is influenced solely from the mean skin temperature and sweat rate as a function of activity levels, Fanger derived a linear relationship between sweat rate and activity levels and another between mean skin temperature and activity levels. The substitution of these two formulas into heat balance equations resulted in the first comfort equation, which was then corrected by combining data from Nevins et al. (Nevins et al., 1966), McNall et al. (McNall et al., 1967) and resulted in the widely used predicted mean vote (PMV) index. PMV predicts the mean thermal sensation of a large group of people and it is expressed as:

$$PMV = [0.303\exp(-0.036\,M) + 0.028]L \qquad (5)$$

$$PPD = 100 - 95exp[-(0.03353\ PMV^4 + 0.2179\,PMV^2)] \qquad (6)$$

where L is the body's thermal load, defined as the difference between the internal heat production and heat loss to the environment. PMV was then incorporated into the predicted percentage of dissatisfied (PPD) index (figure 3-4) which predicts the percentage of people who are likely to be dissatisfied with a given thermal environment (equation 6).

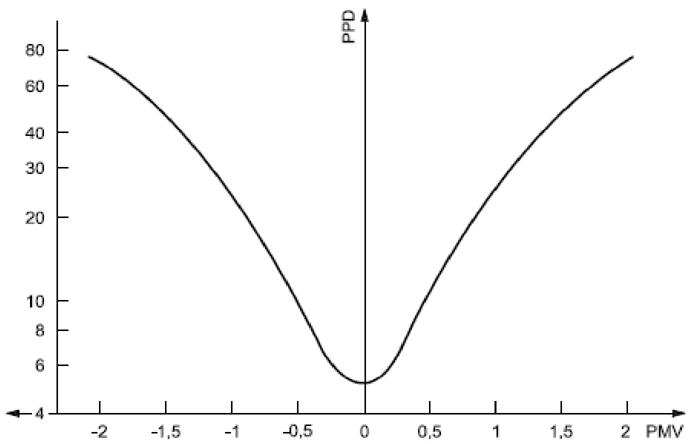



*Figure 3-4: PPD as function of the PMV index.*

### 3.4.2 The adaptive approach

The adaptive approach expresses the natural tendency of people to adapt to the thermal environment and its changes, and contrarily to the heat-balance approach, it is based on findings from field surveys. Its fundamental premise is that "if a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort".

This approach emerged in the 1970s in response to the oil shocks (Fountain et al., 1996). In 1973, Nicol and Humphreys challenged the steady-state theories and introduced the adaptive comfort theory (Nicol and Humphreys, 1973) stating that:

"*We would like to suggest a different approach, namely that use be made of the adaptive principle. If a self-regulating control system is working to secure thermal comfort, the whole system will in any case tend towards its own optimum. The problem then becomes one of providing circumstances in which it may do so easily…*

*…So, in spite of its disadvantages, the field study is likely to remain the principal method of investigating thermal comfort as a self-regulating system*."

Continuing this work, Humphreys conducted a meta-analysis of a large dataset from earlier comfort studies carried out worldwide. The well-known plot of indoor comfort temperatures against the outdoor monthly mean temperature (figure 3-5) demonstrated the influence of outdoor weather on the behavioural adaptation to the indoor environment and revealed a clear division between occupants in free-running and heated/cooled buildings (Humphreys, 1978). For both building types, comfort temperatures were related to outdoor temperature over a considerable range, resulting in a remarkably strong and linear relationship between the two for the free-running buildings and in a curvilinear algorithm for the buildings that were heated or cooled at the time of the surveys.

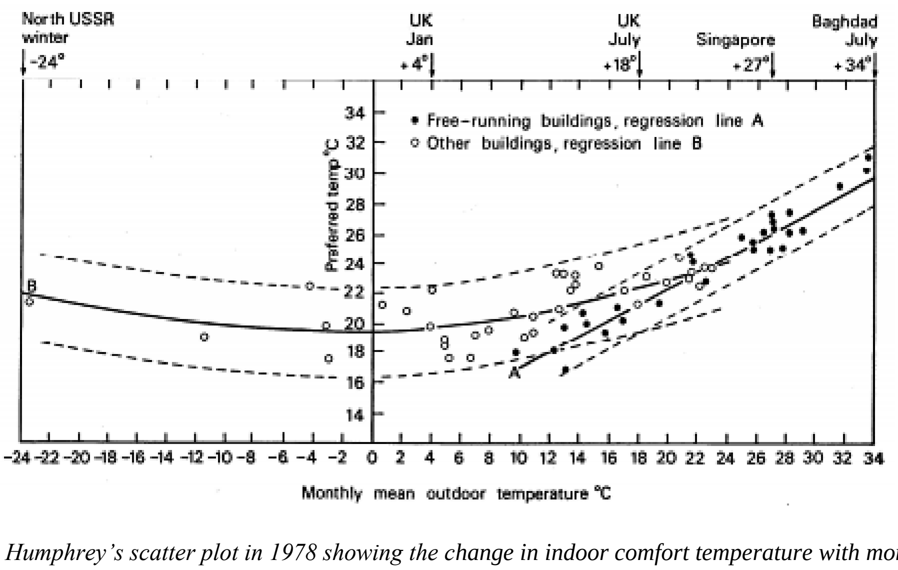



*Figure 3-5: Humphrey's scatter plot in 1978 showing the change in indoor comfort temperature with monthly mean outdoor temperature (Humphreys et al., 2010).*

Similar proposal to Humphrey's was provided from Auliciems. In his study in Australia, Auliciems suggested that the indoor thermal control should be a "thermobile" instead of a thermostat, so that the indoor temperature varies according to the outdoor while providing improved comfort conditions (Auliciems, 1984). Field studies conducted in the following years confirmed this proposal and showed that there is a definite relationship between indoor comfort and outdoor conditions (Nicol et al., 1999).

Although the validity of PMV has been verified by studies in climate chambers, field studies have revealed a wider range of comfortable temperatures indicating that occupants are more tolerant of diversity in thermal environments (Humphreys, 1976; McINTYRE, 1980). In addition, it has been demonstrated that PMV is often an inaccurate predictor of thermal sensation in field studies, as suggested by the systematic bias found between the predicted and actual comfort vote in many studies (Humphreys, 1994; Oseland, 1995).

The research that followed in the next few years led to the proposal of a new adaptive comfort standard for naturally ventilated buildings and to its incorporation as an alternative to the PMV-based method in the international standards (de Dear and Brager, 2002). De Dear showed that PMV over-predicts the subjective warmth in warm environments and concluded that the index may be satisfactory for air-conditioned buildings but not for natural ventilated buildings were temperatures were higher (de Dear, 1994; de Dear and Brager, 1998).

Moreover, Nicol and Humphreys suggested that the discrepancies between PMV and actual mean comfort vote occur also in air-conditioned buildings but are masked from the narrow range of environments. More specifically, they reported that 49 out of 101 air-conditioned buildings in their database (figure 3-6) were found to have a bias outside the confidence limits, 63 had bias of more than ±0.25 ASHRAE scale units and 1 had bias of more than ±1 scale unit (Humphreys and Nicol, 2002). The bias of PMV in field studies has been attributed to a number of reasons, with the most important being that PMV ignores the adaptive capacity of building occupants, as well as a wide range of other factors such demographics (age and gender, thermal history) and occupant expectations.

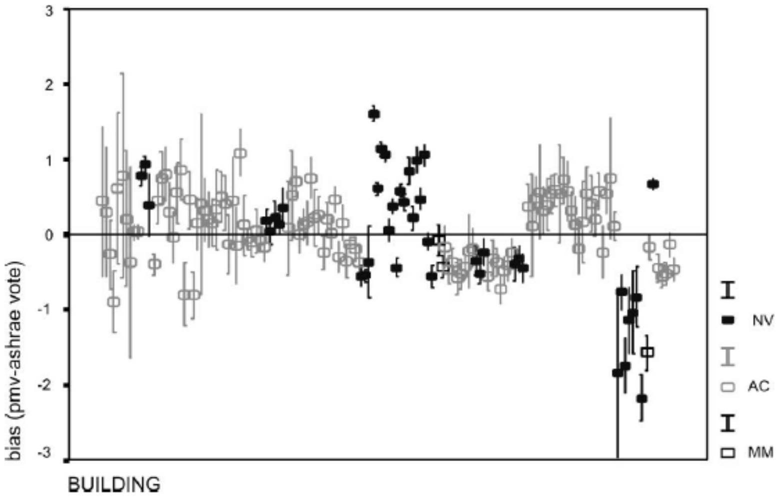



*Figure 3-6: Bias in PMV in naturally ventilated, mixed-mode and air-conditioned buildings (Humphreys and Nicol, 2002).*

## 3.5 Adaptive modes of thermal comfort

With the introduction of the adaptive comfort theory the term “adaptation” in the thermal comfort context is used to describe the actions people undertake and the processes they go through in order to reach a balance between their thermal requirements and their immediate microclimate. The adaptive opportunities can be broadly classified into three categories: physical, physiological and psychological (Brager and de Dear, 1998; Nikolopoulou and Steemers, 2003).

Referring to long-term (days or weeks) acclimatisation and to genetic adaptation, physiological adaptation applies more to extreme conditions rather than to a controlled indoor environment such as an airport terminal building. It involves the changes in the physiological responses which are the result of a repeated exposure to a thermal environment, leading to a gradual decreased strain from such exposure (Nikolopoulou and Steemers, 2003). Studies have shown that the acclimatisation process starts from the first day of exposure and progresses rapidly to full development by the third or fourth day, provided the heat exposures are sufficiently sever to elevate core temperatures. Longer periods have been found to be required for cold acclimatisation or for passive exposures to heat in the course of normal day-to-day sedentary activity (Brager and de Dear, 1998).

On the other hand, the complex context of psychological adaptation finds more applications in the airport terminal environment, where psychological factors based on experience, expectations, time of exposure, naturalness and perceived control, influence the interaction between occupants and thermal environment. Short-term experience determines the day-to-day changes in expectations, while the long-term experience constitutes the developed schemata in people’s mind that affect their choice of action under different circumstances (Nikolopoulou and Steemers, 2003). Both forms of experience play a key role in the modulation of expectations which in turn affects greatly the perception on thermal environments. Thus, expectations influence people’s thoughts on what an environment should be like and not necessarily how it actually is. In free-running buildings occupants expect a variable thermal environment, whereas a narrow temperature range is expected in air-conditioned buildings.

Time of exposure is also a critical factor in the thermal comfort context (Nicol, 2004) as discomfort is not viewed negatively if the exposure to it is short (Nikolopoulou et al., 2001) or the individual anticipates that it is temporary (Nikolopoulou and Steemers, 2003). Uncomfortable conditions caused naturally may also be handled with increased levels of tolerance. This is expressed by the term “naturalness”, employed by Griffiths to describe people’s higher tolerance of wide changes in the physical environment given they are naturally caused (Griffiths et al., 1987; Nikolopoulou and Steemers, 2003).

Furthermore, it has been a common conclusion of many studies that the individual control plays a key role in comfort and satisfaction (Fountain et al., 1996; Mahdavi and Kumar, 1996), and that the impact of perceived control in the determination of thermal comfort assessments is of equal importance to the thermal variables (Paciuk, 1990). Leaman and Bordas have stated accordingly: "People are more forgiving of discomfort if they have some effective means of control over alleviating it. However, many modern buildings seem to have just the opposite effect. They take control away from the human occupants and try to place control in automatic systems which then govern the overall indoor environment conditions, and deny occupants means of intervention." (Leaman and Bordass, 1999).

Physical adaptation includes the behavioural actions people perform to modify their immediate microclimate according to their needs or adjust themselves to it. These actions involve reactive and interactive adjustments made either consciously or unconsciously. Interactive adjustments are actions that people take to modify their surroundings. Depending largely on the opportunities provided by the building, these include opening/closing windows or blinds, use of HVAC controls turning on fans or personal heaters. Reactive adjustments are the personal changes such as modification in clothing levels, in posture and activity, in location (moving to a more comfortable one), as well as the consumption of hot or cold drinks.

Posture has been associated with the indoor temperature. A change in posture can have significant effect on body heat loss as it changes the effective surface area and therefore the metabolic rate per unit surface area (Raja and Nicol, 1997). The consumption of cold and hot drinks is not an exclusive response to thermal stimuli, however, a correlation coefficient of $r = 0.19$ ($p<0.01$) between air temperature and frequency of cold drink consumption was found in the European RUROS project (Nikolopoulou and Lykoudis, 2006). Consumption of drinks can have an altering effect on metabolic heat production. For instance, the consumption of a standard can of drink (330 ml) at 5 °C has a direct sensible cooling effect of 42 kJ to a body at 35 °C. Averaged over an hour this amounts to nearly 12 W of cooling, which is equivalent to a 10% drop in metabolic rate of a standard sized person in a relaxed seated position (Baker and Standeven, 1996; Nikolopoulou and Steemers, 2003).

Clothing adjustment has been frequently highlighted among the principal modes of adaptation. Humphreys found a relatively small change in thermal sensation over the indoor temperature range of 17-30 °C and attributed this insensitivity to thermal conditions largely to changes in clothing (Humphreys, 1976). Similar conclusions have been drawn by other studies who found that clothing adjustments act to moderate changes of thermal sensation with climate (Humphreys, 1973; de Dear and Auliciems, 1985; Schiller et al., 1988; Oseland, 1995). De Dear and Brager also examined clothing changes as indication for behavioural adaptation. They demonstrated that the mean thermal insulation was significantly related to mean operative temperature in both the air-conditioned and naturally ventilated building samples (figure 3-7), with the relationship being weaker in the air-conditioned buildings (de Dear and Brager, 1998).

Fewer studies have been concerned with the short-term clothing adjustment as a thermal comfort moderator. Humphreys stated that within-day changes in clothing for secondary school children showed little temperature dependence (Humphreys, 1973). Newsham and Tiller administered a computer-based questionnaire to survey 55 people in air-conditioned offices twice per day during the autumn and winter. They found that clothing changes in the hour prior to the survey were made on about 15% of occasions (Newsham and Tiller, 1995). Similarly, using hourly questionnaires to 32 people in five offices in Southern Europe during the summer, Baker and Standeven reported clothing adjustments in nearly 7% of the observed hours (Baker and Standeven, 1995).

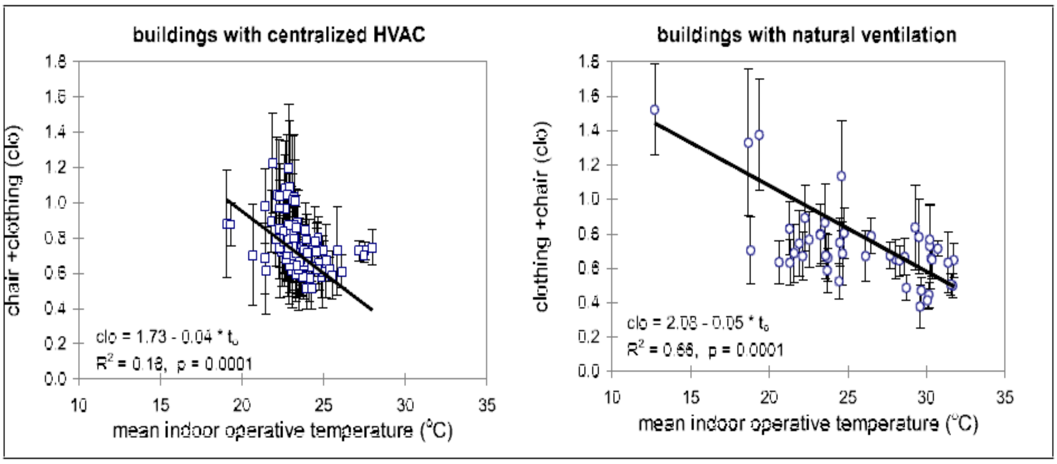



*Figure 3-7: Clothing as an indicator of behavioural adaptation. Dependence of mean (±stdev) thermal insulation (clothes and chair) on mean indoor operative temperature (de Dear and Brager, 1998).*

### 3.6 Attenuation of adaptive capacity in airport terminals

As a result of the diverse spatial and operational attributes typifying the terminal environment, the adaptive capacity can vary between the terminal areas as well as between the population groups. Nowadays, most terminal buildings utilise centralised HVAC systems and therefore the terminal population lacks of interactive adjustments. Few exceptions can be found in some retail facilities and in office rooms equipped with thermostats or single air-conditioning units. The use of personal amenities such as fans and individual heaters is usually prohibited for staff due to health and safety regulations, although this varies between the different employers operating in terminals.

While reactive actions for passengers are possible at almost every space in the terminal, such actions are not evenly attainable among staff members. For instance, employees working behind the check-in desks cannot change posture or activity, similarly to staff in the security areas where the majority performs a standing activity. This is also the case with other staff groups such as those in shopping, currency exchange and customer service facilities. Moreover, the straightforward adaptive actions taken from passengers, e.g. having a drink or moving to a more comfortable space, are not achievable by employees whose degrees of freedom for reactive adaptation are largely dependent on the work requirements.

With respect to the most fundamental adaptive behaviour, clothing alteration, the nature of the airport terminal allows only for restricted clothing adjustments for staff (with only exception some retail employees) who are subject to corporate dress codes. Investigating the clothing behaviour in two indoor environments – shopping mall and call centre – in Australia, Morgan and de Dear found that the day-to-day variation in clothing levels changed significantly in the shopping mall where a dress code was not in place, whereas clothing varied less in the call centre where a dress code was enforced (Morgan and de Dear, 2003).

It is also true that clothing insulation levels may differ significantly between occupants in airport terminals. This applies to the clothing levels of staff as compared to passengers', as well as to the substantial clothing differences between passengers. This reflects the multitude of the decision-making criteria upon which occupants choose their outfits. Expectations on the indoor environment are certainly a factor (Fanger and Toftum, 2002), more applicable to employees, whose long-term and short-term thermal experience in the terminal determines their clothing, or their clothing deviations from the enforced dress codes. Outdoor weather conditions are also among the determinants (de Dear and Brager, 1998; Morgan and de Dear, 2003) for both passengers and staff. Another parameter is the time needed for clothing to catch-up step changes in the thermal environment, which is a factor that formed the basis of the adaptive standards. Humphreys conducted time series analysis (using an exponentially-weighted running mean) and found that clothing might take up to five days to settle to an appropriate level following a temperature change (Humphreys, 1979). In the case of passengers, more factors may also be involved. These include the means of transport to the airport, purpose of traveling, type and duration of flight and the weather conditions at the destination.

From the psychological standpoint, experience and expectations can be rationally presumed as differentiating factors in the adaptive capacity of employees and passengers. For the latter, psychological adaptation may be also influenced by the common stressors in the terminal environment, as discussed in section 2.6. Additionally, time of exposure or alternatively dwell time, allows for significantly different periods of adaptation for the two groups and can differentiate their thermal tolerance.

## 3.7 Lighting and indoor air quality

Indoor air quality and lighting environment are among the basic elements of IEQ that impact occupant satisfaction and comfort, as discussed in section 2.7. The broad topic of IAQ is beyond the scope of this study which focuses exclusively on the $CO_2$ concentrations in the indoor terminal environment. Alongside the thermal conditions, illuminance levels in airport terminals are expected to provide a comfortable environment to both passengers and staff while facilitating the functions and activities performed across the terminal spaces. An interesting link between thermal and visual comfort was reported by Laurentin et al. In their study based on twenty office employees, they noted that when thermal conditions were not viewed as pleasant and acceptable, lighting conditions were also very likely to be perceived as unpleasant (Laurentin et al., 2000; Galasiu and Veitch, 2006).

### 3.7.1 Lighting

In general terms, lighting in the indoor environment serves the purpose of enabling occupant to work and move in safety, to perform tasks correctly and at an appropriate pace and of providing a pleasing appearance (CIBSE, 2006). In airport terminals it is also part of the establishment of character in the different areas of the building. The lighting environment balances between visual performance and visual comfort, terms characteristically segregated by Boyce (Boyce, 1996), or in other words between the right lighting levels for employees' performance and the comfortable lighting levels for passengers' pleasantness.

Preferred illuminance levels vary between individuals, settings and tasks. Field studies have shown that the preferred levels are generally higher than the recommended ones (Tregenza et al., 1974; Galasiu and Veitch, 2006). Despite this variation, relationships between illuminance and preference have been found inconsistent below 400 lux (Veitch, 2001). Systematic research has been also conducted on the non-visual effects of light, which are partly or fully separated from the visual system and associated to human circadian photoreception. Among the most recent and important findings is the discovery, in 2001, of the novel third photoreceptor named "intrinsically photosensitive Retinal Ganglion cell" or ipRGc (Brainard et al., 2001). The ipRGc is located in the human retina and it is the main photoreceptor responsible for the phase shifts of humans' endogenous clock in the light-dark cycle, while it is also associated to mood, alertness and performance (Duffy and Wright, 2005).

Nowadays, there is a trend towards greater natural lighting in airport terminals as a means of reducing the energy consumption for lighting, assisting passenger wayfinding and providing view to outside. For any given terminal there is an optimum glass area which depends on the climatic conditions and the orientation of glass (Edwards, 2005). In combination with daylight responsive dimming controls, the use of daylight can also decrease the internal heat gains associated to artificial lighting and therefore reduce the energy demand for cooling (ACRP, 2010a). Representative examples of airports which have maximised the use of natural lighting in the terminal buildings are Madrid - Barajas, London - Stansted and Chep Lap Kok - Hong Kong International airport.

Research has well documented people's belief that natural light is superior to artificial in its effects on humans, as well as people's preference for daylight and view to outside (Heerwagen and Heerwagen, 1986; Veitch and Gifford, 1996). Daylighting and windows have been associated with physical and psychological well-being, while the view through windows has been suggested as a reliable means of relieving stress (Boyce et al., 2003). On the other hand, windows can also have negative effects on occupant satisfaction, associated with thermal discomfort and glare. Charles et al. found that satisfaction with lighting was higher among respondents sitting closer to a window but satisfaction with ventilation and primarily with thermal comfort was lower. The highest overall environmental satisfaction was expressed when one could see a window but did not sit beside it (Charles et al., 2006; Aries et al., 2010).

Glare is the sensation produced by an excess of light and can result in eye fatigue (discomfort glare) or temporary vision impairment (disability glare) under higher glare levels. It can be caused directly from light sources or by reflection from surfaces in the field of view. Windows are the most common source of glare. However, glare is not confined to natural light and can be caused in artificial lighting conditions as well. Glare sensation varies significantly between individuals and depends on a number of factors including lighting quality, window appearance, view content, type of task and distance from the window (Parpairi et al., 2002; Galasiu and Veitch, 2006). Research has shown the interrelation between quality of the view and perception of lighting quality, indicating that tolerance of high luminosities is higher the more the view to outside is appreciated (Edwards and Torcellini, 2002). Discomfort glare caused from daylight has been found to be tolerated to a much higher degree than available methods predict when there is a pleasant view from the window causing the glare (Chauval et al., 1982; Osterhaus, 2001).

Beyond the visual performance and comfort perspectives, lighting in airport terminals is crucial to surveillance, security and to the wayfinding system of the building. For the latter, it is important to maintain a similar pattern of lighting during day and night so that passenger perception of route and volume does not vary. Accordingly, fluctuation in light levels has been found to influence significantly eye fatigue, distraction, difficulty of seeing letters, and annoyance (Kim and Kim, 2007). Thus, some artificial lighting in terminals is commonly used in the daytime, even if not justified by daylight levels. A typical design pattern for airport terminals is a daylight factor of 1 or 2% in concourses in combination with artificial lighting of about 500 lux. The result is that while electric lighting overwhelms natural lighting, there is still a sense of daylight (Edwards, 2005).

In a study in three airports in Greece, Balaras et al. noted problems such as lack of uniformity, excessive lighting in certain areas as a result of poor solar control and insufficient lighting in other areas of the buildings (Balaras et al., 2003). Similarly to every continuously occupied workspace, the working light level in terminals is normally 200 lux, which is the minimum illuminance required from the regulations (Edwards, 2005; CIBSE, 2012). However, this standard varies between the different lighting requirements across the terminal areas and depends largely on the functional status and the security level of each space. Recommended illuminance levels for the different areas in terminal buildings are provided in the European Standard EN 12464-1 (also adopted in CIBSE Guide A), as shown in table 3-3.

*Table 3-3: Recommended illuminance levels for airport terminal buildings (EN12464-1, 2003).*

| Terminal area | Illuminance (lux) |
|---|---|
| Arrival and departure halls, baggage claim areas | 200 |
| Connecting areas, escalators, travolators | 150 |
| Information desks, check-in desks | 500 |
| Customs and passport control desks | 500 |
| Waiting areas | 200 |
| Security check areas | 300 |

### 3.7.2 Carbon dioxide levels

Carbon dioxide ($CO_2$) is the only gaseous contaminant directly associated to the presence of human occupancy. Humans emit $CO_2$ at a rate that depends on the body size and the level of physical activity. In buildings like airport terminals, the primary source of $CO_2$ is respiration of occupants. An average adult exhales about 35,000 - 50,000 ppm of CO2 which is nearly 100 times higher than the concentration found in acceptable outdoor air (300 - 500 ppm).

Carbon dioxide levels, and specifically peak concentrations, have often been used as rough indicators for the adequacy of the air exchange (Persily and Dols, 1990) and for the isolation of stagnant air pockets where there is little or no air movement (Hess-Kosa, 2011). However, its sole use as an indicator of actual ventilation rates has been often critisised, especially in buildings with variable occupancy and activity levels. Carbon dioxide is also a suitable tracer gas for human emitted bioeffluents (odors) that are considered unacceptable for the overall human comfort inside conditioned spaces and are likely to contribute to deteriorated comfort. There are two kinds of adaptation to odours. In the short-term adaptation, people become less sensitive to odours in periods of about 30 minutes. Over longer periods (weeks or months) people can come to accept odours as normal and harmless and therefore become less aware of them. Conversely, over a period of minutes or hours, the discomfort from exposure to irritants can increase (ISO 6814, 2008; CIBSE, 2006). Furthermore, $CO_2$ measurement can be used as an indicator of excessive population density (e.g. overcrowding) and of changes in occupancy.

In terms of irritation and comfort, the link between $CO_2$ levels and occupant perception of the indoor environment is complex, as it involves a number of issues including the association between $CO_2$ concentration and ventilation, the relation between $CO_2$ levels and other contaminants and the comfort impact of $CO_2$ itself. Carbon dioxide is not considered an indoor air pollutant but at very high concentrations (e.g. greater than 5000 ppm) can pose a health risk (ASHRAE, 2007). For example, studies have reported deepened breathing at concentrations above 20,000 ppm and significantly increased respiration beyond 40,000 ppm. Even higher concentrations, above 100,000 ppm, can result in visual disturbances or loss of consciousness (Lipsett et al., 1994). However, in most buildings it is very rare for carbon dioxide to rise at these levels.

Carbon dioxide levels that are higher than the common ranges found in normal indoor environments have been associated with perceptions of poor air quality, sense of stuffiness, headaches and fatigue, slower work performance and the increased risk of sick leave (Erdmann et al., 2002; Seppanen et al., 1999; Wargocki et al., 2000). Yet, it is believed that these correlations exist because the elevated $CO_2$ concentrations at lower outdoor air ventilation rates are correlated with higher levels of other indoor pollutants that directly cause the adverse effects (Mudarri, 1997). Therefore, the ranges found usually in indoor environments (up to 5000 ppm) are assumed to have no direct impacts on occupants' perception, work performance or health, in agreement to earlier studies that showed no significant relationship between the prevalence of occupant symptoms and $CO_2$ concentrations (Jaakkola et al., 1991).

The American Conference of Government Industrial Hygienists (ACGIH) and the Occupational Safety and Health Administration (OSHA) recommend 5000 ppm (time-weighted average) as the upper limit of exposure for an 8-hour working day (ACGIH, 2011; OSHA, 2012). According to ASHRAE, for sedentary activity levels, steady-state $CO_2$ concentration in a space no greater than about 700 ppm above outdoor air levels, indicate an outdoor air ventilation rate of about 7.5 L/s/person. Laboratory and field studies have shown that this ventilation rate dilutes odours from human bioeffluents to levels at which the majority (80%) of unadapted people (visitors) will be satisfied. Thus, as per ASHRAE, the recommended maximum $CO_2$ concentrations are 1000 - 1200 ppm (ASHRAE, 2007).

### 3.8 Research on the indoor airport terminal environment

With energy accounting for a significant percentage of annual costs for most airports – usually 10% to 15% of total operating budget – efficiency is identified as a high priority in operators' long-range plans (ACRP, 2010b). Because of the large differences in energy demand among airports, a variety of no cost (e.g. adjustment of space temperature settings), of low cost (e.g. improvements in the monitoring and targeting system, sophisticated controls and periodical energy auditing), and of high cost and long-term (e.g. adoption of a CHP or a CHCP system) energy efficiency practices exists for this type of facility (ACRP, 2010b; Cardona et al., 2006). Since airport infrastructure for the next 50 years already exists, most of the long-term actions are applicable only to new terminal buildings. Therefore, significant energy savings in existing facilities can be achieved from retrofit interventions. These reflect the field on which most of the work has been carried out to date.

Parker et al. investigated retrofit pathways, from a technical and economic perspective, for existing terminal buildings in the UK by means of dynamic thermal simulation models. The research involved the calibration of models against monthly utility data and demonstrated that the thermal performance of the buildings is greatly influenced by the internal heat gains associated with equipment and lighting. Specific technologies were assessed as retrofit solutions, showing that the greatest reduction in the terminals' carbon footprint could be achieved with biomass combined heat and power units, whose financial viability, however, is reliant on government subsidy. Reflecting the complexity of retrofit implications in this type of building, the work reported that the technologies found to perform financially best and could achieve the greatest reduction in the carbon footprint are not the most energy efficient ones (Parker et al., 2011; Parker et al., 2012).

Another study focused on the investigation and characterization of phase change materials (PCMs). Applied to panels or integrated into active thermal control systems, PCMs can increase the thermal energy storage capacity of the building structure and provide passive control of the indoor thermal environment in the temperature range of 18-25 °C. Systems were tested in environmental chamber to evaluate their performance characteristics and to examine their integration and control aspects. The systems were modeled in an airport terminal and it was demonstrated that the use of PCMs can provide up to 3 °C reduction in the peak temperatures, thus preventing overheating in the summer months (Gowreesunker and Tassou, 2013; Gowreesunker et al., 2013).

Abdulhameed developed a fuzzy supervisory controller aimed at reducing energy consumption in airport terminals and the associated $CO_2$ emissions. In response to passenger flows, the proposed system was shown to be capable of reducing the energy consumed and $CO_2$ emissions in Manchester Terminal 2 by 40-50% and 30-45% respectively, in winter, and by 21-27% for both qualities in summer (Abdulhameed, 2013).

On the other hand, there are very few studies conducted to date that have attempted to evaluate the indoor comfort conditions in terminal buildings. 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 temperature regulation problems in all three buildings. The results were based on subjective data collected from 285 people and are characteristic of the different satisfaction levels between passengers and staff with all IEQ parameters (section 2.7). With respect to the thermal environment in particular, 70% of employees and nearly all passengers were satisfied in one of the airports. The respective gap was greater in the other two more problematic terminals, where satisfaction was expressed by 80% of passengers and only 40% of staff (Balaras et al., 2003).

Babu took physical measurements and surveyed 128 members of staff and passengers in the terminal of Ahmedabad airport, India, in summer 2007. The study reported that passengers demonstrated higher thermal tolerance when moving from the familiar local environment to a conditioned space and a higher comfort expectation when transitioning from one conditioned space to another. Additionally, the study reported a very high comfortable temperature range in the air-conditioned part of the building, 24-32 °C (Babu, 2008).

Physical and subjective measurements were also conducted over a period of two weeks in summer and winter, in 2008, in Terminal 1 at Chengdu Shuangliu International Airport, China. Neutral temperature was found at 21.4 °C in winter and 25.6 °C in summer for passengers, with the respective comfort zones at 19.2 - 23.1 °C and 23.9 - 27.3 °C. Based on 569 questionnaires, the results showed that 78.3% of passengers were generally satisfied with the thermal environment and 95.8% considered the thermal conditions acceptable, concluding that passengers' adaptive ability is very powerful (Liu et al., 2009).

Existing thermal comfort criteria for airport terminal buildings are sourced from ASHRAE and CIBSE. ASHRAE's design criteria recommend a temperature range of 23-26 °C and a RH range of 30-40% in winter and 40-55% in summer (ASHRAE, 2003). Additionally, ASHRAE views the airport terminal as a "typical" application and therefore an 80% acceptability percentage is considered applicable. CIBSE provides seasonal comfort criteria for five terminal areas, allowing for a narrower temperature range in certain facilities and for a wider thermal variation in other. In areas where people spend more time and perform lighter activities, such as in check-in halls and departures lounges, a two-degree range is recommended for both summer and winter, whereas a wider range is suggested where shorter dwell time is required and more intensive activity levels are assumed, e.g. in baggage reclaim and concourse areas. These criteria are based on the standard activity levels shown in table 3-4, and on clothing insulation levels of 0.65 clo and 1.15 clo for summer and winter respectively (CIBSE, 2006).

*Table 3-4: Recommended comfort criteria for airport terminal areas by CIBSE.*

| | Summer* | Winter* | |
|---|---|---|---|
| | Operative temperature (°C) | | Activity (met) |
| Baggage reclaim | 21-25** | 12-19** | 1.8 |
| Check-in areas*** | 21-23 | 18-20 | 1.4 |
| Concourse (no seats) | 21-25** | 19-24** | 1.8 |
| Customs area | 21-23 | 18-20 | 1.4 |
| Departures lounge | 22-24 | 19-21 | 1.3 |

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

### 3.9 Conclusions

The importance of thermal comfort in airport terminal buildings is reflected from the complexity of the factors typifying the terminal environment. HVAC systems account for a significant proportion of the energy use in terminal buildings, while the indoor thermal environment is expect to meet the thermal requirements of very different population groups. These groups differ in a number of factors including clothing and activity levels, dwell time, familiarity with the indoor environment and expectations, all affecting the thermal perception and adaptive capacity as discussed in this chapter. The terminal environment attenuates certain adaptive opportunities for specific population groups, differentiating further their thermal requirements.

This chapter also discussed the two dominant approaches in thermal comfort research; the steady-state and adaptive approach. The PMV biases have been found generally smaller in air-conditioned than in naturally ventilated buildings. This work uses the PMV index to test its accuracy in mechanically ventilated terminal buildings. Lighting and $CO_2$ levels are also parameters taken into account, as additional contributors to occupants' perception of the indoor environment. The studies conducted to date on the evaluation of indoor comfort conditions in terminal buildings are very few but with two important findings: a) passengers present high levels of satisfaction with the indoor environment and b) passengers and staff present different satisfaction levels with the IEQ parameters.

# CHAPTER 4: CASE STUDIES

## 4.1 Introduction

Three airport terminals were employed as case studies for the evaluation of the indoor thermal conditions and the assessment of people's thermal comfort requirements. The terminals were selected to meet specific criteria, aiming for buildings of different scale and typology and therefore allowing the investigation of a wide range of indoor environments. This chapter discusses the selection criteria and presents the case studies along with a detailed description of the terminal buildings surveyed.

## 4.2 Selection of case studies

The selection of case studies aimed to allow for a representative range of the indoor conditions commonly encountered in airport terminals. Accordingly, the study sought for buildings which differ in a multitude of characteristics that, directly or ultimately, have an impact on the indoor comfort conditions. These include terminal size and capacity, actual passenger traffic, as well as terminal design and spatial characteristics.

Terminal scale was the primary parameter which underpinned the selection process. At its early stage, the focus was on terminal buildings that, in terms of building size and capacity, are good representations of small, medium and large scale airport terminals. Such classification was essential to facilitate the understanding of people's comfort requirements in operationally similar but in environmentally different indoor conditions. Diversity in terminal scale was also planned to allow for a comparative linkage between the similar spaces in the three case studies (e.g. between the check-in areas of different scale) as well as between spaces of similar function within the larger terminals (e.g. among the departures lounge areas found in a sizable terminal).

In addition to the interlock between the indoor environmental conditions and the scale of the terminal building, the latter is associated with non-environmental comfort factors in the terminal settings. These include the length of walking distances and passengers' dwell time, which in turn are related to the activity levels performed in the terminal and the allowable time for adaptation to the indoor environment. As a result of their size, the higher passenger traffic handled and the higher frequency of long-haul flights, large terminals usually require longer periods of time for passenger processing and consequently lengthier dwell times. Therefore, differentiation in terminal capacity and actual passenger traffic between the case studies was necessary to allow the investigation of passengers' comfort conditions over different dwell times and occupancy levels.

Further diversity in the indoor conditions was sought by selecting case studies with dissimilar architectural features and spatial characteristics. From a historical standpoint, airport terminals are a fairly new building concept that has evolved in step with the needs of commercial aviation. Despite their relative novelty, terminal architecture is diverse itself as the development of airport passenger terminals is tailored to a number of safety, operational, environmental, economic and national considerations. Older structures usually possess a combination of differently designed spaces as a result of the terminals' periodic upgrading to meet passenger demands and new aircraft requirements through overhaul, refurbishment or expansion schemes. Accordingly, the case studies were selected to include a variety of terminal areas, ranging from older and most often small and poorly sunlit spaces designed to serve low passenger volumes, to the most contemporary terminal spaces characteristic for their large and open areas where natural light abounds.

The fulfillment of the selection criteria was verified by visits in the prospective sites where the terminal areas were inspected. Manston International airport (MSE), in Kent, was the airport initially approached in the search for a small scale terminal building. The single terminal of the airport was disregarded soon after the visit due to infrequent aircraft movements and very low passenger traffic handled. However, it was used as a pilot to evaluate the research methodology. The selection process was brought to an end when balance between the criteria fulfillment and the negotiations with the airports' authorities was achieved. The airport terminals buildings selected as case studies for on-site surveys are London City Airport (LCY), Manchester Terminal 1 (MAN T1) and Manchester Terminal 2 (MAN T2).

### 4.3 Manston Airport

Manston international airport is situated in the District of Thanet in Kent (51° 20´ 32" N, 001° 20´ 46" E), 11 nautical miles north-east of the city of Canterbury. The airfield at Manston has a long history stretching back to 1915, when aircraft activity at the site began for military purposes. Due to its location, the airport was extensively used during World War II, and in the 1950s, the United States Air Force (USAF) used it as a Strategic Air Command base. In 1960, USAF withdrew from Manston which became a joint civilian and Royal Air Forces (RAF) airport (MSE, 2009).

In 1989, Manston became known as Kent International Airport and a new terminal was officially opened that year, while ten years later the Ministry of Defence sold off RAF Manston. The single-floor terminal building (figure 4-1) spreads over an area of about 1750 $m^2$ and has an annual capacity of 1 mppa[1]. Its basic facilities consist of six check-in desks, one baggage claim

[1] mppa stands for million passengers per annum.

belt, small waiting areas and a single gate lounge. Departures and arrivals are segregated on the two sides of the building, served by a relatively small passenger apron which leads to the runway of 2,752 m long.


(a)


(b)

*Figure 4-1: (a) Aerial picture of terminal at Manston airport (source: Google Earth) and (b) terminal inside view.*

The commencement of Manston’s operation on an exclusively commercial basis, in 1999, followed plans for the airport’s development into a low cost airline hub. However, several suspensions of airline operations hampered prosperity and resulted in sharp fluctuation of passenger traffic over the years (figure 4-2). In 2012, when the study spied out the land of Manston as prospective small-scale case study, traffic did not exceed 8,000 passengers as the terminal was operating only two days a week and handling a maximum of two flights a day. A year later, Manston was proposed as a reliever airport for Gatwick and Heathrow, however, the scheme receded and due to financial difficulties operations ceased in May 2014.

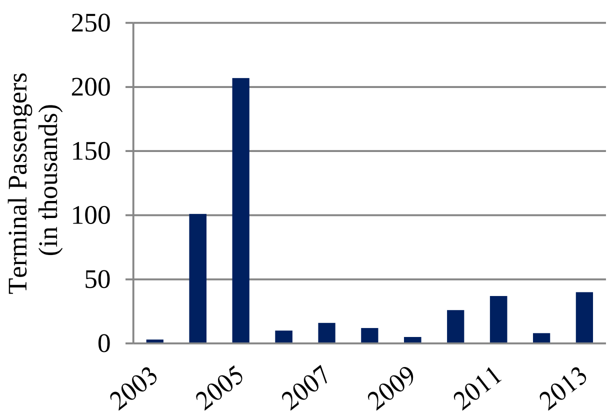



*Figure 4-2: Passenger traffic at Manston airport between 2003 and 2013 (graph based on data from CAA, 2014).*

## 4.4 London City Airport

London City airport is located 6 nautical miles east of the City of London (51° 30′ 19″ N, 0° 3′ 19″ E). The airport lies between Kind George V and Royal Albert Docks in the London Borough of Newham and consequently its early history is closely linked to the operation of Royal Docks. The Royal Albert Dock opened in 1880 following the opening of the Royal Victoria Dock in 1855, which was the earliest dock designed to serve steam ships with a direct rail connection. King George V Dock was built to enhance the trade though the Royal Victoria and Albert Docks and its construction in 1921 completed the royal group of docks, which, as a whole, formed the largest area of impounded water in the world (LCACC, 2008).

Over the period 1910-1950 the Royal Docks were relatively prosperous with the traffic reaching its peak in the 1950s and early 1960s. The switch in Britain's trade following its European Economic Community (EEC) membership and technological changes led to a rapid decline of the shipping activity in the Royal Docks and ultimately to its termination in the early 80s. The plans for LCY airport emerged from the regeneration of London's Docklands and the governmental London Docklands Development Corporation (LDDC) which managed the regeneration of the area in the 80s and 90s. As a result, LCY was built at its current site (figure 4-3) over a period of 18 months between April 1986 and October 1987 (LCACC, 2008).

The single terminal of the airport was built from a hybrid concrete and steel structure, enabling its fast-track construction and its opening on November 5$^{th}$, 1987. The original design criteria catered for 1.2 mppa, whereas nowadays the terminal handles over 3 mppa placing LCY 15$^{th}$ in the ranks among the busiest airports in the UK continuously from 2011 to date (CAA, 2014). The terminal provides services to over 30 destinations, including flights within the UK, international flights to European destinations, as well as the transatlantic route to New York JFK launched in 2009.

Contrarily to the rural Manchester airport terminals, the urban location of LCY has been a growth constrain, resulting among others in limitations to the operational hours. Because of the nearby residential areas, the airport was given planning permission on the condition that it operates only at certain times, with weekend flights cut to a minimum. As a result, the airfield operations run between 6:30 am - 9:35 pm in weekdays and between 6:30 am - 12:30 pm and 12:30 pm - 9:50 pm on Saturdays and Sundays respectively. On the other hand, the airport’s in-city location is advantageous in respect to its business passengers. The proximity of the departure airport to the point of origin appears to be clearly the most influential factor on the airport choice for this passenger category (CAA, 2010). LCY is the most business-centric airport among the London airports, with approximately 63% of its passengers travelling for business purposes and nearly 60% in Banking and Finance and other business services

(LCACC, 2009; CAA, 2010). Passenger type is among the differentiating factors between LCY and the terminals in Manchester airport.

*(a)*

*(b)*

*(c)*

*Figure 4-3: London City airport site: King George V Dock on the left and Royal Albert Docks on the right, (a) in the 50s during the Docks' peak traffic (source: LCACC, 2008), (b) in late 70s when docks were nearing the end of their life, (source: LCACC, 2008) and (c) nowadays, (source: www.londoncityairport.com).*

The two-storey building utilises the linear terminal concept and with a total floor area of nearly 10,000 $m^2$ represents the small scale terminal building among the case studies (figure 4-4). In comparison with its peers, the main terminal building is relatively small; if all the internal walls were removed, a Boeing 747 would fit snugly nose to tail and wingtip to wingtip within the external walls. As a result of the terminal's small size and the focus on business passengers, LCY is characteristic for the short walking distances and the significantly shorter dwell times required, which can be down to 20 minutes from check-in to boarding.


*Figure 4-4: London City main terminal front, south orientated (source: www.londoncityairport.com).*

The terminal houses in total 15 gate lounges, two of which are in the north façade of the main terminal building. Adjoining the west side of the main terminal building, a 300 m long two-storey pier is housing 9 gate lounges segregating arrivals and departures between the two floors, while in 2008 four more gate lounges were constructed in the 150 m long pier on the east apron (figure 4-5). The airport has a single runway of 1,508 m long and 17 aircraft stands on the apron, while more stands are provided at the Jet Centre for corporate aircrafts. As all the aircrafts served at LCY are relatively small and maneuverable, they are parked adjacent and angled nose-out to the pier. Operationally, this allows the aircrafts to move without the use of pushback tractors (tugs) as required at many other airports, while for passengers this means just a few meters walk to and from the aircraft.

*Figure 4-5: London City airport utilises the linear terminal concept with 17 standard aircraft stands and 15 gate lounges in total across the west and east pier (source: Google Earth).*

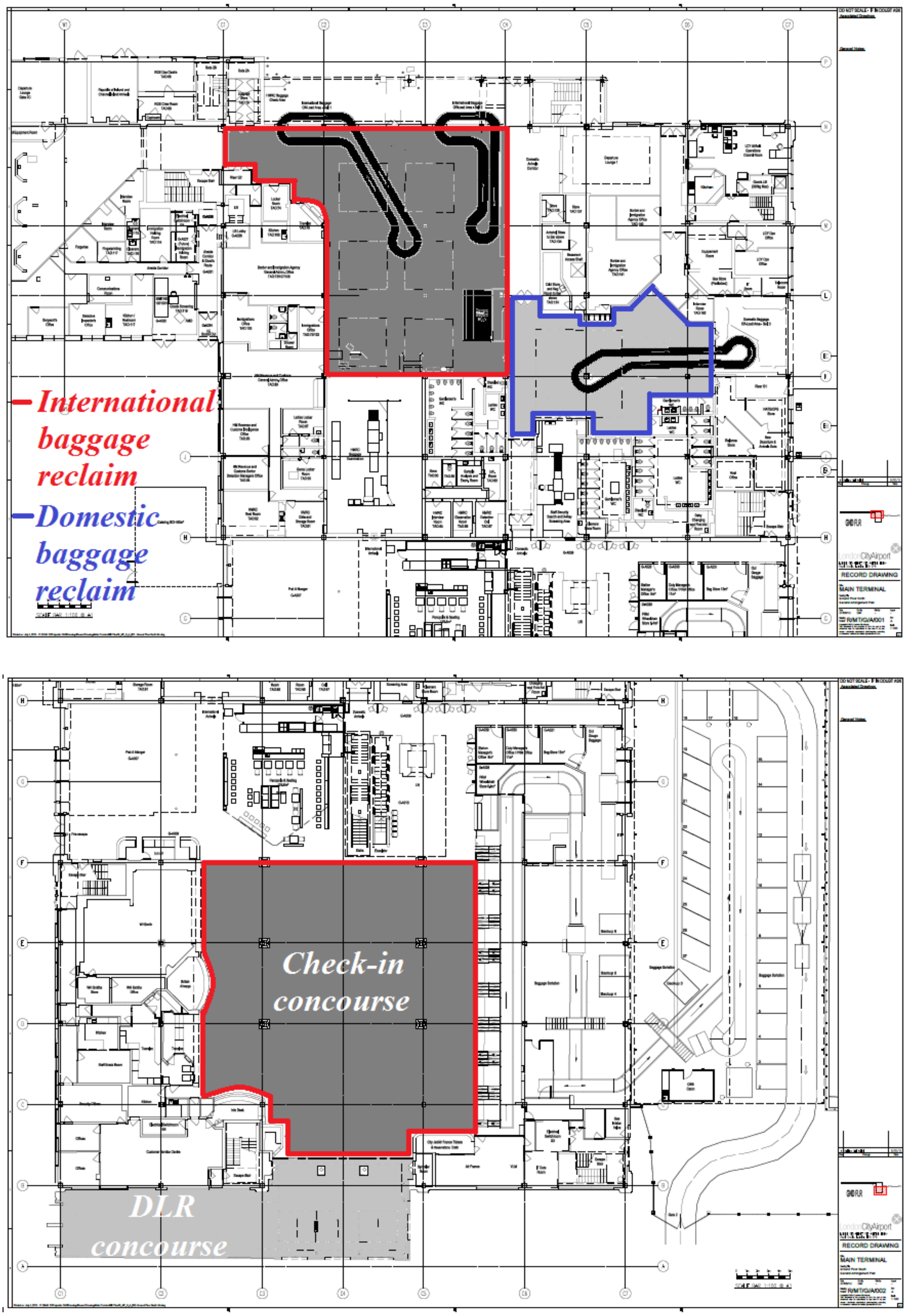
As a result of the terminal’s small size and the continuous rise in passenger demand over the years, the major terminal refurbishments to date have aimed to enhance space utilization. An expansion scheme was run in 1997 for the departures lounge, while in 2001, the terminal building was extended westwards to increase baggage reclaim capacity, improve immigration facilities and house handling agents and control authorities. In 2006, the restaurant areas were re-configured to allow for a 30% increase in seating capacity and two years later a major refurbishment took place in the terminal’s departures lounge for the same purpose.

Also in 2008, a finger extension was built-out on the east apron extension over the King George V Dock (figure 4-6) providing space for the four new integral passenger lounges, while acting as a sound barrier for the nearby residential properties to the south of the airport. In spite of the various extensions and refurbishments over the years, the terminal has retained its original compact nature.

*Figure 4-6: Eastwards extension of LCY terminal on King George V Dock completed in 2008.*

The terminal areas are relatively small with little variance in size and design characteristics between its spaces. In comparison to the interior of Terminal 1 and Terminal 2 at Manchester airport, LCY terminal spaces present the highest degree of uniformity. The terminal’s ground floor accommodates three key areas; the check-in area, the international and domestic baggage reclaim areas and the gate lounges (figure 4-7).

Located south in the building, the check-in area is equipped with self-service kiosks and 17 check-in desks over an area of 520 $m^2$ (figure 4-8b). There are several surrounding retail and handling agent facilities, while part of the check-in area is inevitably used as waiting and salutatory area by meeters and greeters and as the way out by arrived passengers due to the lack of a dedicated arrivals hall. The terminal building is directly linked to the elevated platforms of London City DLR station providing enclosed access to and from the check-in area. This space together with two pairs of double sliding doors on its two sides act as a shelter to the check-in hall against air draughts and direct exposure to outdoor weather (figure 4-8a).




(a)

(b)

*Figure 4-7: LCY ground floor plan (a) north: international and domestic baggage reclaim areas and (b) south: DLR and check-in concourse.*

The northern ground floor houses the international and domestic baggage reclaim areas. The international baggage reclaim area spreads over an area of 370 m$^2$ and is served by two baggage conveyors (figure 4-8c). The domestic baggage reclaim area is smaller, 260 m$^2$, and utilises a single baggage conveyor system (figure 4-8d). Both areas are characteristic of the absence of natural light and for the space conditioning by a single AC unit in each area, as both facilities are not tailored to the terminal's central HVAC system.


*(a)* *(b)* *(c)* *(d)*

*Figure 4-8: Views in the key ground floor areas at LCY: (a) DLR concourse (b) check-in concourse, (c) international baggage reclaim area and (d) domestic baggage reclaim area.*

At the same level and spread across the two piers are the gate lounges (figure 4-9). The gates originally built in the west pier accommodate a maximum of 50 passengers each, in approximately 55 $m^2$ of floor area. Of similar capacity and floor area is the newer gate located at the end of the west pier. On the other hand, the more recent gate lounges in the east pier were designed for higher capacity and account for 90 $m^2$ of floor area each. The relatively small size of the gate lounges along with their glazed façade and the very frequent use of the doors leading to airfield, place the gate lounges among the most vulnerable – to outdoor weather – spaces in LCY. The majority of the gate lounges are centrally conditioned, yet each gate is also equipped with a single air-conditioning unit. The terminal building contains a number of other facilities on its ground floor, such as the airfield operations control room and the security screening area used solely from terminal staff. As these spaces are inaccessible to passengers they are not taken into account in this study.

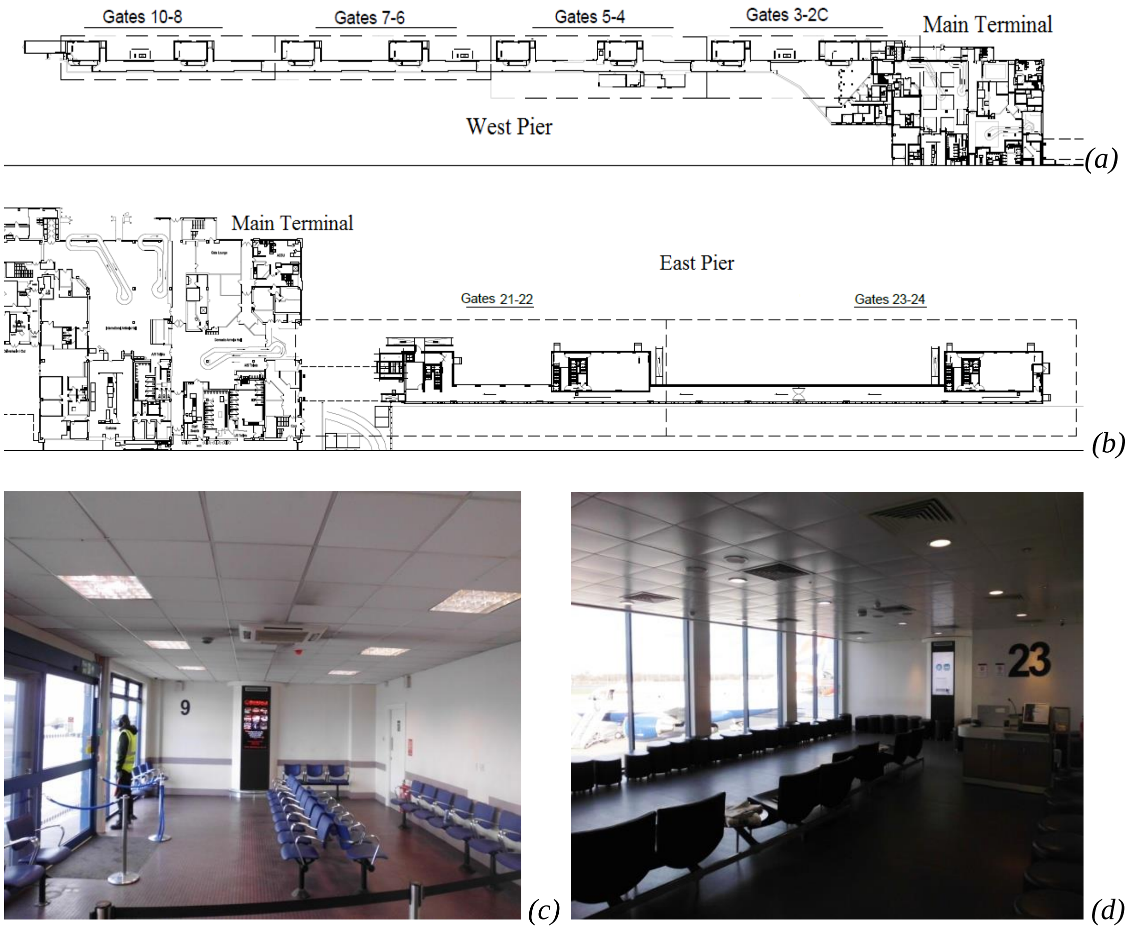



*Figure 4-9: LCY (a) west pier plan, Gates 2-10, (b) east pier plan, Gates 21-24, (c) representative gate 9 in west pier and (d) representative gate 23 in east pier.*

The key passenger facilities housed on the first floor are three spaces along a single passageway that comprise the departures lounge area and the transitional space between landside and airside; the search area (figure 4-10). The latter is located in the SE of the building and utilises three double luggage and human screening systems over an area of 400 $m^2$ (figure 4-11a). A smaller search area of 230 $m^2$ is located nearby on the eastern side of the building and is used in support of the main one during extreme traffic peaks.

The three waiting areas in the departures lounge are the “seating area”, “departures lounge 1” and “departures lounge 2”. The south-orientated seating area comes first into view for a passenger that has just been through the security screening (figure 4-11b). It is the only concourse area of the terminal, other than a large circulation space leading to the main search area, with a high floor-to-ceiling height (8m). Within its 413 $m^2$ floor area, this space provides a number of seats, mostly restaurant dedicated. Adjoining the seating area, departures lounge 2 utilises 126 $m^2$ of floor area to provide additional standard seating (figures 4-11c and 4-11d). It is often used as a quiet working space by passengers travelling on business and is one of the brightest airside spaces in the terminal due to natural light flooding in through the glass curtain wall in the east façade of the terminal.

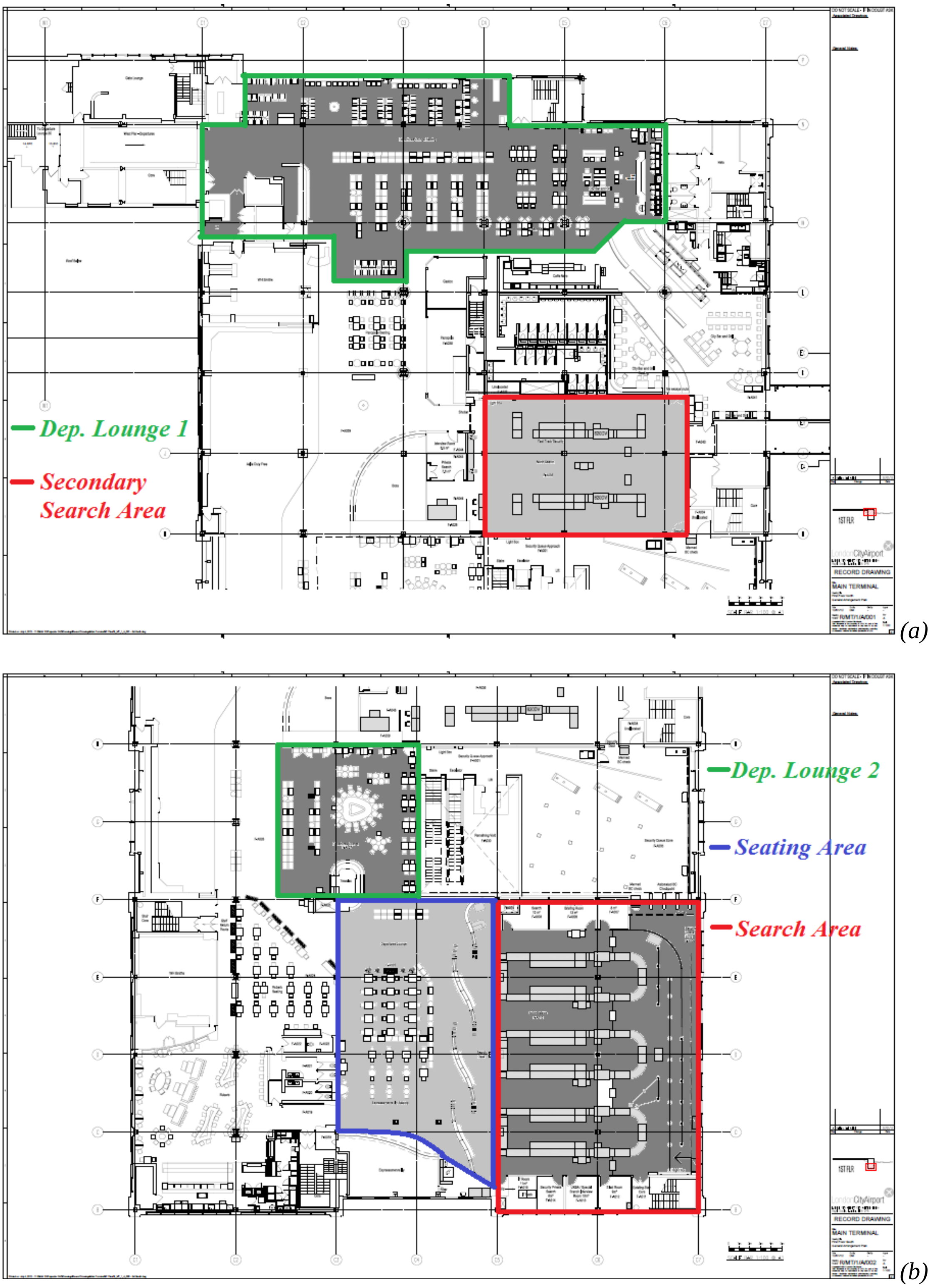
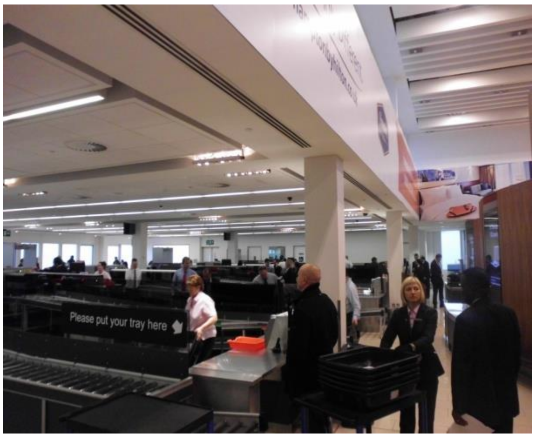


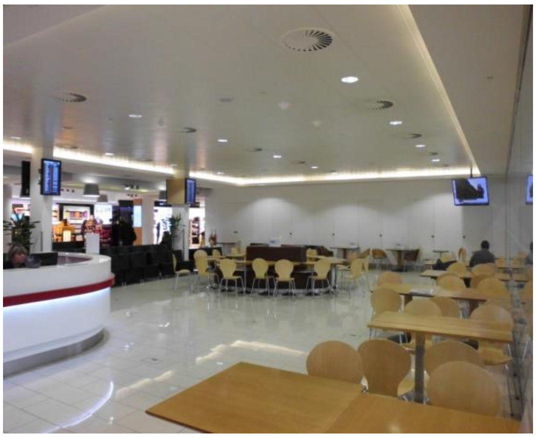

*Figure 4-10: LCY first floor plan (a) north: secondary search area and departures lounge, (b) south: main search area, seating area and departures lounge 2.*

The main and largest waiting area of the terminal is the departures lounge 1 located in the northern side of the building (figures 4-11e and 4-11f). It spreads over an area of 605 m$^2$ and provides access to the two nearby gate lounges of the main terminal building and to those in the east and west pier. It is the only waiting area with direct view to outside though the windows in the north façade and often the most congested among the spaces in the departures lounge. The departures lounge areas are peripherally enriched with several restaurants and shopping facilities, which are also taken into account in this study.




*(a)*

*(b)*



*(c)*

*(d)*

*(e)*

*(f)*

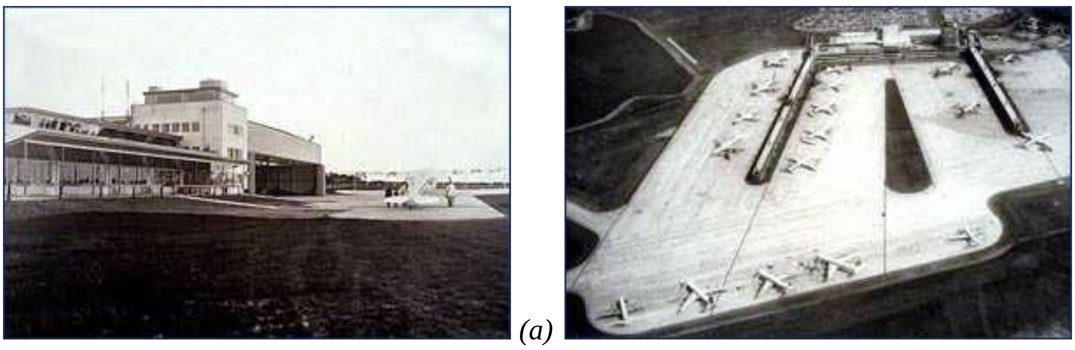
*Figure 4-11: (a) Views in the key first floor areas at LCY: (a) search area (main), (b) seating area, (c) & (d) departures lounge 2, (e) & (f) departures lounge 1.*

The indoor environment in LCY is controlled by means of approximately 13 air handling units, with the temperature set-points being set at 20 °C in winter and 23 °C in summer. However, the set-points are manually adjusted when required due to extreme outdoor weather conditions and/or to very high occupancy levels. As far as the lighting environment is concerned, all passenger-related spaces rely on artificial lighting, with some source of natural light in most areas (e.g. departures lounge 1 and seating area) and complete lack of daylight in fewer spaces (e.g. baggage reclaim areas).

### 4.5 Manchester airport

The international airport of Manchester is located in Ringway, 7.5 nautical miles south west of Manchester city (53° 21 ′14″ N, 002° 16′ 30″ W). Before settling in its current site, the early history of the airport was written in various short-lived airports in and around Manchester. Barton was the last stop, where the airport opened in 1930 but soon after, this site had a number of problems disrupting its services and was considered too small for long-term development. Meanwhile, another airfield was opened in Wythenshawe, in 1929, for temporary use while the airport in Barton was being built (Manchester Airport, 2014).

The construction of the new airfield in Ringway began in 1934. The airport opened in 1938 and during its 14 months of operation handled 7,600 passengers. During the World War II the airport was used for military purposes (training of Britain's Airborne forces) and normal services were resumed in 1946. By 1949 more enhancements were made to the terminal and few years later the runway was extended. A range of changes took place in the 50s and the airport began to operate on a 24-hour basis. However, the major developments took place in the 60s with a new terminal built (today’s terminal 1) along with air traffic control facilities (figure 4-12). In the 80s the airport began to serve direct long-haul international flights and a new “domestic” terminal was built in 1989 (current terminal 3).



*(a)* *(b)*

*Figure 4-12: (a) Ringway airport opening in 25 June 1938, (b) Manchester airport in 1964 (Source:Manchester Airport, 2014)*

Nowadays, Manchester airport has three terminals (Terminal 1, Terminal 2 and Terminal 3) and serves over 100 airlines and 200 destinations worldwide. In 2013 it was the 3rd busiest airport in the UK behind Heathrow and Gatwick. In this year the airport handled nearly 170,000 commercial air movements and over 20 million passengers (CAA, 2014). Among the major features of the airport is its skylink and second runway. The skylink opened in 1997 and connects MAN T1 to MAN T2, utilising travelators to aid passengers with the 10-15 minute walk, while it also links the terminals to the airport's railway station complex. After three extensions of the original runway in 1951, 1969 and 1981, a second parallel and of similar length runway (3,048 m) was granted in 1997 and opened in 2001, placing Manchester airport together with Heathrow as the only airports in the UK with two full-length runways. Contrarily to LCY, the airfield operations in Manchester airport run 24/7.

### 4.5.1 Manchester Terminal 1

MAN T1 opened in 1962 with the original design criteria catering for an annual capacity of 2.5 mppa. Nowadays the terminal can accommodate around 11 mppa and serves both scheduled and charter flights to European and worldwide destinations. It is the largest and busiest among the terminals at Manchester airport and represents the large scale terminal between the case studies. Excluding the large car parking areas assigned to the terminal, the mechanical people movers and the air bridges, the building's facilities are spread over an area of 43,499 $m^2$.

The terminal holds the finger pier and satellite pier systems (figure 4-13) and it was the first terminal in Europe to incorporate piers. It has 28 gate lounges and 24 aircraft stands across the two piers, of which 18 with air bridges. The older pier, named pier C, is 158 m long, extending to 205 m with the satellite of nearly 1,150 $m^2$, and accommodates 13 gate lounges. Pier B is nearly 300 m long and houses 15 gate lounges.

*Figure 4-13: Manchester terminal 1, pier finger and pier satellite serving 24 aircraft stands (source: Google Earth).*

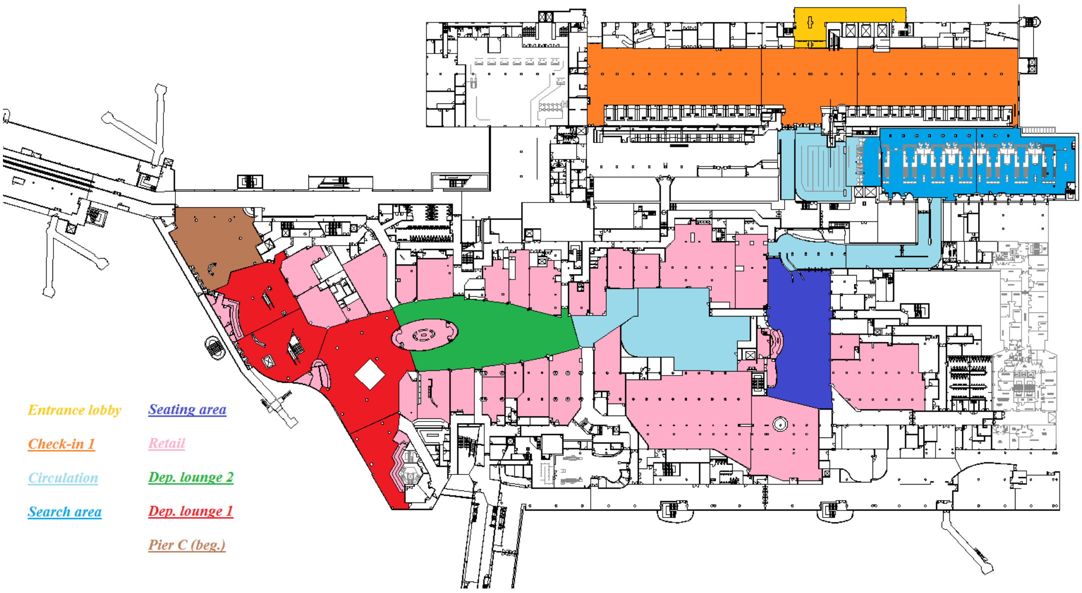
A number of overhauls and expansions have been carried out since the terminal's opening. The most recent ones include a retail upgrade in 2003 and a major redesign process of the terminal between 2005 and 2009. In the latter, the retail and catering facilities were expanded, the security throughput was increased by expanding the search area to 14 lanes and the balance between landside and airside was modified by providing more space to the airside facilities. As a result of the consecutive refurbishment and extensions over the years, MAN T1 is a large complex building accommodating a mixture of spaces with heterogeneous architectural features.

The facilities are spread on four floors, with two of them (ground and second) accommodating the passenger processing spaces. The first floor is mainly offices, while the third floor has plant rooms similarly to the fourth floor which also houses numerous staff-care facilities. Departures and arrivals are well segregated in MAN T1, as served in the second (figure 4-14a) and ground floor (figure 4-15a) respectively.

The second floor accommodates a large check-in area providing 59 out of the 107 check-in desks in MAN T1 (check-in 1; figure 4-14b). A smaller check-in hall is located on the ground floor where 29 desks are operated by a single airline based at Manchester airport (check-in 2; figure 4-15b). The two halls are operationally identical but differ greatly in size and configuration. The main check-in concourse is housed in a space of 4.5 m floor-to-ceiling height and spreads over an area of 2,486 $m^2$, whereas the ground-floor check-in hall is significantly smaller (1,162 $m^2$) and characteristic for the several ceiling height changes across its area, ranging from as much as 5.2 m in some areas to only 2.4 m in other.

The variety of spaces in MAN T1 is also reflected in the diverse departures lounge spaces. Soon after passengers go through the spacious (1,185 $m^2$) and modern search area, they come across the departures lounge consisting of three distinct spaces, which could be also the departures lounges of different terminals. The seating area (figure 4-14c) or the "river of light" (Stageone, 2009), is a 763 $m^2$ space with a floor-to-ceiling[2] height of 7.5 m and characteristic for its dimmed blue lighting design intended to aid with wayfinding and specifically with the way towards the duty free shops. The nearby departures lounges 1 and 2 are next to each other with the lounge 1 (figure 4-14e) being the extension of lounge 2 (figure 4-14d). The latter provides seating in a dim area of 850 $m^2$, characteristic for the low suspended ceiling of 2.6 m. On the other hand, lounge 1 lies over an area of 2,307 $m^2$, with a significantly higher floor-to-ceiling height (7.3 m), where natural light abounds due to the extensive glass wall and rooflight. A common characteristic among all the airside spaces is the strong presence of a variety of retail facilities integrated into the departures lounges.

[2] Refers to suspended ceiling.




*(a)*

*(b)*

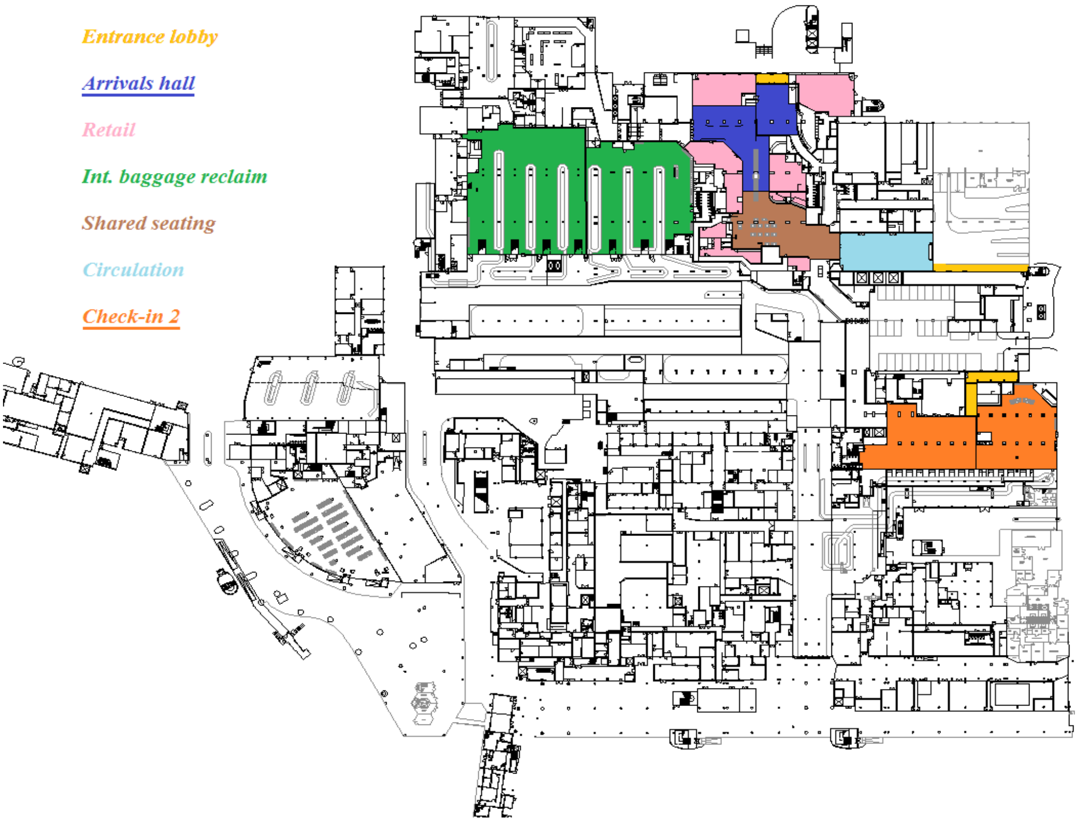
*(c)*

*(d)*

*(e)*

*Figure 4-14: MAN T1 2nd floor, (a) route between check-in hall (top right) to departures lounge (bottom left): check-in hall, search area, circulation, seating area, duty free, circulation, dep. lounge 2 and dep. lounge 1, (b) check-in 1 (main), (c) seating area, (d) dep. lounge 2 and (e) dep. lounge 1.*

Many terminals nowadays put more effort on the departures areas than in the arrivals; the reason being the airside retail revenues. This is also the case with MAN T1 where the arrivals hall uses one of the oldest spaces of the terminal. It is located on the ground floor with a dedicated floor area of 1,070 $m^2$, however, the geometry of the area hinders direct eye contact between exiting passengers and the spaces further away (figure 4-15c). As a result, only a small portion of this large area is practically used by meeters as an arrivals hall. The space is served by two air handling units (AHUs) fed from the central low temperature hot water (LTHW) system for heating and from a chilled water (CHW) system for cooling, while there are also locally controlled reheat coils fed from the LTHW system. However, since the early visits to the terminal, it was apparent that the outdoor weather conditions have a great impact on the indoor thermal environment of this space due to the proximity of the frequently opening doors (two pairs of double sliding doors) to the waiting area.




(a)

(b)


(c)

*Figure 4-15: MAN T1 ground floor (a) arrivals hall (top) and check-in 2 (right), (b) check-in 2 view, (c) arrivals hall view.*

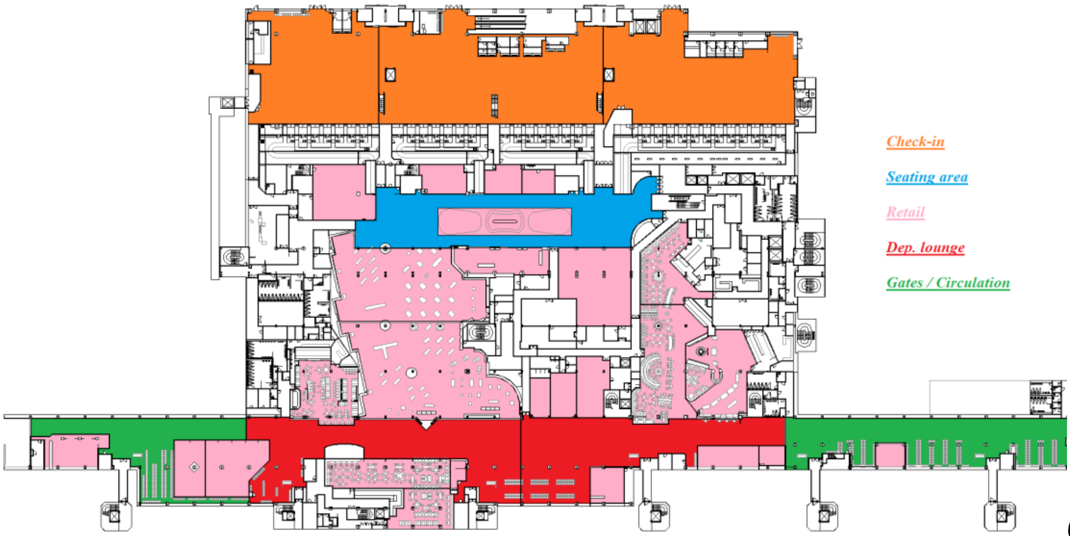
In general, there is a variety of systems used in the spaces of MAN T1, as a result of the new spaces added regularly over the years. For instance, check-in 1 and seating area are conditioned by two AHUs each, by means of LTHW for heating and CHW for cooling. The check-in 2 and search area are served by gas fired AHU with chilled water from the central chilled water supply, while the departures lounges 1 and 2 are fed from multiple AHUs. Moreover, pier B has natural draught convectors on the outside edge with DX cooling down the middle and AHU supply from six AHU's fed by central LTHW and CHW supplies. On the other hand, pier C has multiple AHUs supplied with central LTHW, while the satellite has its own chiller plant. The temperature set-point in all terminal areas is fixed at 21 °C throughout the year. This is a general set-point which means that all the systems within the terminal compensate to achieve it regardless of the external temperature.

### 4.5.2 Manchester Terminal 2

The opening of MAN T2 in 1993 boosted Manchester airport's capacity to 20 mppa. Its facilities are spread over an area of 26,063 $m^2$, which excludes the terminal's car parks, air bridges and travelators. Accordingly, and with a current capacity of 8 mppa, MAN T2 is the second largest terminal in Manchester and represents the medium scale terminal among the case studies. Similarly to MAN T1, the terminal handles scheduled and charter flights to European and worldwide destinations. It employs the linear concept as two piers of 152 m and 331 m long span NW and SE from the main terminal and serve in total 15 aircraft stands (figure 4-16). There are in total 17 gate lounges, of which 14 served by air bridges. In spite of its relative "newness", the terminal has been already extended once in 2003 while a north-west extension is planned aiming for a future terminal capacity of 25 mppa.

*Figure 4-16: Manchester terminal 2 concept with two piers spanning NW and SE from the main building (source: Google Earth).*

The 4-storey terminal is designed with the most contemporary terminal design features compared to its peers in Manchester airport. The vast majority of its zones consist of large open-plan spaces with high ceilings and extensive use of natural light through curtain walls and rooflights. Most key passenger facilities are located on the second floor, including the check-in area, the departures lounge areas ("seating area" and "departures lounge"), numerous retail amenities and the gate lounges (figure 4-17a). The check-in area in MAN T2 is the largest among the case studies (3,470 $m^2$), providing a total of 80 check-in desks and additional self-service kiosks (figure 4-17b).




*(a)*

*(b)*

*(c)*

*(c)*

*(d)*

*Figure 4-17: MAN T2 2nd floor: (a) from top to bottom: check-in hall, seating area, duty free, departures lounge and gates lounges, (b) check-in hall, (c) seating area, (d) duty free and (e) dep. lounge.*

Passengers are then directed to the search area on the third-floor (figure 4-18a). The search area is equipped with 10 lanes of screening systems in a total floor area of 1,278 $m^2$. It is the only short-ceiling space (2.4 m) among the passenger-related areas in MAN T2. The space originally designed to house this critical function is the large area lying between the seating area and the departures lounge, however this is currently used as a duty free facility. With the intention to expand the airside spaces and enhance airside retail activity, the search area was moved in 2009 to its current location which is a result of the unification of smaller separate rooms (figures 4-18b and 4-18c).


*Figure 4-18: MAN T2 3rd floor, search area.*

From the search area, passengers flow down to the second floor coming across the seating area (1,330 $m^2$) where the extensive rooflight dominates its design (figure 4-17c). Seating in this area is exclusively retail-provided. Passenger flow is then directed through the large duty free area (1,615 $m^2$) to the larger departures lounge (1,855 $m^2$). The gates lounges are located on the extension of the departures lounge, across the two diametrically opposed piers. A baggage reclaim area and a dedicated arrivals hall (1,192 $m^2$) are located on the ground floor of the terminal (figure 4-19).

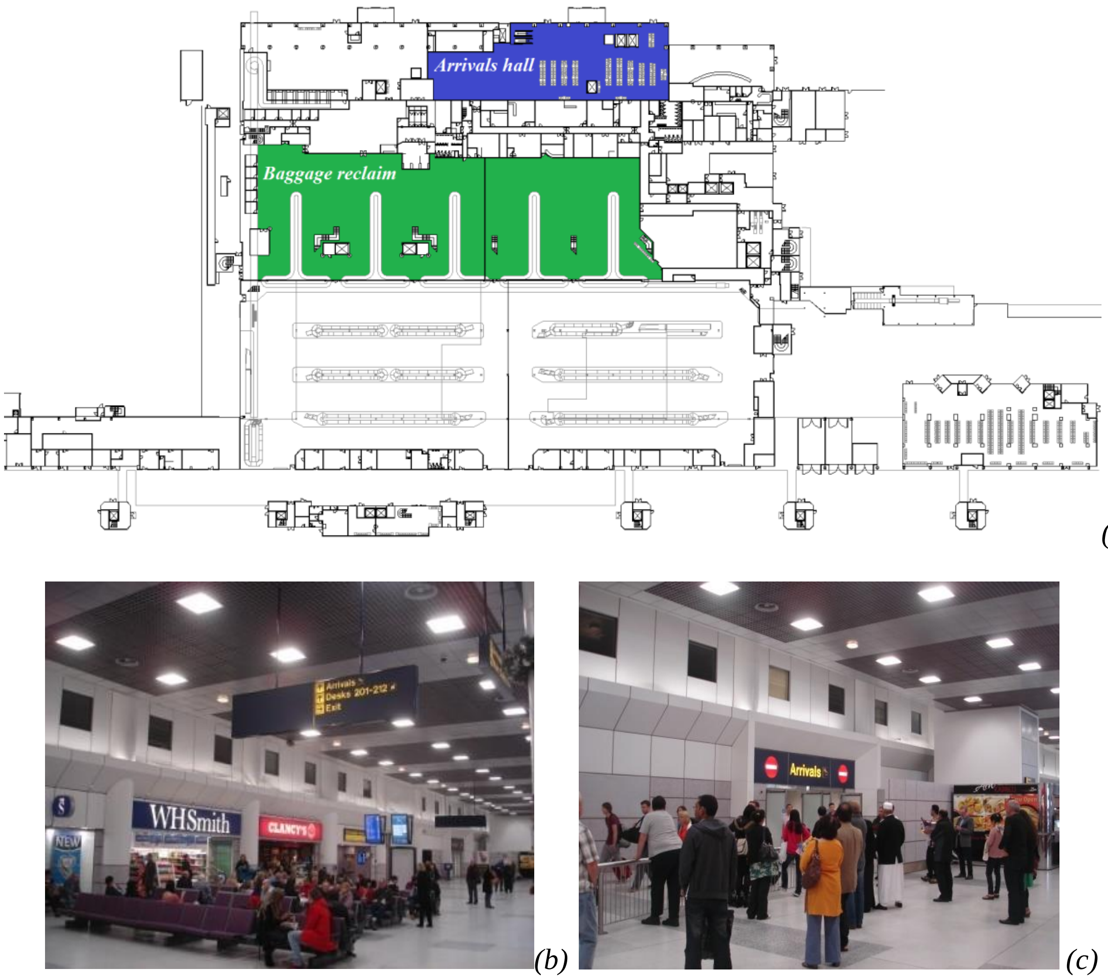



*Figure 4-19: MAN T2 ground floor (a) plan, (b) & (c) views in arrivals hall.*

All spaces in MAN T2 are conditioned by multiple AHUs fed with LTHW from the central plant for heating and with CHW from the central chilled water supply for cooling. Local variable air volume systems (VAVs) are additionally used in certain spaces such as, the search area, the seating area and the duty free. Similarly to MAN T1, the temperature set-point is kept at 21 °C all year round irrespectively of the outdoor weather conditions.

## 4.6 Conclusions

The case studies terminal buildings were selected to represent terminal buildings of three different scales and to provide sufficient diversity in characteristics which would allow the study of a representative range of the indoor conditions commonly experienced in airport terminals. The case studies differ in a number of other characteristics which include the location, design and spatial characteristics, as well as passenger profile and dwell time (table 4-1). LCY is characteristic for its compact and uniform environment and the short dwell times required. MAN T2 features a modern terminal design with large open-plan spaces, whereas the significantly larger MAN T1 combines a variety of spaces as a result of consecutive expansions over the years. The next chapter explains how these parameters were incorporated in the data collection during the surveys and in which way they were used in the data analysis.

*Table 4-1: Summary table of the criteria influenced the selection of case studies*

| | Scale | Floor area ($m^2$) | Capacity (mppa) | Building features |
|---|---|---|---|---|
| LCY | Small | 10,000 | 3 | Built in 1987, compact, short walking distances & dwell times, small & uniform spaces |
| MAN T1 | Medium | 43,499 | 11 | Built in 1962, successive expansions & refurbishments, long walking distances & dwell times, diversity in spaces |
| MAN T2 | Large | 26,063 | 8 | Built in 1992, contemporary, long walking distances & dwell times, large & open, mostly daylit |

# CHAPTER 5: METHODOLOGY OF FIELD STUDIES

## 5.1 Introduction

The work involved extensive environmental monitoring in different terminal areas and questionnaire-guided interviews with the different types of occupants using the terminal buildings. The chapter discusses the development of the tools used for the data collection, the pilot studies conducted to optimize the research methodology, the nature of the field surveys carried out in the three airport terminals and the limitations in data collection.

## 5.2 Equipment design

A microclimatic monitoring equipment was designed for monitoring the indoor environmental conditions in the terminal buildings. The environmental quantities measured include:

- dry bulb temperature, °C
- black globe temperature, °C
- relative humidity, %
- air movement, m/s
- carbon dioxide, ppm
- horizontal illuminance, lux

The first four parameters are the standard environmental measurements required for the investigation of thermal comfort conditions. Measurements of carbon dioxide were used predominantly as an indicator of change in occupancy levels and as an estimate for the adequacy of ventilation rates in the terminal spaces. Illuminance data aimed for the assessment of perception and preference over the lighting environment. The latter two measurements aimed also at investigating possible links between indoor air quality and lighting levels with perception of thermal comfort.

The decision on the instruments was made on the balance between cost and the specifications required, such as accuracy, response time and voltage. The equipment consists of a data logging system, a shielded temperature and humidity probe, a black globe thermometer, an ultrasonic anemometer, a $CO_2$ sensor and a light sensor (figure 5-1), all conforming to ISO 7726 (ISO 7726, 1998). In particular:

- The data logging system consists of a Campbell Scientific CR800 data logger and a PS100-12Vdc rechargeable power supply (battery) with a nominal capacity of 7 Amp hours.

- A Campbell Scientific CS215 probe was used to measure dry bulb temperature and relative humidity. The probe utilises a single chip element incorporating a temperature and RH sensor. The temperature sensor presents an accuracy of ±0.4 °C over +5 °C to +40 °C (or ±0.3 °C at 25 °C) and a response time of 120 s (63% response time in air moving at 1 m/s). As far as the RH sensor is concerned, this has an accuracy of ±4% over 0-100% (or ±2% over 10-90%) at 25 °C and is compensated – in terms of temperature dependence – to better than ±2% over -20 to 60 °C. The probe was housed in a Campbell Scientific MET 21 unaspirated radiation shield. Its white outer reflective surface combined with the inner barrier of non-reflective black louvres prevents sunlight from reaching the sensor, whilst still allowing the air to flow through the sensor.

- Black globe temperature was measured with the black globe sensor commonly used in indoor applications. The sensor uses a thermistor inside a 15 cm (6") hollow copper sphere, painted black to measure radiant temperature. The overall probe accuracy is a combination of the polynomial error, the precision of the bridge resistors and the thermistor's interchangeability specification. In the worst case scenario, all errors can result in an accuracy of ±0.3 °C in the range of -3 °C to 90 °C.

- A Gill-make ultrasonic anemometer (Windsonic - option 1) was employed for the measurement of air movement. The principle of operation lies on the measurement of the times taken for an ultrasonic sound pulse to travel from the north to the south transducer, and their comparison with the travel time of a pulse from the south to the north transducer. Similarly, the Windsonic compares the times between west and east, and east and west transducers. Its accuracy (±2% at 12 m/s), operational range (0-60 m/s) and resolution (0.01 m/s) were appropriate for measuring the low air velocities expected indoors, while its short response time (0.25 s) would allow the detection of rapid air changes (draughts), e.g. from the opening of sliding doors.

- Carbon dioxide levels were measured by means of a COZIR ambient $CO_2$ sensor with a measurement range of 0-2000 ppm. The sensor has an accuracy of ±50 ppm ±3% of reading and was calibrated to have the fresh air baseline at 380 ppm.

- Horizontal lighting levels were measured by a Skye-made SKL2630 HOPL lux sensor with a wide working range and a prompt response time of 0-500 klux and 50 ms respectively. The sensor uses a silicon photocell detector and has been fitted with a large area photodiode for increased sensitivity at low light levels.

*Data logging system & battery*

*Radiation shield*

*Black globe thermometer*

*Anemometer*

*$CO_2$ sensor*

*Lux sensor*

*Figure 5-1: Data logging system and sensors.*

Major considerations in the instrumentation design were mobility, size and security screening. More specifically, the study required the investigation of the immediate microclimate people experience and therefore an easily transportable system was required. Accordingly, a hand trolley was employed to haul the equipment and confer flexibility in the transitions from space to space. The instruments were mounted onto four crossarms spanning from a main rod of 1.65 m high (figure 5-2). Exceptionally, the $CO_2$ sensor was placed close to the interface between rod and crossarms to prevent deceptive readings from people coming very close to the equipment. Leveling units and stands were fitted on the crossarms to ensure the correct positioning of the sensors. The lux sensor and anemometer were placed diametrically opposed spanning to a total length of 51 cm and 48 cm from the rod. Similarly, the diametrically opposed black globe and the shielded temperature and RH probe extend to a length of 35 cm and 48 cm respectively.

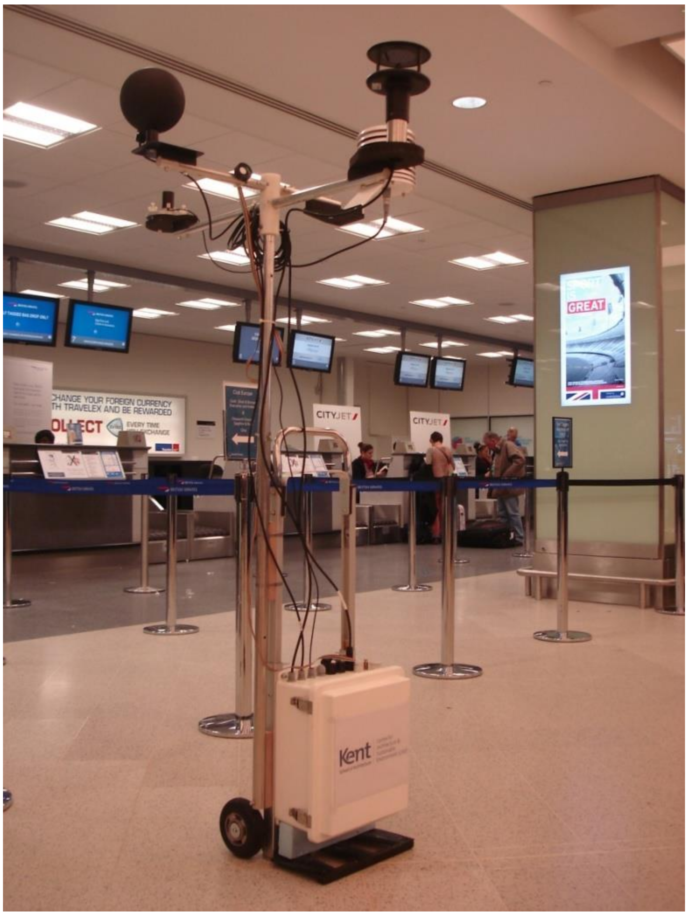



*Figure 5-2: Instrumentation trolley system consisting of data logging system, shielded temperature and RH probe, anemometer, black globe thermometer, lux sensor and $CO_2$ sensor.*

The arrangement of the instruments and the total length of the arms were determined from the distance between the sensors required to ensure their unhindered function. The rod’s height was decided according to the study’s requirement to measure all environmental quantities at the average height of a standing person (1.7 m). In its white fibreglass-reinforced polyester enclosure, the data logging system was placed on the base of the trolley to keep the structure’s centre of gravity close to the floor level. The minimum dimensions of the screening machines in the airports were also among the parameters determining the overall size of the structure’s main body (i.e. without the crossarms). In addition, the system was designed to be dismountable for passing through security screening while moving from landside to airside.

The system was wired and programmed thereafter to record readings of all environmental quantities at one-minute intervals (program in appendix B). The frequency of readings was determined from the study’s requirements and the instruments’ specifications. For instance, a key consideration in respect to the readings from the CS215 temperature and RH probe was the avoidance of errors due to self-heating. These errors can become significant when readings are taken very frequently and in conditions of very low air movement; as expected in mechanically ventilated terminal buildings. This is because the sensor contains active elements, where power dissipated in them can raise their temperature resulting to a slight over-reading of temperature and under-reading of RH. Therefore, a frequency of no more often than every 5 seconds was necessary for this sensor to prevent measurement errors.

### 5.3 Questionnaire design

A standardised questionnaire (appendix A) was developed to collect subjective data essential for the evaluation of the indoor comfort conditions. The study adopted the method of structured interviews as the most appropriate technique for data gathering in the airport terminal environment. Structured interviews are advantageous in that they allow the acquisition of the required information in full range and depth from large numbers of people, while providing the researcher with control over possible misinterpretations and completion time of the questionnaire. The design process involved a number of considerations, including question types and wording, ordering and arrangement of items as well as the narrow time allowance of passengers and staff in terminal buildings.

The questionnaire comprises of open-ended, partially closed-ended and closed-ended questions, with the latter being the majority of the items as required from the quantitative nature of the research. Closed-ended or forced choice questions ask the respondent to choose from a limited number of alternatives, are easier and quicker to answer and easier to analyse statistically. The survey includes nominal and ordinal close-ended questions and a combination of 3-point, 5-point and 7-point scales for the assessment of perception and preference responses. Important consideration in the construction of all types of forced-choice questions was to ensure that the response categories are exhaustive and mutually exclusive.

Partially closed-ended questions provide a compromise between open-ended and closed-ended questions. They were used in cases where the alternative “other”, with a blank space next to it, was necessary to ensure exhaustion or where further information on a given response was required. Open-ended questions ask participants to formulate their own responses and allow for a greater variety of answers. However, they can be very demanding for respondents who may require a considerable amount of time to formulate an answer and they are more difficult to analyse as they are hard to quantify and take time to be coded in some manner. Therefore, open-ended questions were kept to a minimum. A semantic feature of both partially closed-ended and open-ended questions is the length of the blank space provided; a single line encourages a short answer, whereas several lines would indicate that a longer response is expected.

As a wide variety of respondents from different backgrounds was expected to be encountered, the questions were worded in simple English to diminish possible confusion and to make sure that items are perceived in the same manner by all participants. Active rather than passive voice was applied to all questions which were designed without possessive forms and grammatical complexities to minimise the cognitive demand on respondents (Brislin, 1986). The questionnaire was also deliberately kept free of words such as “and” and “or” which can often result in double-barreled questions and mislead the interviewees when more than one issue is raised in a single question. Moreover, consideration was given to ensure that wording does not produce loaded (e.g. with emotionally laden terms) and leading questions that sway respondents to answer in a fallacious manner (Foddy, 1994). Lengthy questions were avoided (Fink, 2003) and all items were kept shorter than the maximum number of 16 and 20 words per sentence, as recommended by Brislin and Oppenheim respectively (Brislin, 1986; Oppenheim, 1992).

The questions were arranged in subsets according to their relevance and ordered as such to endow the survey with a natural flow. This is essential to ensure that the general concept being investigated is made obvious to the respondents, while it also assists the interviewees to focus on one issue at a time. The layout of the questionnaire was also determined from the significance and nature of the questions. Important topics were addressed early rather than late in the questionnaire, whereas demographic questions were placed at the end. Although this piece of information is important for researchers, many respondents view it as boring and lose interest in the survey (Jackson, 2011). For the same reason, open-ended or longer questions were not used in the beginning of the questionnaire. Last but not least, questions of sensitive nature were also placed at the end of the questionnaire, as respondents are more likely to answer them if they have already committed themselves in answering questions of less sensitive nature (Jackson, 2011).

The questionnaire was drafted on a single page and consists of five sections. **Section A** (figure 5-3) classifies the interviewees in preliminary population groups – employees, passengers, well-wishers and other – and further into staff and passenger subgroups (question 1). This was intended to facilitate the separate investigation of the comfort requirements for the various population groups, e.g. for passenger and staff, for the different types of staff and for leisure versus business passengers. The question works also as a filter (funnel) question for section D; all non-employees respondents are excluded from this section. Next, section A requests information on covariates that can affect thermal sensation (questions 2-5). These include the consumption of drinks, modification of clothing levels and the activity level in the preceding 15 minutes, as well as the respondent’s dwell time by the time of the interview. Studies suggest that information on the activity levels 15 minutes prior to the survey may improve the prediction of thermal sensation (Goto et al., 2002; Chun et al., 2008). More generally and assuming steady climatic conditions, standards state a minimum period of occupation necessary for occupant to ascertain a valid reaction to the thermal environment. ISO 10551 recommends a period of at least 30 minutes, whilst ASHRAE suggests a stay of no less than 15 minutes (ISO 10551, 2001;

ANSI/ASHRAE, 2004). Taking these into account, the study adopted the "15 minutes" interval as more applicable to the airport terminal environment for questions 3-5, and applied it as the spacer interval in the dwell-time question 2.

Date: .............Location in terminal:................Start Time: ...............Gender: □ Female □ Male

Current Activity: □ Seated □ Standing □ Standing, light activity

**SECTION A**

**Q1. What is the main purpose of your visit to the airport today?**

□ Working here as.........................□ Travelling to.......................for □leisure or □business

□ Meeter / Greeter □ Other...........................................

**Q2. How long have you been in this terminal building?**

□ <15 mins □ 15-30 mins □ 30-60 mins □ >60mins

**Q3. What was your activity in the last 15 minutes?**

□ Seated, relaxed □ Sedentary activity □ Standing, light activity

□ Standing, medium activity □ Walking □ Other.....................

**Q4. Have you modified your clothing during the past 15 minutes?**

□ Yes, clothes on □ Yes, clothes off □ No

**Q5. Have you consumed any drink in the last 15 minutes?**

□ Yes ( □ Hot drink □ Cold drink ) □ No

*Figure 5-3: Section A of the questionnaire – interviewee classification and covariates of thermal sensation.*

**Section B** (figure 5-4) elicits information for the subjective evaluation of the thermal environment. The questionnaire uses the widely applied 7-point ASHRAE scale for the assessment of thermal sensation (question 6) and a 5-point scale for thermal preference (question 7). Seven-point scales have been commonly used in psychological studies and has been concluded that seven represents the optimum number distinguishable to people for describing different levels of sensation (Miller, 1956; Nicol et al., 2012). The adopted 5-point thermal preference scale has been applied in many comfort studies (McCartney and Nicol, 2002) and its use is suggested to overcome the ambiguity of thermal condition acceptability and to prevent overlapping with cultural use of words, such as "nice and warm" or "nice and cool" (Nicol et al., 2012). Similar form of questions was adopted to assess other environmental parameters. These include a 5-point scale for the sensation and preference over the air movement (questions 8 and 9), as well as the 5-point and 3-point scales for the subjective assessment of air freshness and humidity conditions respectively (questions 10 and 11).

**SECTION B**

**Q6. How do you feel at the moment?**

□ Cold □ Cool □ Slightly Cool □ Neither cold nor hot □ Slightly warm □ Warm □ Hot

**Q7. How would you prefer to be at the moment?**

□ Much warmer □ A bit warmer □ No change □ A bit cooler □ Much cooler

**Q8. How would you describe the air movement at the moment?**

□ Very low □ Low □ Neither low nor high □ High □ Very high

**Q9. Would you prefer the air movement to be:**

□ Much more □ A bit more □ No change □ A bit less □ Much less

**Q10. What do you think of the air at the moment?**

□ Stuffy □ A bit stuffy □ Neither stuffy nor fresh □ A bit fresh □ Fresh

**Q11. How do you find the humidity conditions inside this terminal?**

□ Damp □ Neither damp nor dry □ Dry

*Figure 5-4: Section B of the questionnaire – evaluation of thermal environment.*

**Section C** (figure 5-5) poses questions about the lighting environment and the overall comfort state of interviewees. Similarly to the assessment of subjective warmth, a set of a 7-point and a 5-point scale items is employed to understand interviewees' perception and preference over the lighting environment (questions 12 and 13). Another pair of perception-preference questions (questions 14 and 15) focuses particularly on the daylight respect and was applied during the daytime in spaces with at least some source of natural light. The corresponding 5-point sensation and 3-point preference scales were used to understand the interaction between occupants and space and to evaluate the importance of natural light. Leaning towards the same direction, two dichotomous questions on glare and lighting distribution (questions 16 and 17) complete the lighting-related set of questions.

Thereafter, interviewees were asked to state which environmental factor – among air temperature, humidity, air movement, air freshness and daylight – they consider the most important in the terminal building and to assess their overall comfort state (questions 18 and 19). The latter aimed for the assessment of the interactions between different aspects of the terminal environment (ASHRAE, 2010; Nicol et al., 2012). Section C closes with the two single open-ended items of the questionnaire, where participants are asked about the terminal aspects they (dis)like the most (questions 20 and 21). These questions were worded generically to allow issues of any nature to be raised and to ascertain the impact of the environmental and non-environmental conditions on people's overall comfort levels in the airport terminals.

**SECTION C**

**Q12. How would you describe the overall lighting environment at the moment?**

□ Very bright  □ Bright  □ Slightly bright  □ Neither bright nor dim  □ Slightly dim  □ Dim  □ Very dim

**Q13. Would you prefer it to be:**

□ Much dimmer  □ A bit dimmer  □ No change  □ A bit brighter  □ Much brighter

**Q14. What do you think about the daylight at the moment?**

□ Very little  □ Little  □ Sufficient  □ Much  □ Very much

**Q15. Would you prefer the daylight to be:**

□ Less  □ No change  □ More

**Q16. Have you experienced discomfort due to glare during your stay in this terminal?**

□ Yes  □ No

**Q17. Overall, do you find the light well distributed?**

□ Yes  □ No

**Q18. How would you rate your overall comfort in this terminal at the moment?**

□ Very comfortable  □ Comfortable  □ Slightly comfortable
□ Slightly uncomfortable  □ Very uncomfortable

**Q19. Which one do you consider the most important factor in this building?**

□ Air temperature  □ Humidity  □ Air movement  □ Air freshness  □ Daylight

**Q20. What do you like the most in this space?**

............................................................................................................................

**Q21. What you do not like the most in this space?**

............................................................................................................................

*Figure 5-5: Section C of the questionnaire – evaluation of lighting environment, overall comfort and general issues.*

Due to their repeated exposure in the indoor environmental conditions in the terminal buildings, employees are the most valuable source of information as far as the longstanding issues are regarded. Therefore, an additional section in the questionnaire, **section D** (figure 5-6), was designed exclusively for terminal staff to seek for such issues as well as for further data that can affect staff's adaptive opportunities and comfort levels. Some of the questions deal with sensitive topics and therefore the whole section lies towards the end of the questionnaire. In particular, staff members are further classified according to their employment status and the period of time they have been working in the terminal building (questions 22 and 23). Both variables are used to reflect staff's degree of experience with the indoor conditions.

Subsequently, the survey seeks information on existing environmental and non-environmental issues in the terminal building through the partially closed-ended question 24. As there is a wide range of employees in terminal buildings working under dissimilar conditions, terminal staff was asked for possible controls over the indoor environmental conditions and whether these controls find them satisfied (questions 25 and 26). Furthermore, employees were asked to rate the clothing policy of their employer in maintaining their thermal comfort and the effect the environmental conditions have on their productivity (questions 27 and 28).

**SECTION D (only for airport employees)**
**Q22. Are you working full or part-time?**
□ Full-time □ Part-time

**Q23. How long have you been working at this terminal?** .......years .......months

**Q24. Have you noticed any environmental condition problems in this terminal?**
□ Thermally related.............................□ Visually related..............................
□ Other.................................................□ Nothing

**Q25. Do you have any control over your thermal and visual environment?**
□ No □ Yes (What kind of control?.............................................................................)

**Q26. How would you describe this control?**
□ Satisfactory □ Neither satisfactory nor unsatisfactory □ Unsatisfactory

**Q27. How would you rate the clothing policy in maintaining your thermal comfort?**
□ Flexible □ Neither flexible nor inflexible □ Inflexible

**Q28. How would you describe the effect of the environmental conditions on your productivity?**
□ Negative (why?.................................) □ Neither negative nor positive □ Positive

*Figure 5-6: Section D of the questionnaire – further information on the indoor environment from the staff perspective.*

**Section E** (figure 5-7) focuses on demographics and questions of sensitive nature including age (using age groups), place of residence and origin, educational level and professional status (questions 29-33). Data on age groups, educational level and professional status were planned to be used as parameters to search for differences on other variables, e.g. thermal requirements or overall comfort, while the place of residence and origin reflects the thermal history of the interviewee. At the end of the questionnaire, detailed notes on the interviewees' garments were kept in order to estimate clothing insulation, based on the clothing insulation levels for separate garment pieces (appendix C) provided in ISO 7730 (ISO 7730, 2005).

SECTION E
**Q29. What is your age group?** □ <18 □18-24 □25-34 □35-44 □45-54 □55-64 □>65

**Q30. Do you live in the Greater London area?**
□ Yes □ No (Where do you live?..........................................................)

**Q31. Have you always lived in this area?**
□ Yes □ No (Where are you from?..........................................................)

**Q32. What is your educational level?** □ Primary □ Secondary □ College □ University

**Q33. Are you a:** □ In employment □ Pensioner □ Housekeeper □ Student □ Other......

CLOTHING
Trousers / Skirt / Dress: □ short(s) □ long / □ light □ normal □ thick
Shirts/blouses: □ T-shirt □ Short sleeves □ Long sleeves – light, Long sleeves – thick
Sweater / Jacket / Coat : □ short □ long / □ thin □ normal □ thick
Footwear: □ Closed □ Open □ Boots

End Time:................

*Figure 5-7: Section E and closure of the questionnaire.*

## 5.4 Pilot studies

Subsequent to the completion of the design process, pilot studies were conducted in actual airport terminal environments (table 5-1). Through these early surveys the study aimed to identify potential inadequacies in the proposed research methodology, optimize the research procedure and provide insights on the possible outcomes of the research. In particular, the questionnaire was tested to ensure that words and terms are clear, response categories are adequate, format and layout are friendly, the language is culturally appropriate, the flow of questions is logical and that the projected completion time is achievable.

The first pilot study was conducted in March 2012, in Manston international airport, Kent. The very low aircraft and passenger traffic may have precluded it from being among the case studies but anointed it as the suitable site for the collection of preliminary data. During the two-day pilot, the microclimatic monitoring equipment and questionnaire were tested in the check-in hall and departures area of the terminal where 52 passengers, staff and well-wishers were interviewed. The data analysis validated the research methodology, however, the survey itself revealed two drawbacks. Part of the sample population misinterpreted the question “How do you find the air quality at the moment?” with alternatives provided on a 5-point scale from “very poor” to “very good”. Therefore, this question was removed. In addition, responses in the question “What do you think of the air at the moment?” with a 3-point response scale (“stuffy”, “neither stuffy nor fresh” and “fresh”) demonstrated the need to enrich the scale with the addition of “a bit stuffy” and “a bit fresh” alternatives, resulting in a 5-point scale.

*Table 5-1: Airport terminal buildings where pilot studies were conducted.*

| Terminal | Spaces | Date |
|---|---|---|
| Manston | Check-in, dep. lounge | 9 – 10 March '12 |
| Manchester T1 | Circulation, seating area, dep. lounge 1 | 16 April '12 |
| Manchester T2 | Seating area, dep. lounge | 17 April '12 |
| Manchester T1 | Check-in 1, check-in 2, seating area, dep. lounge 1, arrivals hall | 27 – 29 June '12 |

Additional feasibility studies were conducted in MAN T1 and MAN T2. The significance of these surveys lies on the opportunity provided to carry out pilots in several areas of the prospective case studies and during traffic peaks when time matters. The single-day surveys in MAN T1 and MAN T2, in April 2012, resulted in the shortening of two crossarms and the rearrangement of the sensors to allow passing through shortcut security doors. Together with the

3-day survey in MAN T1, in June 2012, the pilots in Manchester airport involved 213 questionnaires, improved significantly the interviewing techniques and confirmed the effectiveness of the data collection methodology.

### 5.5 Data collection: environmental & human monitoring

The actual field studies involved extensive monitoring of the indoor environmental conditions across the different terminal areas and simultaneous questionnaire-guided interviews with terminal users. Each terminal was surveyed in summer and winter to allow for the seasonal variations and for a week-long period of time to include quiet and busy days. The terminals were monitored continuously during the airfield opening hours to get the daily peak and off-peak traffic profiles. Accordingly, surveys were conducted from 5:00 am to 9:00 pm every day in MAN T1 and MAN T2, similarly to the weekdays in LCY, where monitoring was limited between 6:30 am - 12:30 pm on Saturdays and 12:30 pm - 9:50 pm on Sundays due to its restricted airfield operation in weekends.

The spaces surveyed in each terminal (table 5-2) involve landside and airside facilities and include check-in halls, security search areas, circulation spaces, seating areas, departures lounges, retail facilities, gate lounges, baggage reclaim areas and arrivals halls. The monitoring equipment was moved from space to space several times a day so that terminal areas are monitored repeatedly during the week-long surveys at different times of the day. In smaller spaces (e.g. gate lounges) the equipment was placed at a central point. For the majority of terminal spaces, however, a multi-point monitoring was required to ensure representative readings. This was necessary where the selection of a single representative point was not possible due to space arrangements and safety considerations, in very large spaces (e.g. check-in hall in MAN T2), as well as in spaces with non-uniform characteristics (e.g. different conditions expected close to a glazed curtain wall than further inside the space).

Prior to measurements, a tune-up period of about 3 minutes was applied for the sensors when moving within a space. Due to the longer period of time required for the black globe to equilibrate, this was extended to about 10-20 minutes when the transition involved spaces with significantly different intake of sunlight (e.g. from the dim and artificially lit departures lounge 2 to the bright and abundantly sunlit departures lounge 1 and vice versa, in MAN T1).

The questionnaire-based interviews were taking place in close proximity to the monitoring equipment. The selection of interviewees was random in order to get a representative sample population of passengers, staff, meeters and greeters. Introductory to the interviews, participants were briefly informed for the questionnaire's source and purpose and were assured for the confidentiality of their responses, with the latter being extremely important for terminal staff.

The average time for the questionnaire completion was approximately 5 minutes for passengers and a minute longer for employees.

*Table 5-2: Seasonal on-site surveys in a wide range of terminal spaces at LCY, MAN T1 and MAN T2.*

| Terminal | Spaces | Date |
|---|---|---|
| London City | Check-in, search area, dep. lounge 2, retail, dep. lounge 1, gates, int. baggage reclaim | 28 May – 3 June '12 |
| | | 29 Jan – 4 Feb '13 |
| Manchester T1 | Check-in 1, check-in 2, search area, circulation, seating area, dep. lounge 2, retail, dep. lounge 1, Pier C (beg), Pier C (gates), Pier B (gates), arrivals hall | 22 – 28 Aug '12 |
| | | 3 – 10 Dec '12 |
| Manchester T2 | Check-in, search area, seating area, retail, dep. lounge, gates, arrivals hall | 29 Aug – 6 Sep '12 |
| | | 11– 18 Dec '12 |

## 5.6 Limitations in data collection

Safety and security are nowadays major considerations for airports across the globe. Inevitably, the project planning and execution was influenced in various respects by the necessary security measures in the three case studies, with the greatest limitations being associated to data collection aspects.

An initial effect was the delayed commencement of the field surveys as a result of the prolonged procedures required for the acquisition of the security pass. The pass was an essential means of obtaining access to the terminals' airside facilities and permission for using the monitoring equipment and questionnaire across the terminal spaces. The course of action included extensive paperwork, visits and negotiations with the airports' authorities as well as the completion of the General Security Awareness Training (GSAT) in the two airports. The process was brought to an end after a period of only two weeks for London City and nine months for Manchester airport, while in the meantime the questionnaire and equipment were being set up.

The lack of pass had an impact on the pilot studies conducted in MAN T1 and MAN T2, where surveys would have been conducted ideally to all pursued terminal spaces. This would have allowed for a greater degree of familiarity with the terminal spaces and practices before the conduction of the actual surveys. The absence of such authorization at the time resulted in the – under surveillance – piloting of only few landside and airside areas for a limited period of time, yet, without influencing the methodology evaluation.

Safety and security-related were also limitations of the actual field studies in all three case studies. Passenger safety was among the basic considerations in the selection of monitoring point(s) within a space, while in the case of LCY overcrowding often hampered the relocation of the monitoring equipment. A limitation that was ultimately overcome was the equipment's transition from landside to airside. Normally, this required disassembling of the crossarms and sensors which was easy but time-consuming, given that such transitions were taking place many times a day. This hindrance was eliminated through the day-to-day contact with security staff, resulting in the use of the swab device as the sole means of security check in some cases and/or in the use of the search areas dedicated to terminal employees in other.

On the contrary, this was not the case with the insuperable limitation, which resulted in the exclusion of the baggage reclaim areas in MAN T1 and MAN T2 from the monitored spaces. Specifically, a short passage link between the baggage reclaim rooms and the nearby airside areas required the use of an "airfield" pass for the doors' opening, thus forbidding the access to baggage reclaim. In addition, a post-survey limitation was the difficult and eventually confidential acquisition of the terminal buildings' drawings. Therefore, the drawings are presented with removed or modified features.

Limitations also applied in the gathering of supplementary data from the airports that – although were beyond the scope of the study – would allow the assessment of the thermal environment from a mechanical perspective. These include energy consumption data, the type of HVAC systems and the locations of air supply diffusers in all the terminal spaces monitored, as well as the temperature of the supplied air and the air supply rates. The incorporation of such information in the data analysis would provide a better understanding of the parameters determining the thermal conditions while allowing the investigation of the impact a respective energy strategy has on occupant's comfort.

Most of these data, however, were either unavailable or incomplete due to different circumstances and particularities in each terminal. For instance, while datasets of monthly electrical energy use were obtained for MAN T1 and MAN T2, thermal energy consumption (gas) data were completely unavailable. This was because MAN T1 gas consumption was on the same network ("Prime 1") as MAN T3 and the boiler meter at MAN T1 was not logged. Thus, stripping out the individual terminals consumption was not possible. Similarly, it was unfeasible to segregate the consumption of MAN T2 and MAN T3 as the boiler meter for the latter was bypassed and the boiler meter for the former was also not logged. Moreover, MAN T2 gas consumption was on a different network ("Prime 2") which was feeding the airport's Cargo centre as well. Further investigation revealed the reasons behind this complexity; the meters had not been logged due to financial constraints and due to the airport's appraisal that such an action would have no financial benefit (payback).

The information obtained with respect to the type of HVAC systems in the surveyed spaces was presented in chapter 4. However, a comparative analysis between different systems/spaces was impractical because many of the spaces were served by two or more different systems. This is also among the reasons why the terminal areas in this study were defined according to their function, the physical boarders between them and the different design characteristics. As far as the consideration of the locations where air is supplied from, this was limited by the large number and complexity of the spaces monitored. This was also the case with the data regarding the air supply rate and therefore this was assumed to be 10 L s-1 per person, as recommended by CIBSE for this type of buildings (CIBSE, 2006). Due to the incomplete nature of the technical data discussed above, these were disregarded as to ensure uniformity in the data analysis between the three terminal buildings.

### 5.7 Conclusions

The chapter discussed the development of the survey tools used for the data collection during the on-site surveys in the three case study terminal buildings. A portable microclimatic monitoring equipment was designed to monitor the immediate environmental conditions people experience across the different terminal spaces. The environmental quantities measured include dry bulb and black globe temperature, RH, air movement, as well as carbon dioxide and horizontal illuminance levels.

A standardised questionnaire was developed to collect subjective data for the evaluation of comfort conditions through interviews with randomly selected passengers, staff and other terminal users. The questionnaire uses a combination of open-ended, partially closed-ended and closed-ended questions written in an approachable manner for respondents of different backgrounds. Items include 3-point, 5-point and 7-point subjective scales for the assessment of perception and preference over the indoor conditions, while additional data gathered include the activity levels during and 15 minutes prior to the questionnaire, dwell time, clothing insulation and demographic data.

Following their development, monitoring equipment and questionnaire were piloted in actual airport terminal environments resulting in modifications for the surveys' optimization. The chapter also discussed the framework of the subsequent field surveys and the research limitations applied due to the nature of the case studies. Lastly, the chapter addressed the framework of the statistical analysis which led to the research outcomes presented in the next chapter.

# CHAPTER 6: DATA ANALYSIS

## 6.1 Introduction

This chapter presents the results derived from the analysis of the data collected in the three terminal buildings. Following a synopsis of the statistical analysis plan and the description of the sample population, section 6.4 addresses the parameter “clothing” and provides an overview of the environmental conditions along with an outline of satisfaction levels.

Section 6.5 evaluates the comfort conditions for the entire terminal population. The assessment of sensation and preference over the thermal environment succeeds the calculation of neutral and preferred temperatures to specify the thermal requirements. Afterwards, the section assesses the lighting environment and closes with an appraisal of the environmental aspects influencing overall comfort and the relative importance of the environmental and non-environmental parameters.

Subsequently, section 6.6 differentiates between the user groups and investigates the comfort conditions from the standpoint of passengers and staff. It reveals different comfort requirements, quantifies the thermal conflict and stresses the different perception and preference over lighting. Towards the end, it examines the significance of the indoor environment for the two groups.

Section 6.7 provides a spatial analysis for the different terminal buildings. It looks thoroughly at the thermal conditions across the terminal spaces and highlights the formative factors of the thermal environment. Moreover, it examines the thermal requirements in the different spaces and locates the thermal conflict between passengers and staff. Section 6.8 summarises the findings which are discussed in chapter 7.

## 6.2 Statistical analysis

The study used the Statistical Package for Social Sciences (SPSS 19) as the means for the statistical analysis of the data collected. A standardised statistical analysis plan, aligned with the project’s objectives, was developed to ensure uniformity in data analysis. The plan involved:

- management of raw data and investigation of data quality
- descriptive statistics and correlation analysis between environmental and subjective data
- a series of statistical tools (e.g. t-tests, ANOVA, ANCOVA, post-hoc comparisons)
- checks regarding the violation of the assumptions underlying the various techniques
- development of mathematical models for the prediction of thermal comfort

Data analysis was terminal and season specific, with the data sets being analysed for the terminal population as a whole and separately for passengers and staff. In spaces where more than a monitoring location was employed, an average value was taken for each environmental quantity measured. Preliminary analysis focused on data quality control to ensure that data meets the requirements and do not violate the assumptions of the statistical tests to follow. Where assumptions were violated, alternative non-parametric techniques were applied and/or supplementary tests were conducted to validate the results. For instance, in cases where data did not meet the basic assumption of homogeneity of variance underlying ANOVA, the significance of the results was determined by the Welch and Brown-Forsythe tests and subsequently from Tamhane's post hoc tests. In the very few cases where these tests were ineffective, the non-parametric alterative of Kruskal-Wallis test was adopted.

Additionally, the environmental variables were statistically treated to allow joint analysis with the subjective data. This included the calculation of mean radiant and operative temperature and the correspondence of each questionnaire to an average value of each environmental quantity. The data logger was programmed to measure globe temperature ($T_g$) which was used for the calculation of the mean radiant temperature for a standard globe by forced convection (ISO 7726, 1998):

$$\bar{T}_r = \left[(T_g + 273)^4 + 2.5 \times 10^8 \times {V_{air}}^{0.6}(T_g - T_a)\right]^{1/4} - 273 \qquad (1)$$

The mean radiant temperature was in turn used for the calculation of the operative temperature (CIBSE, 2006):

$$T_{op} = [T_a \times (10 \times V_{air})^{0.5} + \bar{T}_r] \,/\, [1 + (10 \times V_{air})^{0.5}] \qquad (2)$$

Correlation analysis was performed to identify shared variance between variables. Assuming linear relationships, Pearson (2-tailed) correlation was used between interval level (continuous) variables, as well as between a continuous and a dichotomous variable. Spearman correlation analysis was conducted to investigate the strength and direction of the relationship between the variables that do not meet the criteria for Pearson correlation. In both cases, a significance level of at least $p<0.01$ was considered for the statistical significance of the results.

In the development of mathematical models the study used the binning method; the purpose being to minimise the impact of outlying data points that are based on relatively small number of observations. For the evaluation of neutral temperatures, for instance, the operative temperature was binned into half-degree increments and the mean thermal sensation vote was calculated for each bin. Working with the bin-mean values instead of the individual responses, the linear regression models fitted between the mean scores of thermal sensation and the operative temperature were weighted according to the sample size within each half-degree bin; i.e. according to the number of thermal sensation votes falling in each temperature bin, thus ensuring that any outliers representing small sample sizes have relatively little effect on the slope of the model.

Grouping on the axis of the independent variable generally improves the correlation ($R^2$). However, if binning is coarse the variation in the data is hidden while the correlation coefficient and the regression coefficient (gradient) may be altered considerably producing misleading results. Therefore, the decision on the bins used was taken upon the preliminary investigation of the effect of different numbers and widths of bins. For example, binning the operative temperature into 1.0 °C and 2.0 °C increments was found to be too coarse for the ranges of operative temperature monitored and thus grouping of 0.5 °C was applied. In general, the binning method can give a good visual portrayal of trends in the data, while the inspection of the bin-means is useful in finding out whether a linear fit is satisfactory, or whether a more complex model is required. For this reason, it was also used in the investigation of the relationship between RH (%) and sensation as well as between illuminance and the respective sensation and preference votes.

Two statistical techniques were applied for the calculation of preferred temperatures; probit analysis and linear regression. Probit models require binary responses whereas the questionnaire item has five alternatives. For this reason, thermal preference was initially transformed into a 3-point variable by merging the responses for a “much cooler” and “a bit cooler” environment to “prefer cooler”, similarly to the “much warmer” and “a bit warmer” responses represented by “prefer warmer”. The “no change” responses were then split evenly and randomly into the “prefer warmer” and “prefer cooler” categories. Data was classified into half-degree (ºC) increments and the number of preference votes was proportionally weighted with the sub total number of responses in each operative temperature bin. Probit analysis was performed separately for the percentages of “prefer warmer” and “prefer cooler” responses with the SPSS probit procedure. Preferred temperature was then obtained by the simple calculation equating the two probit models. This technique confirmed the results obtained from the linear regression analysis in some cases but failed in others due to the narrow temperature range. Consequently, in order to ensure uniformity, linear regression analysis was adopted as the method for the estimation of preferred temperature in all case studies. Moreover, PMV was calculated as per ISO 7730 and was used to assess its accuracy in predicting the thermal sensation and thermal neutrality in the mechanically ventilated terminal buildings.

## 6.3 Description of sample population

A total of 3,087 people were interviewed in the surveyed terminals. The sample population presents a 50:50 male-female ratio (table 6-1) and consists of people aged from less than 18 years to over 65 years. Interviewees were classified into three prime groups consistent with the distinct nature of occupancy they represent: a) employees, b) passengers, and c) meeters, greeters and other (table 6-2). The relevant magnitude of the groups is representative of the occupancy profile in a typical airport terminal, where population is dominated by passengers and complemented by terminal staff and well-wishers.

*Table 6-1: Number of male and female interviewees in the surveyed terminals.*

| | LCY | | MAN T1 | | MAN T2 | | Total |
|---|---|---|---|---|---|---|---|
| | Summer | Winter | Summer | Winter | Summer | Winter | |
| Females | 203 | 197 | 331 | 236 | 276 | 300 | 1543 |
| Males | 200 | 218 | 332 | 299 | 262 | 233 | 1544 |

*Table 6-2: Number and type of interviewees in the surveyed terminals.*

| | LCY | | MAN T1 | | MAN T2 | | Total |
|---|---|---|---|---|---|---|---|
| | Summer | Winter | Summer | Winter | Summer | Winter | |
| Employees | 68 | 72 | 103 | 71 | 65 | 86 | 465 |
| Passengers | 320 | 332 | 462 | 425 | 406 | 388 | 2333 |
| M/G/O* | 15 | 11 | 98 | 39 | 67 | 59 | 289 |
| Total | 818 | | 1198 | | 1071 | | 3087 |

*Meeters, greeters and other.

With a total passenger sample population of 2333 people, passengers account for 80% of the sample population in LCY and for 74% of the population in MAN T1 and MAN T2. Based on median values, the average passenger in the three terminals was 35-44 years old, educated at college (for MAN T1 and MAN T2) or university (for LCY) level and in employment. The majority of passengers were UK residents, living in areas other than Greater London (for LCY) and Greater Manchester, Lancashire (for MAN).

The passenger population consists of arriving and predominantly departing passengers, with the former interviewed exclusively in the baggage reclaim areas[3] and arrivals halls and the latter across all other terminal spaces. The profile of departing passengers handled in the three terminals differed considerably in terms of journey purpose. Over half the passengers flying from LCY (52%) were travelling on business, whereas this percentage was significantly smaller

[3] As highlighted in chapter 4, baggage reclaim areas were surveyed only at LCY due to access issues at MAN T1 and MAN T2.

for MAN T1 (14%) and particularly low for MAN T2 (3%) which serves predominantly leisure passengers (table 6-3).

*Table 6-3: Passenger characteristics of residency and journey type.*

| | % of total passenger population | | | | % of departing passengers | |
|---|---|---|---|---|---|---|
| Terminal | UK resident | Local resident* | Arrived | Departing | Flying for business | Flying for leisure |
| LCY | 60% | 44% | 9% | 91% | 52% | 48% |
| MAN T1 | 70% | 40% | 5% | 95% | 14% | 86% |
| MAN T2 | 90% | 46% | 3% | 97% | 3% | 97% |

*Living in the Greater London area for LCY and in the Greater Manchester area, Lancashire, for MAN.

Data concerning the time people had spent indoors (by the time of the questionnaire) reveal that dwell time varied between passengers departing from the three terminals. Its importance lies in the allowable time for people to adapt to the thermal conditions in the terminal building. An overview of these data suggests that 82% of passengers flying from LCY spent up to an hour in the terminal, with the corresponding percentage being lower for MAN T1 (63%) and MAN T2 (52%).

Although useful in providing an overall picture, these figures include data collected in the landside of the terminals. The significantly shorter dwell time in LCY is the combined result of the terminal's small size - that provides short walking distances and quick transition from check-in to boarding - and the fast passenger processing policy. The role of these two parameters is further highlighted when considering the time passengers spent airside, i.e. beyond the check-in and security points. Accordingly, almost 80% of passengers in LCY stayed maximum an hour airside, with a considerable fraction - about 40% - spending up to 30 minutes. The latter was true for only 19% and 14% of passengers flying from MAN T1 and MAN T2, where dwell time for the majority exceeded an hour (figure 6-1).

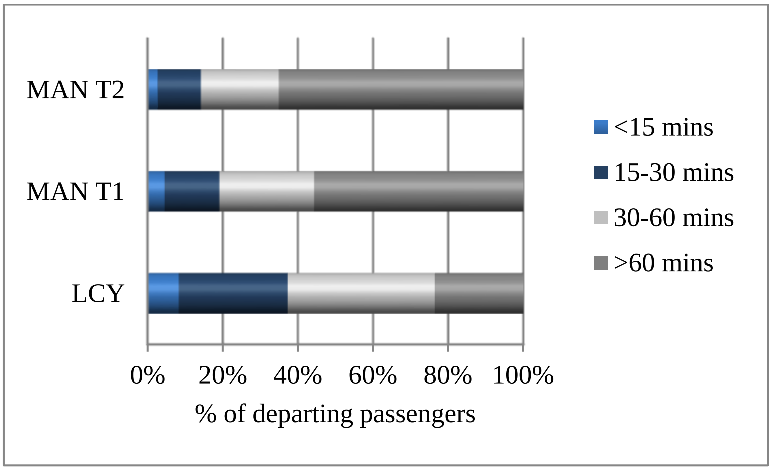



*Figure 6-1: Airside dwell time for departing passengers.*

In total, 465 members of staff were interviewed in their workspace. Employees constitute the second largest group representing 17%, 15% and 14% of the population in LCY, MAN T1 and MAN T2 respectively. The average employee in LCY and MAN T1 was 25-34 years old and 35-44 years old in MAN T2, college graduate and had been working 4 years in LCY, 5 years in MAN T1 and 7 years in MAN T2. Reflecting staff's dwell time, nearly 80% of interviewed employees were working full-time and 20% on a part-time basis. Employees were classified into airport, airline, security, police and retail staff according to the space they occupy and the nature of work (table 6-4).

*Table 6-4: Classification of employees interviewed in the surveyed terminals.*

| | LCY | | MAN T1 | | MAN T2 | |
|---|---|---|---|---|---|---|
| Staff type | Frequency | % of staff | Frequency | % of staff | Frequency | % of staff |
| Security | 38 | 27% | 29 | 17% | 27 | 18% |
| Airline | 40 | 29% | 33 | 19% | 32 | 21% |
| Retail | 37 | 26% | 53 | 30% | 57 | 38% |
| Airport | 21 | 15% | 55 | 32% | 35 | 23% |
| Police | 4 | 3% | 4 | 2% | 0 | 0% |
| Work status | Full-time | Part-time | Full-time | Part-time | Full-time | Part-time |
| | 79% | 21% | 80% | 20% | 76% | 24% |

In general, there is a wide range of terminal staff engaged with different aspects of security, such as immigration control, luggage and body screening and space surveillance. In this study, the term "security" is used to picture employees working exclusively in the search areas, where tasks involve mostly standing-light and standing-medium activity levels. Employees carrying out security-related tasks in other terminal areas were incorporated into the category "airport" staff. The negligible number of police officers interviewed in two terminals was singled out – rather than forming another category – due to their significantly higher clothing insulation and the very short dwell time, as they move across the terminal spaces.

The category "airline" represents the different types of passenger handling agents employed by the various air carriers operating in the terminal. Airline staff works mainly in the check-in halls, involved predominantly in sedentary and secondarily in standing activities. For a fraction of airline employees, work responsibilities entail also short-term transitions to other spaces such as to the gate lounges for passenger boarding.

"Airport" employees comprise a wide range of personnel such as immigration officers, IT technicians and engineers, customer service agents, terminal team leaders, coordinators, arrivals agents, terminal duty officers and security agents, who are most often employed by the airport and work across the terminal areas. Employees working in any type of retail facility such restaurants and bars, duty free and currency exchange shops are described as "retail" staff.

The population of meeters, greeters and other accounts for 3%, 11% and 12% of the sample population in LCY, MAN T1 and MAN T2. It consists mainly of well-wishers interviewed in the landside areas of the terminals (check-in and arrivals halls) where activities most commonly involve seating and standing. In addition, this group includes very few cases[4] of other short-stay visitors, such as people conducting surveys on behalf of the Civil Aviation Authority (CAA) and the Office for National Statistics. The age-grouping percentage distribution for the total population at each terminal is provided in figure 6-2 along with the respective distributions separately for passengers and staff.

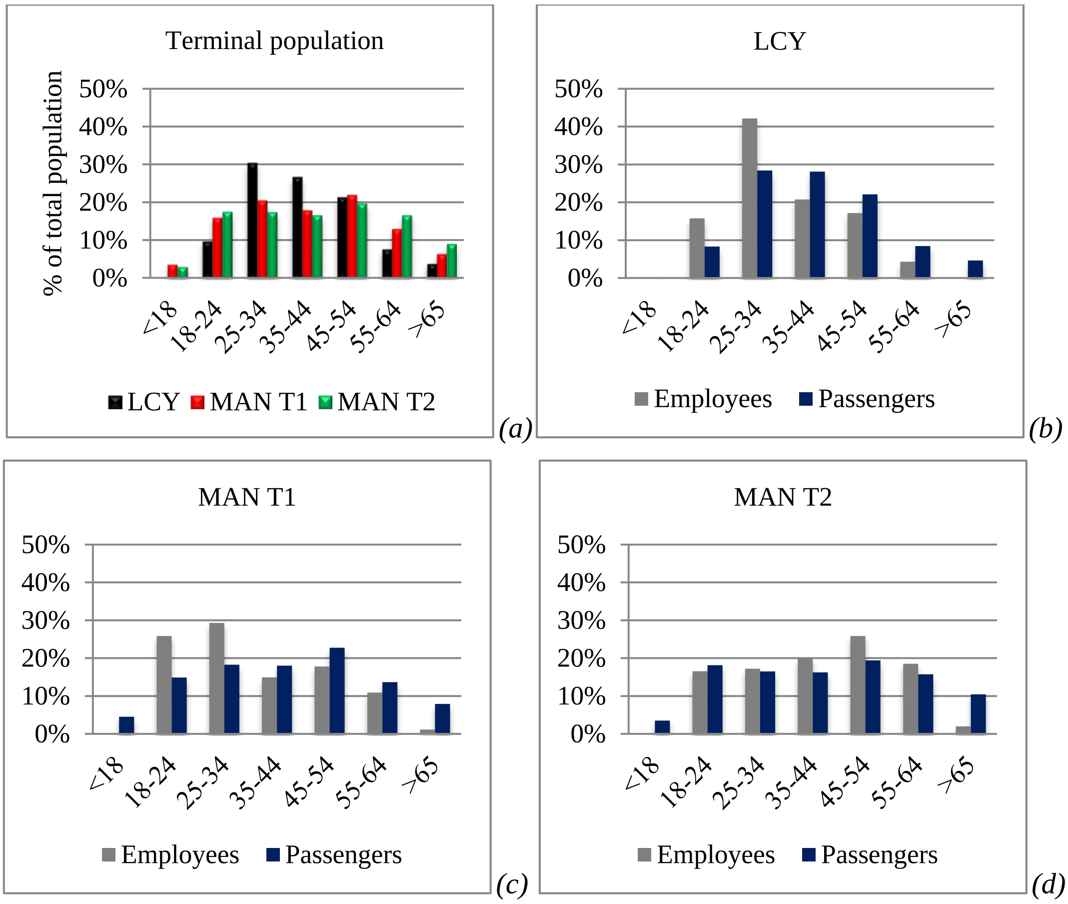



*Figure 6-2: Age group frequency distribution of (a) total terminal population, and of passengers and staff in (b) LCY, (c) MAN T1 and (d) MAN T2.*

## 6.4 Environmental conditions and satisfaction

This section presents the environmental conditions people experienced in the three terminal buildings along with the outdoor weather conditions during the surveys. It also provides an

[4] In particular there were 3 cases of other short-stay visitors in LCY, 4 in MAN T1 and 11 in MAN T2.

outline of satisfaction with the indoor conditions. A similar analysis focused on passengers and staff reveals a satisfaction gap between the two groups. The section closes with an investigation of the clothing levels worn in the terminals.

### 6.4.1 Indoor and outdoor conditions

Figure 6-3 illustrates the profile of mean hourly outdoor temperature throughout the surveys[5]. During the summer monitoring period in LCY the mean daily temperature (24h-average) ranged between 11.0 - 20.0 °C. Significantly narrower was the corresponding range in Manchester; 15.0 - 16.0 °C for MAN T1 and 10.0 - 16.0 °C for MAN T2. In winter, the mean daily temperature fluctuated between 3.9 - 12.0 °C for LCY and within the range of 0.9 - 6.6 °C and -1.6 - 6.3 °C for MAN T1 and MAN T2 respectively.

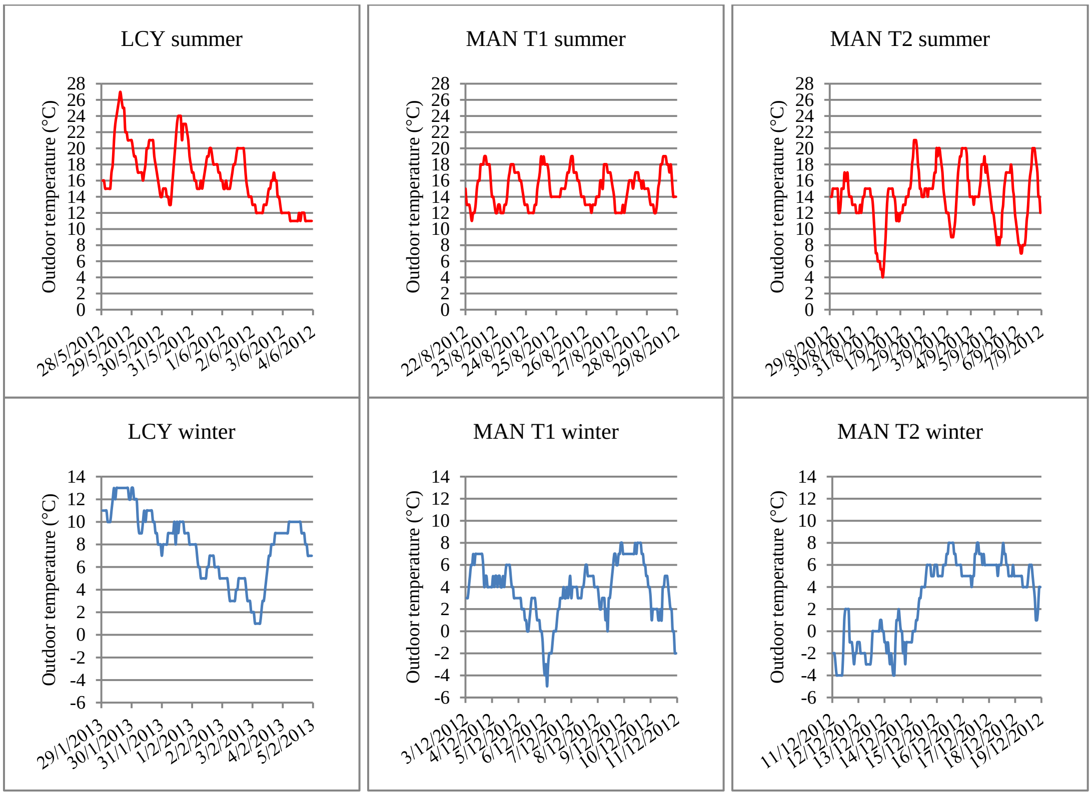



*Figure 6-3: Mean hourly outdoor temperature throughout the summer and winter surveys.*

A summary of the environmental quantities measured in the three terminal buildings is provided in table 6-5. The small-sized LCY exhibited the least variable thermal environment among the case studies. As the respective seasonal standard deviations suggest, temperature was clustered closely to the mean value in both seasons. In fact, operative temperature presented a narrow range of 4.4 °C in summer and 3.6 °C in winter, with the lowest and highest temperatures

[5] Source of outdoor temperature data: http://www.wunderground.com/

occurring during the occupancy lows and peaks respectively. The mean temperature for summer (23.3 °C) and winter (23.4 °C) imply no significant seasonal differentiation. The former matches the summer temperature set-point while the latter lies 2.4 °C higher than the winter set-point.

In the larger MAN T2, temperature ranged between 20.6 - 26.3 °C in summer and 18.9 - 24.5 °C in winter. The mean temperature in winter (21.1 °C) was equal to the flat temperature set-point adopted throughout the year whilst in summer (23.3 °C) was 2.3 °C higher. As the respective standard deviations suggest the thermal environment in MAN T2 was more rigid in winter and variable in summer, similarly to LCY.

The large scale and spatial diversity of MAN T1 are attributed to a wider thermal diversity. Operative temperature presented the highest variance among the case studies as well as the widest range in both seasons; 19.1 - 25.4 °C in summer, when the mean temperature (22.0 °C) was a degree higher than the set-point and 16.2 - 25.6 °C in winter when the mean temperature (21.3 °C) coincided with the set-point.

*Table 6-5: Mean values of indoor environmental quantities monitored in summer and winter.*

| | | Summer | | | | | Winter | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $T_{op.}$* (°C) | $V_{air}$ (m/s) | RH (%) | $CO_2$ (ppm) | Illum. (lux) | $T_{op.}$ * (°C) | $V_{air}$ (m/s) | RH (%) | $CO_2$ (ppm) | Illum. (lux) |
| LCY | Mean | 23.3 | 0.12 | 50.4 | 483 | 339 | 23.4 | 0.13 | 32.3 | 817 | 300 |
| | SD | 0.9 | 0.06 | 3.0 | 138 | 680 | 0.6 | 0.04 | 7.0 | 152 | 390 |
| | Min | 21.4 | 0.04 | 44.7 | 324 | 80 | 21.7 | 0.04 | 21.7 | 660 | 70 |
| | Max | 25.8 | 0.58 | 64.1 | 1095 | 7999 | 25.3 | 0.26 | 53.3 | 1333 | 3746 |
| MAN T1 | Mean | 22.0 | 0.15 | 57.5 | 648 | 260 | 21.3 | 0.16 | 32.5 | 770 | 485 |
| | SD | 1.5 | 0.05 | 5.8 | 172 | 223 | 2.0 | 0.16 | 5.9 | 107 | 1044 |
| | Min | 19.1 | 0.04 | 46.6 | 298 | 40 | 16.2 | 0.03 | 23.2 | 587 | 20 |
| | Max | 25.4 | 0.32 | 73.8 | 1059 | 1854 | 25.6 | 1.04 | 53.1 | 1365 | 8173 |
| MAN T2 | Mean | 23.0 | 0.18 | 51.1 | 726 | 836 | 21.1 | 0.16 | 32.6 | 752 | 480 |
| | SD | 1.3 | 0.11 | 6.8 | 209 | 957 | 0.9 | 0.09 | 6.0 | 159 | 536 |
| | Min | 20.6 | 0.04 | 37.6 | 490 | 20 | 18.9 | 0.04 | 22.0 | 284 | 40 |
| | Max | 26.3 | 0.55 | 66.6 | 1380 | 6431 | 24.5 | 0.49 | 44.5 | 1273 | 3498 |

*Temperature set-point is 23°C in summer and 21°C in winter for LCY, and 21°C throughout the year for MAN T1 & MAN T2.

Indoor and outdoor temperatures are weakly correlated for LCY and MAN T1. On the contrary, a strong relationship was revealed for MAN T2 associating nearly 50% of the temperature variance indoors to outdoor temperature (figure 6-4). Such a relationship could suggest a building management system utilizing outdoor weather data. As a matter of fact, both MAN T1 and MAN T2 are equipped with outdoor temperature sensors but there are reservations regarding their location and calibration. Consequently, outdoor temperature is not taken into consideration in the implemented HVAC control strategies; evident also from the adoption of a flat temperature set-point throughout the year. On the other hand, the two buildings differ in terms of air quality control strategy. Unlike MAN T1, the newer MAN T2 is equipped with air quality sensors installed prior to the smoking ban in 2007. The building's integrated BMS system utilises air quality data ($CO_2$ and VOC) to control the amount of fresh air injected indoors, which explains the relationship for MAN T2.

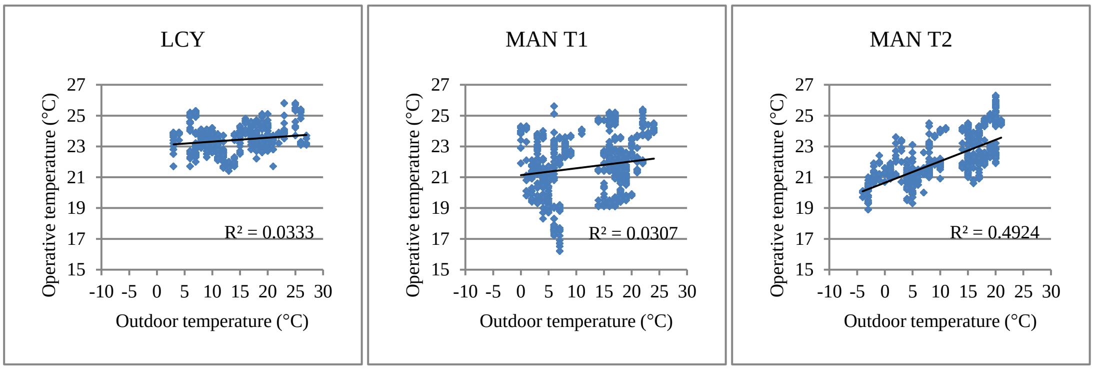



*Figure 6-4: Relationship between outdoor and indoor temperature in the three terminal buildings.*

Air movement was in general very low in all three terminals, resulting in average values within the range of 0.1 - 0.2 m/s. Air velocities beyond the upper comfort boundary of 0.3 m/s occurred sporadically in certain spaces exposed to outdoor wind through openings (e.g. the gate lounges in LCY and the arrivals hall of MAN T1). Although none of the buildings include (de)humidification in their control strategy, in all cases the mean RH (%) levels remained within the seasonal range recommended by ASHRAE (section 3.8). Along with the values of standard deviation, the range of illuminance (table 6-5) is indicative of the variety of lighting environments across the different terminal areas.

The mean $CO_2$ levels indicate sufficient ventilation rates in all buildings and lie well below the ASHRAE recommended maximum concentration range of 1000-1200 ppm. The higher concentrations recorded during occupancy peaks remained close to the maximum recommended range. In all cases, operative temperature was correlated with $CO_2$ concentration with the relationship between the two being moderate[6] for LCY (0.44, $p<0.01$) and weak for MAN T2 (0.13, $p<0.01$) and MAN T1 (0.06, $p<0.05$).

[6] Different authors provide different classifications. The study adopts that of Cohen for behavioral sciences: correlation coefficient (r) is small if $\pm0.10 \leq r \leq \pm0.29$ demonstrating a weak relationship, medium if $\pm0.30 \leq r \leq \pm0.49$ for a moderate relationship and large if $\pm0.50 \leq r \leq \pm1$ for a strong relationship COHEN, J. 1988. *Statistical Power Analysis for the Behavioral Sciences*, L. Erlbaum Associates..

As a result of the small volume of spaces and the highly variable traffic handled within the day in LCY, occupancy levels had a significant effect on its indoor thermal environment in both seasons. Statistically, this is confirmed by the large correlation coefficients for summer (0.62, $p<0.01$) and winter (0.55, $p<0.01$). Expressed as coefficient of determination[7], the seasonal coefficients show that $CO_2$ and therefore occupancy levels explained nearly 30% of the temperature variance in winter and 40% in summer.

Further to this point, LCY handled a secondary occupancy peak in the morning, a low in the afternoon with mostly landings (rather than take-offs) taking place and a main peak in the evening. The mean hourly profile of temperature and $CO_2$ concentration are similar to each other and both reflect the terminal's operational profile (figure 6-5). Operative temperature followed the morning occupancy peak and the respective low in the afternoon with approximately a 2-hour time lag, as well as the subsequent rise and main occupancy peak in the evening with a 30-minute time lag.

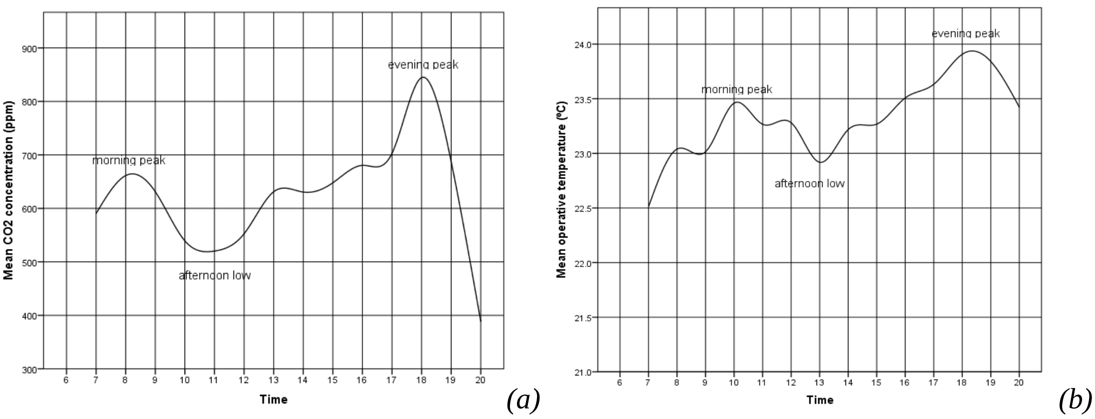



*Figure 6-5: Profile of mean hourly (a) $CO_2$ concentration and (b) operative temperature in LCY.*

On the contrary, the relationship between temperature and $CO_2$ concentration is weaker for MAN T1 and MAN T2, as the considerably larger volume of spaces does not allow for an analogous temperature increase when occupancy levels are on the rise. In seasonal terms, however, the correlation is statistically significant for summer with the respective coefficients being 0.29 for MAN T1 and 0.37 for MAN T2, $p<0.01$.

The reason underlying the insignificance of the relationship in winter is associated to the terminals' operational profile at this time of the year. Serving predominantly holiday destinations, MAN T2 experienced significantly lower passenger traffic during the winter surveys, presenting a main occupancy peak early in the morning and a secondary in the midday. MAN T1 handled high passenger volumes in both seasons (higher in summer due to the extra flights scheduled to holiday destinations). Unlike summer, however, occupancy in winter did

[7] Coefficient of determination or percentage of variance = squared r value expressed as percentage.

not fluctuate significantly on a daily basis. Consequently, in both terminals $CO_2$ concentration and therefore occupancy levels did not vary enough to achieve statistical significance in winter.

### 6.4.2 Satisfaction and overall comfort

Satisfaction with the indoor environment was evaluated by means of preference votes. More specifically, the study used the questionnaire items 7, 9 and 13 (appendix A) to assess satisfaction with “thermal comfort”, “air movement” and “lighting”. The assessments lie on the assumption that a person requiring no change is satisfied with the prevailing conditions. This approach was adopted to avoid the vagueness of (dis)satisfaction underlying the preference votes for “a bit” different environment. Votes for slight adjustments of a certain condition, such as a “bit cooler” for the thermal environment and a “bit brighter” in respect to the lighting environment, may imply satisfaction for some people and dissatisfaction for others, depending on expectations and tolerance levels. Therefore, people who responded “no change” in the preference questions were regarded as satisfied with the respective conditions. Moreover, question 10 was used to evaluate satisfaction with air freshness. Responses including “neither stuffy nor fresh”, “a bit fresh” and “fresh” were assumed to signify satisfaction. In the following figures, satisfaction with the indoor conditions is juxtaposed with overall comfort levels derived directly from the respondents’ self-assessed state of comfort.

The results (figure 6-6) show that a considerable fraction of people was dissatisfied with the thermal environment in all three terminals. More specifically, satisfied was slightly less than half the population in LCY (43%) and MAN T1 (47%) and slightly more than half the people in MAN T2 (54%). From a seasonal point of view, nearly half the population in LCY (47%), MAN T1 (47%) and MAN T2 (49%) required no change in summer, percentage which remained unaffected for MAN T1 in winter. On the other hand, satisfaction in LCY decreased to 38% in winter, conversely to MAN T2 where the respective percentage increased to 58%.

Satisfaction with air movement was similar, expressing the minority of 44% of people in LCY and a very narrow majority in MAN T1 (52%) and MAN T2 (53%). In all cases, the seasonal profile was essentially unchanged between summer and winter, as the slight decrease in LCY and increase in MAN T1 and MAN T2 in winter is statistically negligible. More votes denoting satisfaction were received with respect to air freshness, accounting for 60%, 69% and 73% of respondents in LCY, MAN T1 and MAN T2 respectively. Higher were also the satisfaction levels with the lighting environment, representing 64%, 60% and 67% of the population in LCY, MAN T1 and MAN T2.

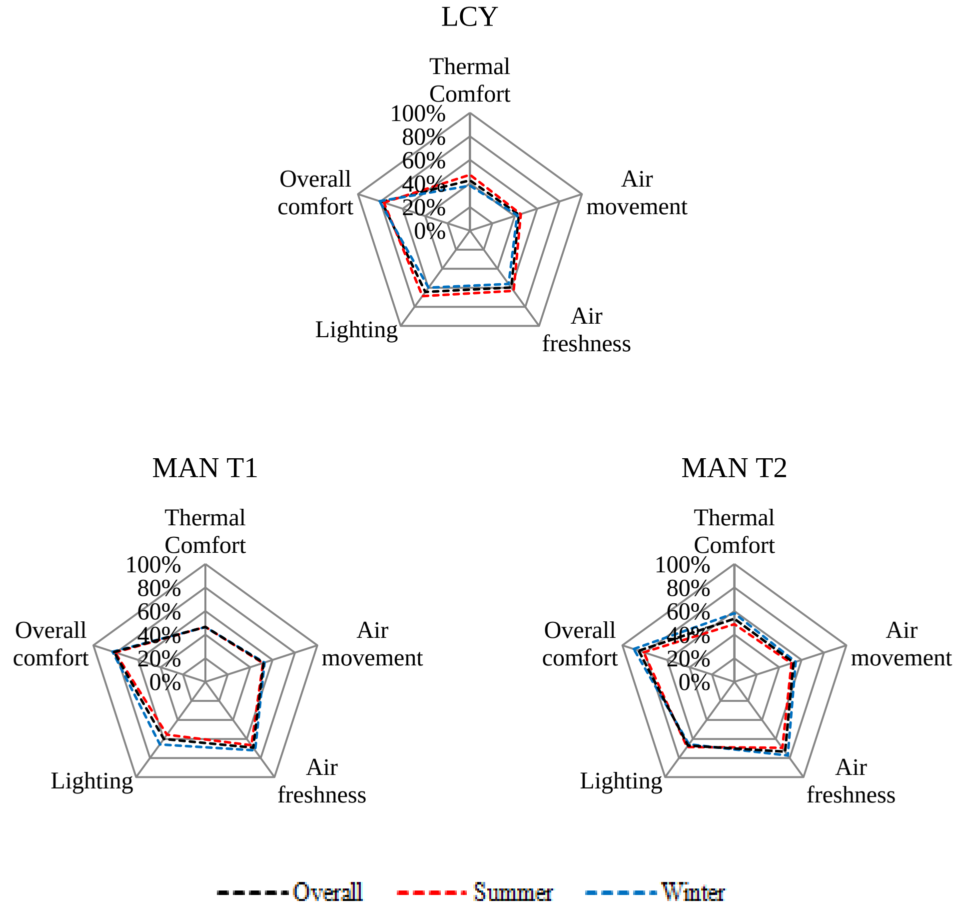


*Figure 6-6: Satisfaction levels with the indoor conditions in summer, winter and overall.*

In spite of the relatively low satisfaction levels with the indoor conditions, overall comfort levels were significantly higher; 79%, 82% and 85% of the population in LCY, MAN T1 and MAN T2 reported to be comfortable. To a great extent, this gap is attributed to the particular approach of the term satisfaction as addressed at the beginning of the section. Beyond that, however, the perceived importance of the environmental conditions in airport terminals is an unknown factor, provided that in such facilities a number of other, non-environmental parameters may well impact overall comfort (e.g. amount of space, wayfinding, time and speed of processing). This aspect is explored in section 6.5.6.

Under the same assumptions, a comparative analysis conducted for passengers and staff revealed a significant satisfaction gap between the two groups. In all three terminal buildings dissatisfaction was considerably higher among staff in summer as well as in winter (figure 6-7). More specifically, nearly 2/3 of employees preferred a thermal environment other than the one experienced in their workspace. In LCY and MAN T2 the low satisfaction levels among staff were essentially the same in summer and winter, whereas dissatisfaction for staff in MAN T1 rose in winter when only 27% of employees found the thermal conditions "just right". On the other hand, passengers presented higher satisfaction levels with approximately 50% requiring no change. An exception, however, is LCY where the percentage of satisfied passengers was limited to 38%, implying a thermal issue in the terminal during winter.

Moreover, a significant fraction of staff, in the range of 60-80%, preferred change in air movement in their workspace, whereas such requirement was expressed by 40-50% of passengers in the three terminals. Widespread among employees was the assessment of indoor air as “stuffy”, as stated from 40-60% of staff, with the same notion being reported by 20-40% of passengers. Considerable are also the different satisfaction levels regarding the lighting environment. About 30-40% of passengers would prefer either brighter or dimmer lighting levels, while such preference expressed 40-65% of terminal staff.

The prevalent satisfaction gap between passengers and staff in all terminals implies different comfort requirements between the two groups. The latter is also reflected in the considerably higher percentages of uncomfortable employees (23-49%) as opposed to passengers (8-21%).

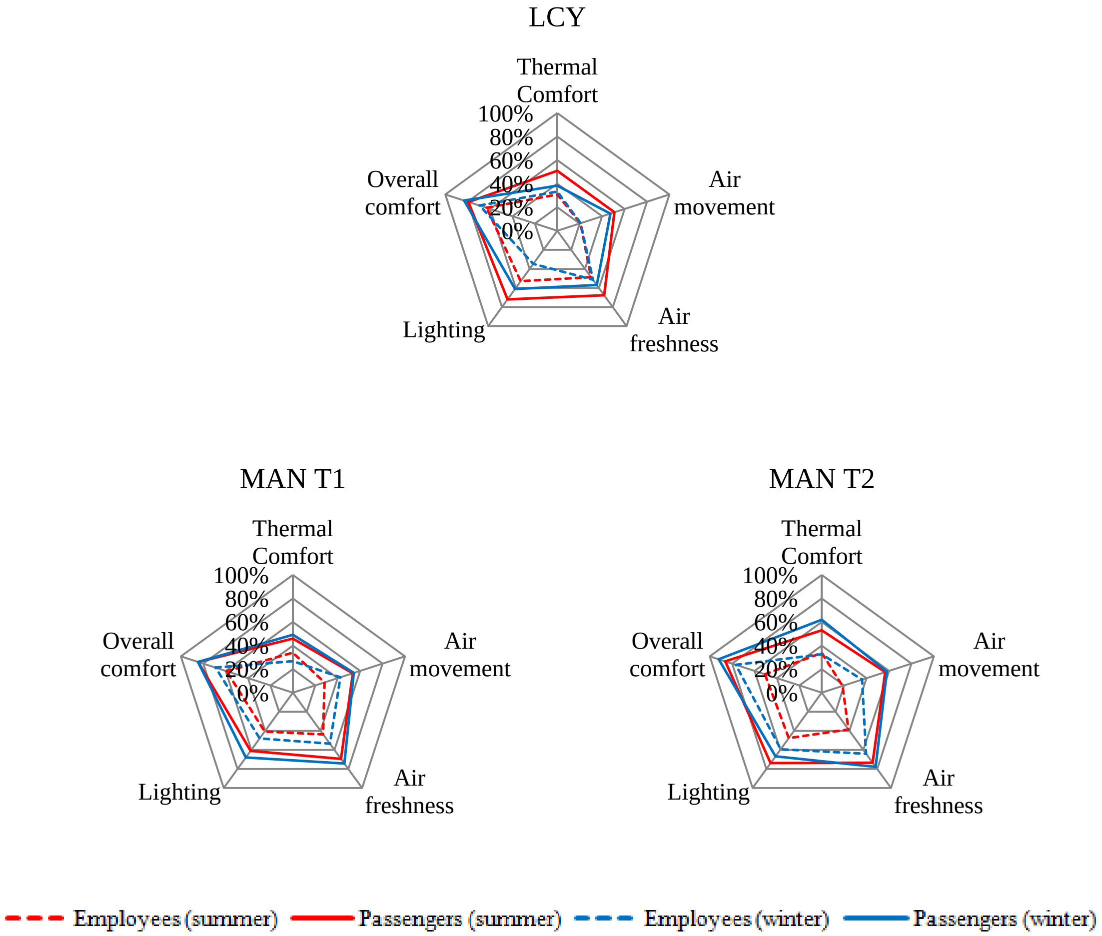



*Figure 6-7: Satisfaction levels of passengers and staff with the indoor conditions in summer and winter.*

### 6.4.3 Clothing

Being among the major differentiating factors between occupants in airport terminals, clothing is an essential component in understanding thermal comfort conditions in such facilities. The data analysis showed that outdoor – rather than indoor temperature – explains better the variance in clothing people wear in the terminals. The relationship between operative temperature in MAN T2 and clothing insulation is statistically significant and strong. The respective relationship for MAN T1 achieved statistical significance but is very weak. As a result of the very narrow indoor temperature range and the shorter dwell times, no significant relationship was established for LCY (figure 6-8a). On the other hand, external temperature explains approximately 50% of the variance in clothing levels worn in all terminal buildings. The relationship between the two is better described with an exponential rather than by a linear expression (figure 6-8b).

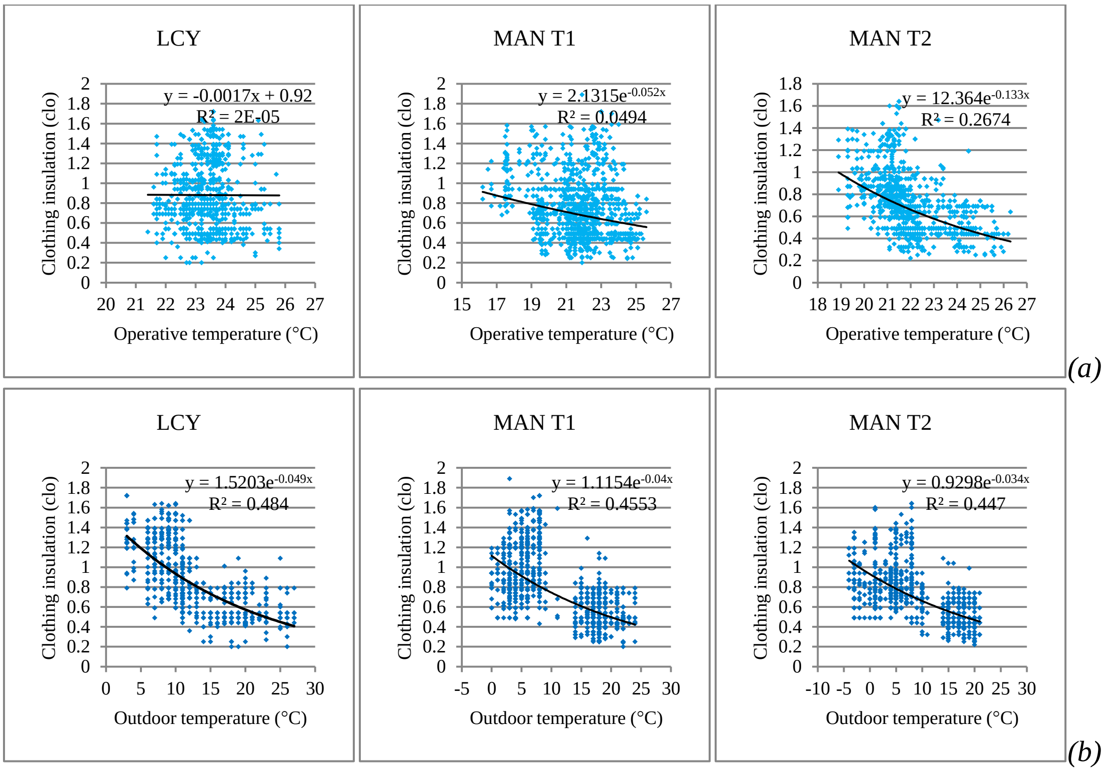



*Figure 6-8: Relationship between clothing insulation and (a) indoor operative temperature, (b) outdoor temperature.*

The mean clothing insulation for the total population was very similar at 0.57 clo in summer and increased to nearly 1.0 clo in winter. An examination of the clothing values separately for passengers, staff and MGO (table 6-6) shows that the overall higher clothing levels in winter were due to the increased clothing insulation worn by all population groups at this time of the year. This increase, however, was lower for staff and significantly higher for passengers and MGO, thus reflecting the greater impact of weather conditions on their outfits. In fact, outdoor temperature explains nearly 50% of the variance in passenger clothing and up to 65% of the clothing variation for MGO (figure 6-9). For staff, whose outfits are largely dependent on certain clothing policies, outdoor temperature explains 41%, 22% and 33% of the variance in LCY, MAN T1 and MAN T2 respectively.

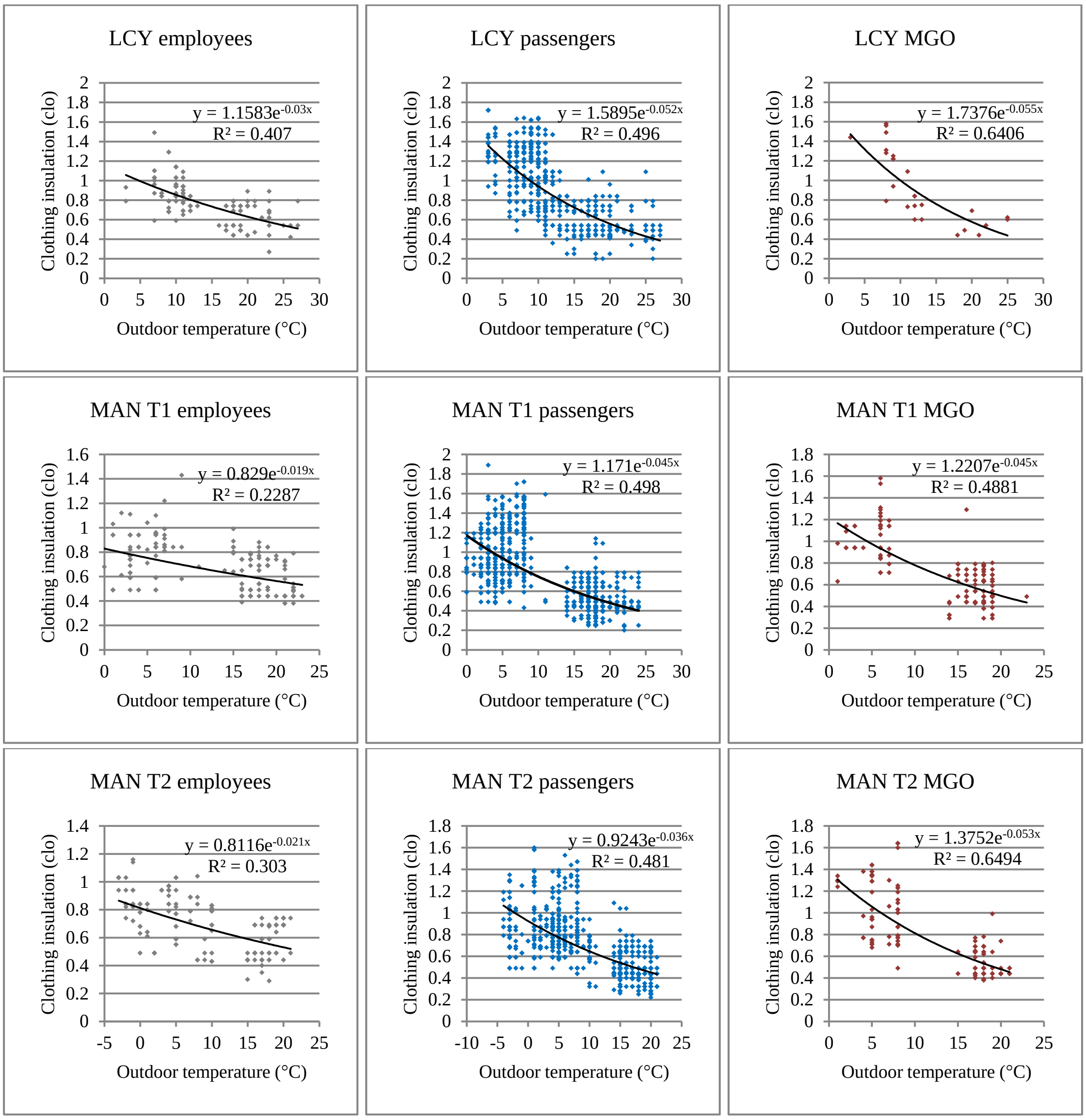



*Figure 6-9: Relationship between clothing insulation and outdoor temperature for staff, passengers and MGO.*

The mean clothing insulation for staff ranged between 0.56 clo and 0.64 clo in summer and between 0.79 clo and 0.90 clo in winter. For passengers and MGO this was 0.50-0.64 clo and 0.54-0.67 clo in summer, rising to 0.88-1.15 clo and 1.05-1.28 clo in winter respectively, and thus resulting in distinct variations between the groups. The larger effect of outdoor weather on passenger and MGO clothing in winter is also reflected in the higher standard deviations for the two groups (table 6-6). Moreover, the lower winter values for passengers handled in MAN T2 which serves mostly holiday destinations in warmer climates, suggest that destination is also among the parameters influencing passenger clothing.

*Table 6-6: Mean values and standard deviation of clothing insulation (clo) for terminal users.*

| | | | LCY | | MAN T1 | | MAN T2 | |
|---|---|---|---|---|---|---|---|---|
| | | | Summer | Winter | Summer | Winter | Summer | Winter |
| Clothing insulation | 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 |
| | | MGO | 0.67 | 1.28 | 0.57 | 1.04 | 0.54 | 1.05 |
| | 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 |
| | | MGO | 0.17 | 0.15 | 0.16 | 0.21 | 0.12 | 0.29 |

## 6.5 Comfort conditions for the terminal population

This section investigates the range of comfort conditions while accounting for the entire sample population at each terminal building. Subjective and environmental data are used to assess the thermal and lighting environment, to evaluate the comfort conditions and assess their importance in the complex terminal environment.

### 6.5.1 Subjective sensation of warmth

Figure 6-10 illustrates the frequency distribution of actual thermal sensation (TS) and PMV for each terminal. The profile of TS suggests that the general perception of the thermal environment lay more on the warm, rather on the cool side of the ASHRAE scale in all buildings. In seasonal terms, this was true for both summer and winter, with the mean TS presenting small seasonal change in MAN T1 and MAN T2 and a significant increase towards warmer sensations in LCY during winter (table 6-7).

*Table 6-7: Mean value and standard deviation of thermal sensation in summer and winter.*

| | Summer | | Winter | |
|---|---|---|---|---|
| | Mean TS | SD | Mean TS | SD |
| LCY | 0.48 | 1.06 | 0.87 | 1.08 |
| MAN T1 | 0.44 | 1.16 | 0.57 | 1.26 |
| MAN T2 | 0.56 | 1.16 | 0.46 | 1.25 |

More specifically, most people in LCY (83%) and MAN T1 (78%) experienced acceptable TS in summer, when “neither cold nor hot” received the highest response (38% in LCY and 33% in MAN T1), yet very close to “slightly warm” (33% in LCY and 29% in MAN T1). As a result of the increased clothing worn (table 6-6), the majority of sensations in both terminals (87% in

LCY and 76% in MAN T1) shifted towards warmer votes in winter. “Slightly warm” became then the most frequent TS while a considerable percentage of people (1/4 in LCY and 1/5 in MAN T1) reported to be “warm”.

On the other hand, the TS profile in MAN T2 was very similar between the two seasons despite the cooler indoor conditions and the relatively small increase of clothing insulation in winter. The majority of votes (78% in summer and 79% in winter) lay within the categories “neither cold nor hot”, “slightly warm” and “warm”. In both seasons “slightly warm” was the most frequent sensation, representing one out of three interviewees.

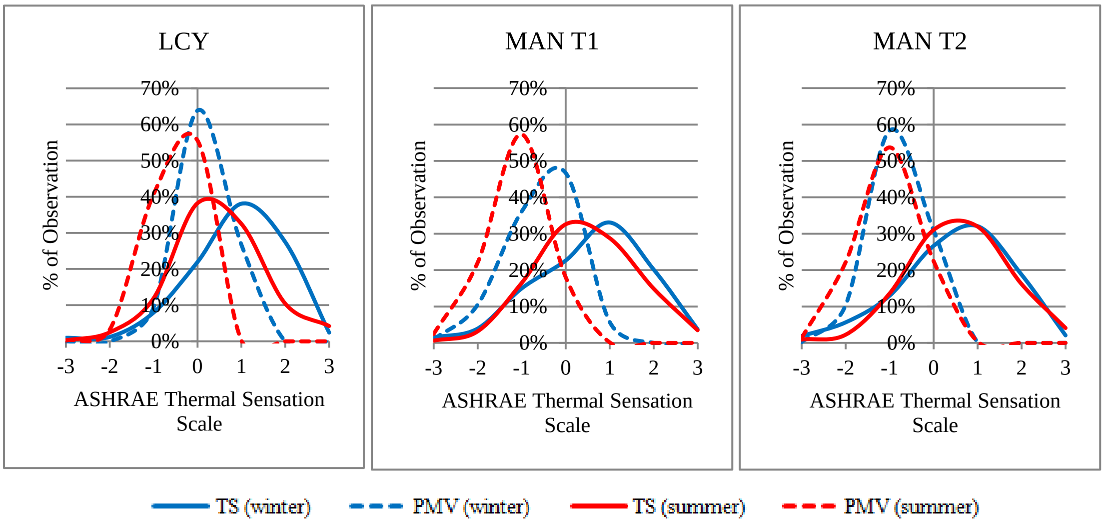



*Figure 6-10: Percentage distribution of actual and predicted thermal sensation.*

PMV follows the seasonal shift of TS in LCY and MAN T1, and agrees with the seasonal consistency in MAN T2. However, it implies a significantly narrower range of TS in all terminals and considerably cooler sensations in both summer and winter. In particular, the mean absolute TS-PMV discrepancy ranges between 1.04 and 1.67 (ASHRAE scale units) and is higher for summer (table 6-8). Moreover, a qualitative comparison between PPD and the actual percentage of unacceptable sensations reveals a reverse pattern between the two. While PPD implies a higher percentage of dissatisfied in summer, more unacceptable sensations were actually experienced during winter in all terminals. The most significant seasonal increase occurred in LCY where most unacceptable sensations were associated to “warm” votes.

*Table 6-8: Percentage of unacceptable TS, PPD and mean absolute discrepancy between PMV and TS.*

| | Summer | | | Winter | | |
|---|---|---|---|---|---|---|
| | % of unaccept. TS | PPD | TS-PMV discrepancy* | % of unaccept. TS | PPD | TS-PMV discrepancy* |
| LCY | 17% | 15% | 1.19 | 32% | 10% | 1.04 |
| MAN T1 | 22% | 34% | 1.62 | 29% | 21% | 1.39 |
| MAN T2 | 23% | 32% | 1.67 | 28% | 25% | 1.53 |

* mean absolute discrepancy measured in ASHRAE scale units.

Pearson (2-tailed) correlation analysis shows that TS correlates better with operative temperature than with any other of the environmental variables. The relationship is weaker for LCY and MAN T2 and stronger for the more variable thermal environment of MAN T1 (table 6-9). Interestingly, a positive correlation was also found with $CO_2$ levels, implying that TS had an increasing trend in overcrowded conditions (figure 6-11). The effect was stronger in LCY and MAN T2 and weaker in MAN T1.

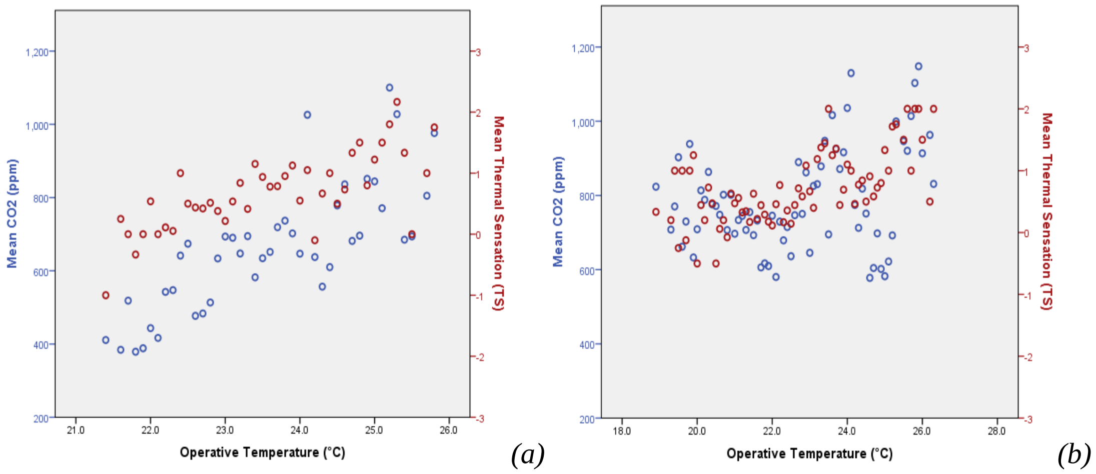



*Figure 6-11: Relationship of operative temperature, $CO_2$ levels (occupancy) and TS in (a) LCY and (b) MAN T2.*

Furthermore, correlation analysis revealed weak, yet significant relationship between TS and the respondents' activity level 15 minutes prior to the questionnaire, suggesting that having performed lighter activities people reported cooler TS (table 6-9). Conversely, this demonstrates a tendency towards warmer sensations experienced by people with higher metabolic heat generation, associated to higher activity levels such as walking or walking while carrying luggage. Clothing levels (0.21, $p<0.01$) and air movement (0.11, $p<0.01$) are also among the quantities correlated with TS in LCY, whereas the corresponding relationships for MAN T1 and MAN T2 do not achieve statistical significance.

*Table 6-9: Quantities correlated to TS in all terminals, Pearson (2-tailed) correlation coefficients.*

| | $T_{op}$ | $CO_2$ | 15′ met |
|---|---|---|---|
| LCY | 0.25 | 0.23 | 0.18 |
| MAN T1 | 0.40 | 0.06* | 0.09 |
| MAN T2 | 0.20 | 0.25 | 0.14 |

*significant at $p<0.05$ level, all other at $p<0.01$.

### 6.5.1.1 The determining factors

Correlation analysis enables the identification of the variables that share variance with TS. However, a certain variable that does not vary sufficiently to produce a statistically significant relationship with TS may still have a significant influence through its interrelationship with other variables. Therefore, multiple regression analysis was performed to identify the set of variables that best predicts TS and to investigate the relative importance of the variables involved. Accordingly, operative temperature, air movement, RH, clothing insulation and the activity levels during and 15 minutes prior to the questionnaire were all taken into account and regressed against TS.

Standard and hierarchical multiple regression were the first – among the different methods of multiple regression implemented – to be disregarded. While standard multiple regression would allow the examination of the variables' interrelationship, it does not serve the purpose of identifying the set of variables that best predicts TS as all variables are entered in the model. On the other hand, hierarchical (sequential) multiple regression presupposes a theoretical background; variables are entered in steps according to the assessment of each variable in terms to what it adds to the prediction of TS after the previous variables have been controlled for.

Therefore, the multiple regressions performed were stepwise, thus allowing the control of the variables entering the models and the order they go into the equation, through a set of statistical criteria. The analysis tested all three approaches of stepwise regression - "forward selection", "backward selection" and "stepwise" (combination of the first two) - with the latter resulting in models of higher statistical significance.

The study did not aim to include or exclude variables according to their F-value, therefore the probability (significance) of F was instead selected as the stepping method criterion. The entry and removal criteria were set to 0.05 and 0.10 respectively, meaning that a variable is selected for analysis if the significance of F is less than 0.05 and is removed if the significance level is greater than 0.10. Cases with ±3 standard deviations or beyond from the mean score were considered outliers and were removed. The assumptions of data normality and independence of variables were checked by the inspection of the histogram of standardised residuals, the normal probability plot (P-P) of standardised residuals and the scatterplot. Alongside the TS model produced from the entire dataset of each terminal, separate models were developed for summer and winter. All models are significant at the $p<0.005$ level.

The results show that the combination of variables explaining better TS in LCY consists of operative temperature, clothing and 15′ met, and is supplemented with the square root of air movement in the case of MAN T1 and MAN T2 (table 6-10). The unstandardised coefficient ahead of each variable indicates the amount of change expected in TS for every one-unit change in the value of that variable, provided that all other quantities in the model are held constant. For instance, 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 TS. In other words, the temperature change required to shift TS in LCY by one unit is 2.7 °C. Similarly, people's TS in MAN T1 and MAN T2 would not present a unit change unless they experience a temperature change of 3.3 °C and 4.1 °C respectively.

*Table 6-10: TS models with comfort variables.*

| | | *TS model* | F/$F_{critical}$ | $R^2$ |
|---|---|---|---|---|
| LCY | All data | $\boldsymbol{TS = 0.369\ T_{op} + 0.613\ clo + 0.556\ (15'met) - 9.24}$, | 52.8/2.6 | 0.16 |
| | Summer | $TS = 0.278\ T_{op} + 0.565\ (15'met) – 6.74$ | 23.0/3.0 | 0.10 |
| | Winter | $TS = 0.446\ T_{op} + 0.499\ clo + 1.8\ (met) – 12.127$ | 21.2/2.6 | 0.14 |
| MAN T1 | All data | $\boldsymbol{TS = 0.305\ T_{op} + 0.512\ clo + 0.251\ (15'met) – 0.958\ (V_{air})^{0/5} – 6.492}$ | 72.5/2.4 | 0.20 |
| | Summer | $TS = 0.301\ T_{op} + 0.257\ (15'met) – 2.002\ (V_{air})^{0/5} – 5.774$ | 49.7/2.6 | 0.19 |
| | Winter | $TS = 0.303\ T_{op} – 0.737\ V_{air} – 5.75$ | 70.6/2.4 | 0.21 |
| MAN T2 | All data | $\boldsymbol{TS = 0.246\ T_{op} + 0.803\ clo + 0.588\ (15'met) – 1.257\ (V_{air})^{0/5} – 5.76}$ | 30.7/2.4 | 0.11 |
| | Summer | $TS = 0.342\ T_{op} + 0.502\ (15'met) + 0.02\ RH – 1.71\ (V_{air})^{0/5} – 8.283$ | 28.3/2.4 | 0.18 |
| | Winter | $TS = 0.252\ T_{op} + 0.824\ clo + 0.159\ (15'met) +0.025\ RH – 7.234$ | 11.6/2.4 | 0.09 |

The unstandardised coefficients are measured in the unit of the variable they accompany. On the contrary, the standardised coefficients for each variable (table 6-11) are all measured in standard deviations, thus enabling the comparison of the relative strength of the various predictors within the models. Accordingly, the results show that the variable making the strongest contribution to explaining TS is operative temperature in all cases.

*Table 6-11: Standardised coefficients and significance levels for the TS predictors in table 6-10 (in bold).*

| | | $T_{op}$ | Clo | 15′met | $V_{air}^{0/5}$ |
|---|---|---|---|---|---|
| LCY | Standardised coefficient | 0.284 | 0.196 | 0.190 | n/a |
| | Significance level | 0.000 | 0.000 | 0.000 | n/a |
| MAN T1 | Standardised coefficient | 0.448 | 0.133 | 0.072 | -0.083 |
| | Significance level | 0.000 | 0.000 | 0.006 | 0.002 |
| MAN T2 | Standardised coefficient | 0.315 | 0.188 | 0.173 | -0.122 |
| | Significance level | 0.000 | 0.000 | 0.000 | 0.000 |

As discussed in the previous section, "clothing" was found to be significantly correlated with TS only for LCY. Interestingly, the results reveal that in all cases clothing levels make the second strongest unique contribution (behind operative temperature) to explaining TS, when the variance explained by all other variables in the model is controlled for. Similarly, air movement was individually found not to share variance with TS in all cases, but controlling for the other variables involved, it makes a significant contribution to explaining TS in MAN T1 and MAN T2.

#### 6.5.1.2 Effect of age, gender, drinks and clothing modification

An independent-samples t-test was conducted to investigate potential differences in TS between males and females. The mean clothing insulation worn by men and women was identical in all cases (table 6-12). The results are universal among the case studies and demonstrate that the marginally higher TS reported by males in all terminals is statistically insignificant (table 6-13). Moreover, a one-way analysis of variance between-groups was performed to explore the impact of age on TS, with the results suggesting no significant difference between people of different age groups (table 6-14).

*Table 6-12: Mean clothing insulation (clo) for males and females.*

| | Summer | | Winter | |
|---|---|---|---|---|
| | Females | Males | Females | Males |
| LCY | 0.63 | 0.66 | 1.09 | 1.14 |
| MAN T1 | 0.54 | 0.55 | 1.00 | 0.99 |
| MAN T2 | 0.52 | 0.51 | 0.89 | 0.88 |

*Table 6-13: T-test results showing no significant difference in TS scores between males and females.*

| | Females | | Males | | | | |
|---|---|---|---|---|---|---|---|
| | Mean TS | SD | Mean TS | SD | t value | t critical | p value |
| LCY | 0.64 | 1.11 | 0.72 | 1.06 | t(816) = -0.96 | ±1.96 | 0.34 |
| MAN T1 | 0.46 | 1.26 | 0.54 | 1.16 | t(1196) = -1.09 | ±1.96 | 0.28 |
| MAN T2 | 0.45 | 1.30 | 0.58 | 1.08 | t(1069) = -1.71 | ±1.96 | 0.09 |

*Table 6-14: ANOVA results demonstrating no impact of age on TS.*

| | F value | F critical | p value |
|---|---|---|---|
| LCY | F(6,811) = 1.1 | 2.11 | 0.35 |
| MAN T1 | F(6,1191) = 1.6 | 2.11 | 0.15 |
| MAN T2 | F(6,1064) = 0.8 | 2.11 | 0.55 |

A one-way analysis of variance was also conducted to investigate whether a change in clothing levels 15 minutes prior to the questionnaire had an impact on TS. Therefore, the test was used to compare the mean scores of clothing insulation between three population groups; those who had not altered their clothing and those who had added or removed clothing. The respective frequency distribution was found nearly identical for all terminals, where the vast majority of people had not altered their clothing levels, while among those who did, cloth removal was the most frequently action taken (table 6-15). Moreover, most of the people who had modified their clothing reported acceptable TS but expressed a preference for a change in the thermal environment, preferring predominantly cooler conditions.

*Table 6-15: Clothing modification 15 minutes prior to questionnaire.*

| | % of total population | | | % of people who altered their clothing | |
|---|---|---|---|---|---|
| | No change | Clothes on | Clothes off | Acceptable TS | Preferred warmer or cooler |
| LCY | 83% | 2% | 15% | 80% | 54% |
| MAN T1 | 83% | 3% | 14% | 71% | 66% |
| MAN T2 | 86% | 2% | 12% | 57% | 54% |

As a result of the high numerical difference between the three groups, the assumption of homogeneity of variance underlying ANOVA was violated in some of the tests[8]. For these cases, the significance of the results was determined from the Welch and Brown-Forsythe tests and subsequently from Tamhane's post hoc tests[9]. The results (table 6-16) achieved statistical significance for MAN T1 and MAN T2. In these cases, interviewees who had reduced their clothing levels reported higher mean TS than those who added clothing, while between the two lies the mean TS of those made no change. Therefore, the results suggest that a 15-minute interval was insufficiently allowing clothing modification to impact TS.

*Table 6-16: Mean value and standard deviation of clothing insulation for people who did and did not alter their clothing levels 15 minutes prior to the questionnaire.*

| | LCY | | MAN T1 | | MAN T2 | |
|---|---|---|---|---|---|---|
| | Mean TS | SD | Mean TS | SD | Mean TS | SD |
| Clothes on | 0.00 | 1.41 | -0.28 | 1.45 | 0.11 | 1.85 |
| Clothes off | 0.69 | 1.07 | 1.01 | 0.97 | 0.87 | 1.31 |
| No change | 0.69 | 1.08 | 0.45 | 1.21 | 0.47 | 1.16 |

Furthermore, the study investigated the potential effect of drinks on TS, as their consumption has been demonstrated to affect the metabolic heat produced (Baker and Standeven, 1996; Nikolopoulou and Steemers, 2003) and hence TS. This was done by means of a one-way

[8] If sig < 0.05 in Levene's test for homogeneity of variance than the assumption for homogeneity is violated.

[9] Tamhane's T2 is among the post hoc tests that are appropriate when variances are unequal and provides conservative pairwise comparisons based on t-test.

analysis of covariance (ANCOVA), thus allowing for the control of indoor temperature and additionally for the evaluation of the extent that the consumption of drinks is a response to the thermal conditions. Therefore, the dependent variable was TS, the independent variable was the one grouping people according to whether they had a hot drink, a cold drink or no drink 15 minutes prior to the questionnaire, while the operative temperature played the role of the covariate. Preliminary checks were conducted to ensure that there is no violation of the assumption underlying the ANCOVA test (assumption of normality, linearity, homogeneity of variances, homogeneity of regression slopes and reliable measurement of the covariate).

The results (adjusted values in table 6-17) are significant at $p<0.05$ but not uniform between the case studies. In LCY, the mean TS for people who consumed a cold drink (mean TS = 0.47) was 0.29 units lower than for those who had no drink (mean TS = 0.76), with the difference being equivalent to nearly 40% cooler TS. Very similar is the result for MAN T2; people who had a cold drink (mean TS = 0.30) reported 0.27 units lower TS than those who did not have a drink (mean TS = 0.57), equivalent to a 50% difference. On the other hand, the corresponding difference for MAN T1 was only 0.07 units and statistically insignificant. Moreover, the results for MAN T1 show that the mean TS score for the people who had a hot drink was 0.43 and 0.39 units higher than for those who had a cold drink and no drink respectively. This result, however, was not confirmed for LCY and MAN T2.

*Table 6-17: Effect of drinks on TS while controlling for indoor temperature (adjusted) and without (unadjusted).*

| | | | Adjusted** | | Unadjusted*** | |
|---|---|---|---|---|---|---|
| | | N* | Mean TS | St. Error | Mean TS | St. Dev. |
| LCY | Hot drink | 97 | 0.46 | 0.13 | 0.47 | 1.00 |
| | Cold drink | 205 | 0.47 | 0.08 | 0.53 | 1.12 |
| | No drink | 765 | 0.76 | 0.04 | 0.74 | 1.08 |
| MAN T1 | Hot drink | 92 | 0.85 | 0.12 | 0.78 | 1.26 |
| | Cold drink | 259 | 0.42 | 0.07 | 0.48 | 1.26 |
| | No drink | 847 | 0.49 | 0.04 | 0.48 | 1.18 |
| MAN T2 | Hot drink | 97 | 0.51 | 0.12 | 0.43 | 1.07 |
| | Cold drink | 205 | 0.30 | 0.08 | 0.31 | 1.23 |
| | No drink | 765 | 0.57 | 0.04 | 0.58 | 1.21 |

*N = sample size (in the case of MAN T2 there were 4 missing values out of the 1071 in total)
** Adjusted values = controlling for the operative temperature
*** Unadjusted are the values without the effect of operative temperature

Therefore, it can be concluded that the consumption of drinks may impact TS but the effect is small. In fact, the effect size can be seen from the partial eta squared value, which converted into a percentage shows how much of the variance in TS is explained by the consumption (or not) of drinks, while controlling for temperature. Accordingly, this is only 1.5% for LCY, 0.9% for MAN T1 and 0.8% for MAN T2.

Furthermore, table 6-17 shows that the adjusted and unadjusted scores of mean TS for each group are nearly identical in most cases. In other words, with and without controlling for temperature the mean TS value for each group is almost the same. For instance, without controlling for temperature, the mean difference in TS between people who had a cold drink and no drink in LCY would be 0.21 units (instead of 0.29 units), while the corresponding difference for the case of MAN T2 remains unchanged (0.21 units). Therefore, although operative temperature has a statistically significant effect on TS, the results indicate that – within the range found in the terminals – temperature has little to do with the decision of having a drink.

### 6.5.2 Assessment of thermal preference

The examination of thermal preference (TP) votes provides further information about the thermal requirements of people in the three terminals. Operative temperature is the environmental quantity correlated better with TP in all cases. The relationship between the two is weaker in LCY (0.27, $p<0.01$) and MAN T2 (0.31, $p<0.01$) and stronger in the more variable thermal environment of MAN T1 (0.41, $p<0.01$). People engaged in higher activity levels 15 minutes prior to the questionnaire tended to prefer cooler thermal conditions, as the respective correlation coefficients suggest (0.12 for LCY, 0.10 for MAN T1 and 0.14 for MAN T2, $p<0.01$).

For LCY and MAN T2, where elevated $CO_2$ concentrations were associated with higher indoor temperatures (section 6.4.1) and warmer TS (figure 6-11 and table 6-9), a significant but weak relationship was also found between occupancy levels and thermal preference (0.16, $p<0.01$ for LCY and 0.23, $p<0.01$ for MAN T2). The relationship's positive direction indicates the tendency of TP votes towards a cooler thermal environment in crowded conditions.

In both summer and winter, preference over the thermal environment in all terminals converged at two votes expressing the majority of interviewees; "no change" and "a bit cooler" (figure 6-12). However, the relevant magnitude between the two and their seasonal changes draw different conclusions for each building. In summer, TP profile was very similar with almost 50% of people in all terminals finding the thermal environment 'just right' and nearly 40% preferring cooler conditions. This pattern was reversed in LCY during winter, when the TS profile was suggestive of overheating. In fact, the majority (53%) preferred a cooler thermal environment, with nearly half the people preferring "a bit cooler" in particular.

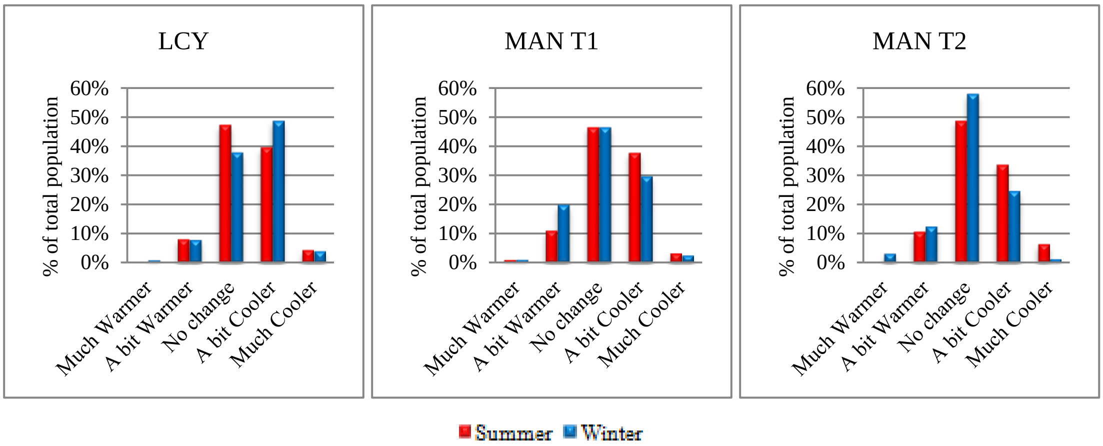



*Figure 6-12: Percentage distribution of thermal preference votes.*

In MAN T1 the percentage of people desiring no change remained unchanged in winter (nearly 50%). Compared to summer, the preference for a cooler environment represented a slightly lower, yet significant fraction of interviewees (one out of three). However, what stands out in the winter profile is the respectful fraction of people preferring a warmer thermal environment. Reflecting the cooler conditions experienced in certain terminal areas at this time of the year, this percentage was nearly twice of that in summer and represented 20% of the population.

MAN T2 is the only terminal where more people found the temperature “just right” in winter (nearly 60%). Yet, similarly to LCY and MAN T1, the majority of interviewees requiring a change in winter preferred to be cooler, with such preference expressing 25% of people.

Interestingly, a cross-tabulation of TS and TP reveals that neutral (“neither cold nor hot”) was not the desired TS for the majority of people in the terminal buildings. Having assumed that “no change” response denotes satisfaction, the results show that 51%, 62% and 59% of people in LCY, MAN T1 and MAN T2 - who were satisfied with the thermal conditions - had reported TS other than neutral (figure 6-13). The vast majority of them had felt either “slightly cool” or “slightly warm”, with the latter sensation receiving higher response. Significantly lower, yet respectful, was the fraction of the people in MAN T1 (17%) and MAN T2 (14%) who had reported “unacceptable” TS while requiring no change. This reflects the diversity of comfort requirements across the different thermal environments coexisting in these terminals and represent predominantly warm sensations reported under cooler thermal conditions.

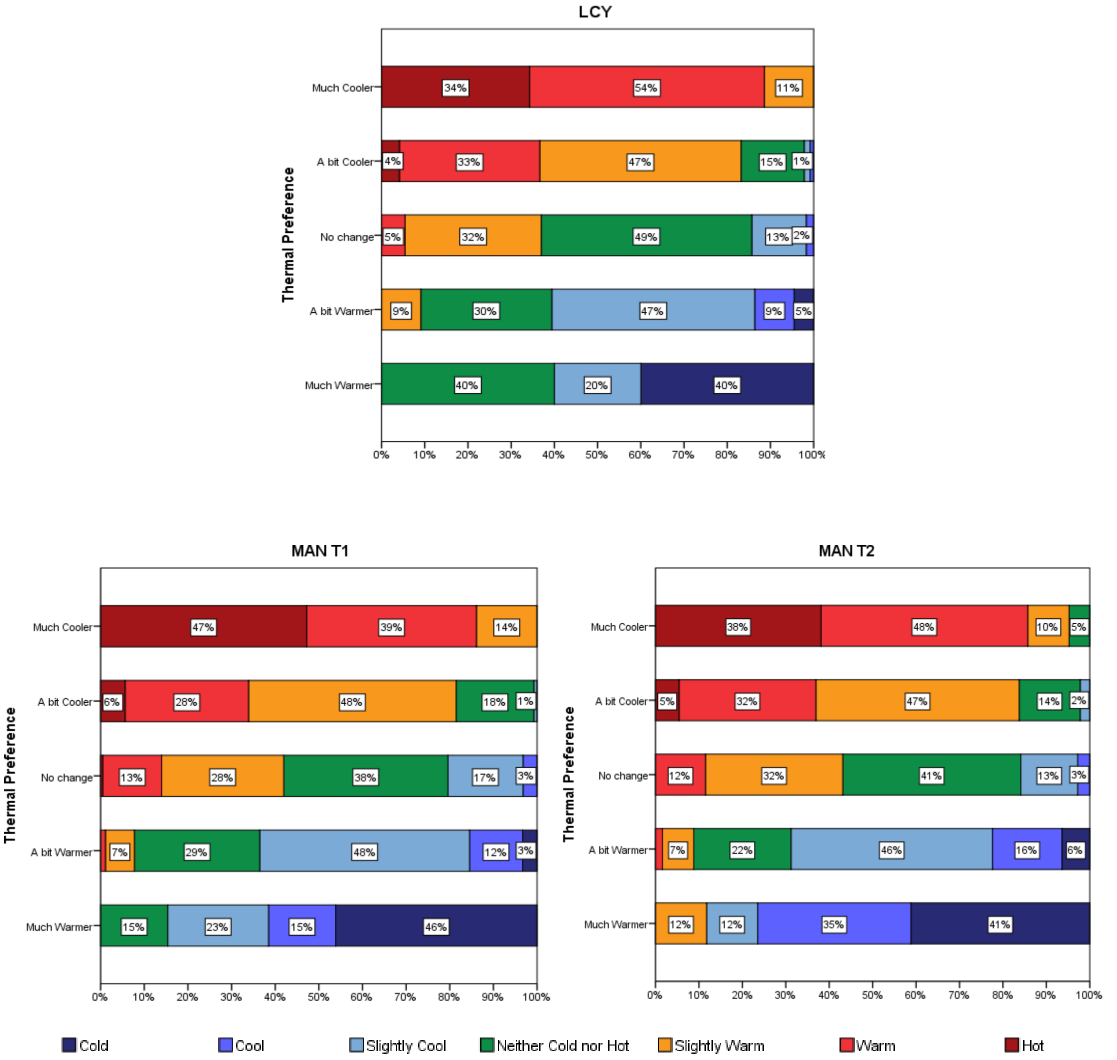



*Figure 6-13: Breakdown of thermal sensation votes at each thermal preference category.*

### 6.5.3 Perception and preference over air movement and sensation of air humidity

As discussed in section 6.4.1, air movement was on average very low with small variance in all terminal buildings. As a result, the relationship between air movement and people's respective sensation is weak for MAN T1 (0.18, p<0.01) and MAN T2 (0.08, p<0.01), while there is no significant correlation between the two for LCY. The sensation of air movement is better correlated with operative temperature (-0.11 in LCY, -0.25 in MAN T1 and -0.34 in MAN T2, p<0.01) than with any other of the environmental variables, suggesting that people tended to assess air movement - through a temperature assessment - as low at higher temperature levels.

Other quantities found to be significantly correlated with the assessment of air movement include the 15′ met in LCY (-0.14, p<0.01) and MAN T1 (-0.08, p<0.01), and the clothing insulation levels in MAN T1 (0.07, p<0.05) and MAN T2 (0.20, p<0.01). The first relationship reflects people's tendency to assess the air movement as low when engaged in activities of higher intensity. On the other hand, the positive relationship with clothing associates assessments for higher air movement with people dressed in warmer outfits. This suggests that occupants who perceived the air movement as high had either added clothes or were wearing outfits of high thermal insulation to keep warm.

In all terminals air movement was rarely evaluated as “high” and almost never as “very high”. On the contrary, widespread among the population was the assessment of air movement as “neither low nor high” and “low”, with the two cumulatively accounting for 70-80% of the responses in summer and winter (figure 6-14). In LCY and MAN T1 the two categories received nearly the same response in both seasons, whilst in MAN T2 the most popular sensation was “low” in summer and “neither low nor high” in winter. Notable is also the percentage of people who felt it was “very low”, particularly in summer when this notion represented nearly 20% of occupants in LCY and MAN T1 and 25% of occupants in MAN T2.

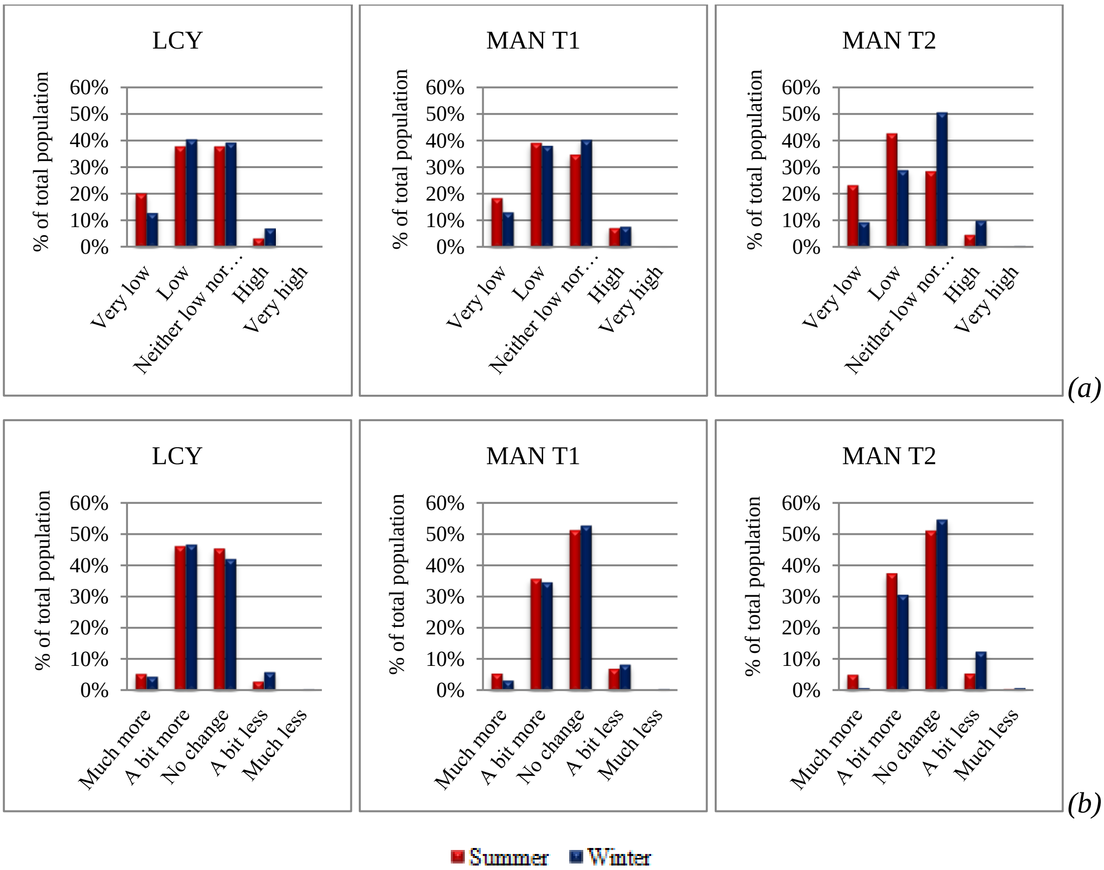



*Figure 6-14: (a) Perception and (b) preference over air movement (sensation of “very high” and preference for “much less” air movement are below 1%).*

Similarly to the sensation, preference over the air movement is better correlated with operative temperature (-0.14 in LCY, -0.30 in MAN T1 and -0.29 in MAN T2, $p<0.01$) than with any other of the environmental variables. The relationship implies preference for more air movement the higher the temperature was sensed. Once again, air movement is not correlated with people's preference in LCY but only in MAN T1 (0.15, p<.0.01) and MAN T2 (0.07, p<0.05).

In both seasons the preference profile was dominated by two responses; "no change" and "a bit more", with almost the same frequency in LCY and with more people requiring no change in MAN T1 and MAN T2 (figure 6-14). More specifically, "no change" preferred nearly half the people in all terminals, while "a bit more" was widespread among those requiring a change. Such preference was expressed by at least one out of three in MAN T1 and MAN T2, and by nearly half the respondents in the warmer LCY, thus suggesting that warm rather than cool conditions were an issue in summer and winter. This is also apparent from the cross examination of the sensation and preference votes. The vast majority of people who perceived the air movement as "neither low nor high", yet preferring a change, preferred higher air movement. Additionally, the percentage of people requiring no change while having assessed it as high was considerable (31- 43%; figure 6-15).

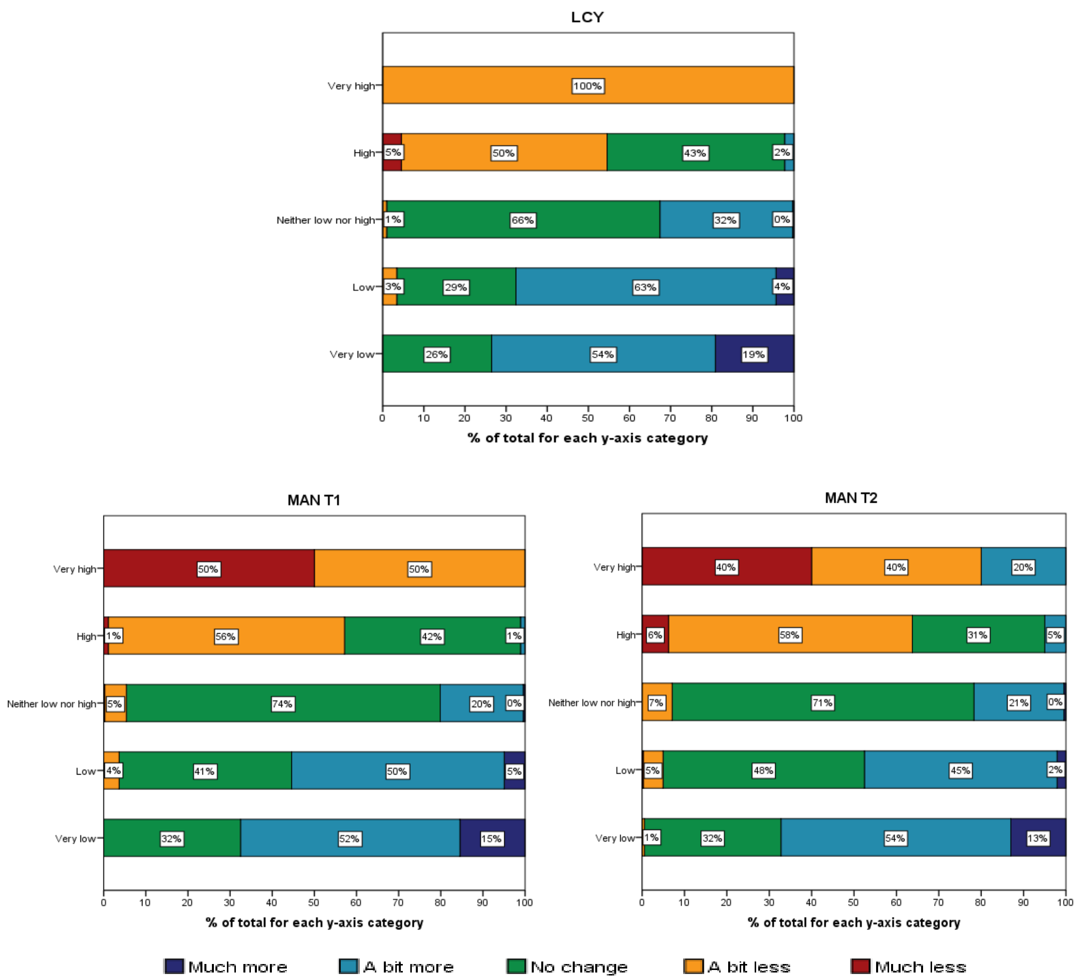



*Figure 6-15: Cross-examination of preference and sensation over the air movement in (a) LCY, (b) MAN T1 & (c) MAN T2, based on summer and winter data.*

As far as the air humidity is concerned, the majority of interviewees (58-75%) in the three terminals assessed the conditions as “neither damp nor dry” in summer and winter. However, the sensation of dryness in winter was increased, as noted by nearly 33% of people in LCY and MAN T1, while such notion was expressed by 33% of respondents in MAN T2 in both seasons (figure 6-16).

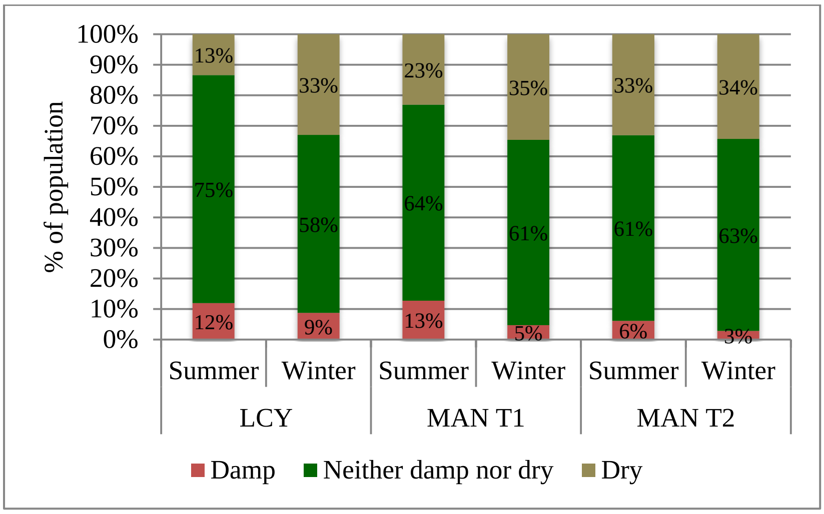



*Figure 6-16: Subjective assessment of humidity conditions in summer and winter.*

The relationship between RH (%) and the respective sensation is significant only for LCY (-0.17, p<0.01) and MAN T1 (-0.18, p<0.01). The direction of the relationship verifies people’s assessment, as it implies drier sensation the drier the environment was. Further to this point, RH (%) was binned in 5% increments, the mean sensation score was calculated for each bin (table F-1, appendix F) and regressed against RH (%). The models (significant at the 99% level or better) confirm the relationship but the very low gradients show that the small variance of RH (%) indoors cannot change people’s sensation (figure 6-17).

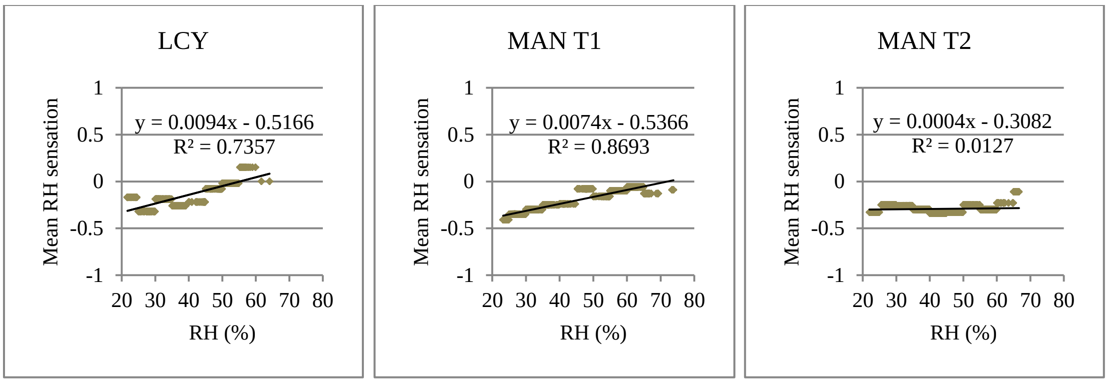



*Figure 6-17: Relationship between mean RH sensation (from -1 = dry to +1 = damp) & RH (%).*

### 6.5.4 Comfort temperatures

The section focuses on the calculation of neutral and preferred temperature along with the evaluation of the temperature range that 80% and 90% of occupants would find acceptable.

#### 6.5.4.1 Neutral temperature

Weighted linear regression was performed to calculate the actual and predicted neutral temperatures for the terminal population (de Dear et al., 1997). Operative temperature was binned into half-degree (°C) increments and the mean values of TS and PMV were calculated for each bin (tables F-2, F-3 and F-4 in appendix F). Assuming a linear relationship between temperature and TS, linear regression models were fitted between mean TS and operative temperature, as well as between mean PMV and temperature. The data was binned so that regression models weigh each point according to the sample size; i.e. according to the number of TS votes within each temperature bin. Cases with ±3 standard deviations or beyond from the mean score were considered outliers. The general form of the regression models is:

$$\text{Mean TS or Mean PMV} = \text{a} + \text{b} \times (\text{T}_{\text{op}})$$

Neutrality and predicted neutrality was then obtained by solving the terminals' regression equations for mean TS = 0 and mean PMV = 0 respectively. All presented models (figure 6-18) achieved a statistical significance level of 99% or better.

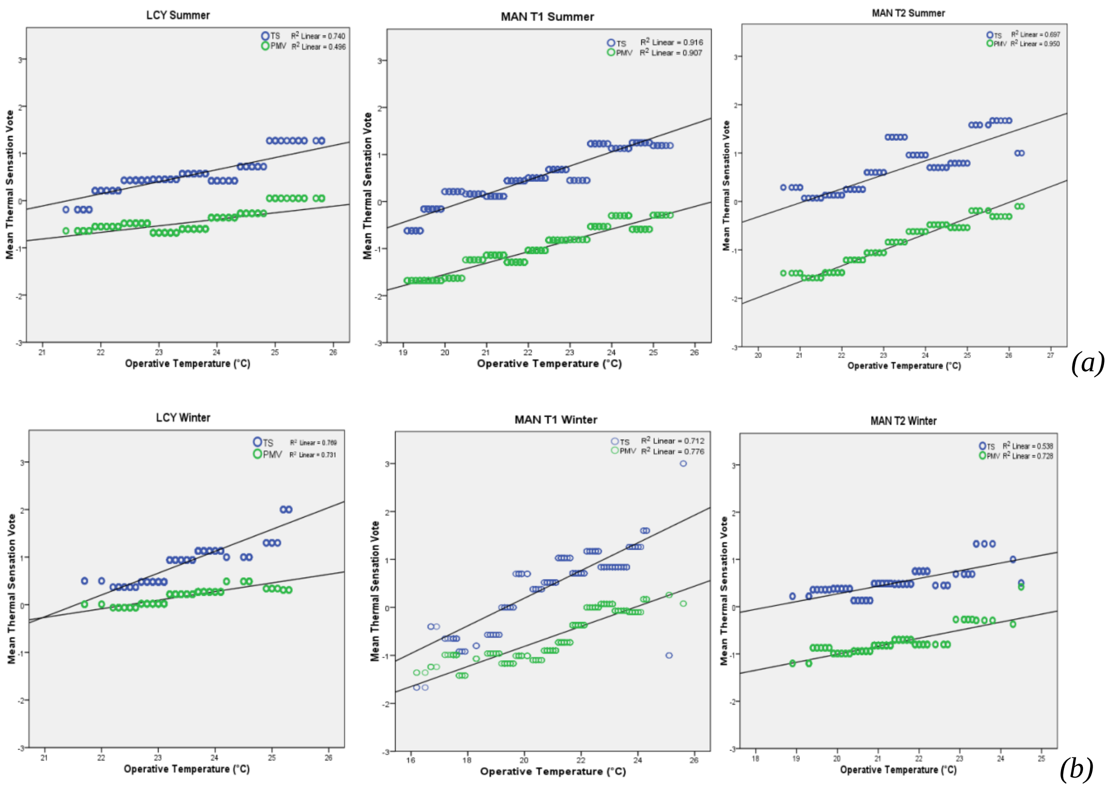



*Figure 6-18: Relationship between actual and predicted thermal sensation with operative temperature in (a) summer and (b) winter.*

Representing thermal sensitivity, the slope of the regression models demonstrates a similar rate of TS change in all terminals during summer. More specifically, the temperature change required to shift TS by one unit is 3.9 ºC in LCY, 3.4 ºC in MAN T1 and 3.5 ºC in MAN T2. For winter, the gradient varies widely between the case studies. Thermal sensitivity was greatly increased in LCY, where the TS change rate was one unit for every 2.2 ºC temperature change. In MAN T1, thermal sensitivity and rate of TS change remained close to the summer levels, while the reduced thermal sensitivity in MAN T2 indicates that the mean TS would not be altered with temperature changes below 6.2 ºC.

Interestingly, the results reveal that neutral temperature lies below the mean operative temperature people experienced in all terminals, in summer and winter (table 6-18). More specifically, neutrality in summer was lower by 1.6 ºC in MAN T1 and by 1.9 ºC in LCY and MAN T2. In spite of the increased thermal sensitivity in LCY during winter, the neutral temperature was identical in both seasons and consistently lower than the mean operative temperature by 1.9 ºC. In MAN T1 and MAN T2, neutrality in winter was lower than the mean operative temperature by 1.9 ºC and 2.8 ºC. Results based on the regression models derived from PMV imply significantly higher neutral temperatures than the actual ones, with the discrepancy between the two ranging from 1.0 ºC to 7.6 ºC.

*Table 6-18: TS & PMV regression models, neutral temperatures (°C) and acceptable ranges in summer & winter.*

| | | | Slope | Constant | $R^2$ | $T_{neutral}/T_{mean}$ (°C) | 80% accept. (°C) | 90% accept. (°C) |
|---|---|---|---|---|---|---|---|---|
| Summer | Actual | LCY | 0.256 | -5.49 | 0.74 | **21.4** / 23.3 | 18.1 – 24.8 | 19.5 – 23.4 |
| | | MAN T1 | 0.300 | -6.13 | 0.92 | **20.4** / 22.0 | 17.6 – 23.3 | 18.8 – 22.1 |
| | | MAN T2 | 0.289 | -6.11 | 0.70 | **21.1** / 23.0 | 18.2 – 24.1 | 19.4 – 22.9 |
| | Predicted | LCY | 0.139 | -3.72 | 0.50 | 26.8 / 23.3 | 20.7 – 32.9 | 23.2 – 30.4 |
| | | MAN T1 | 0.241 | -6.36 | 0.91 | 26.4 / 22.0 | 22.9 – 29.9 | 24.3 – 28.5 |
| | | MAN T2 | 0.327 | -8.53 | 0.95 | 26.1 / 23.0 | 23.5 – 28.7 | 24.6 – 27.6 |
| Winter | Actual | LCY | 0.459 | -9.88 | 0.77 | **21.5** / 23.4 | 19.7 – 23.4 | 20.4 – 22.6 |
| | | MAN T1 | 0.288 | -5.58 | 0.71 | **19.4** / 21.3 | 16.4 – 22.3 | 17.6 – 21.1 |
| | | MAN T2 | 0.163 | -2.99 | 0.54 | **18.3** / 21.1 | 13.1 – 23.6 | 15.3 – 21.4 |
| | Predicted | LCY | 0.181 | -4.07 | 0.73 | 22.5 / 23.4 | 17.8 – 27.2 | 19.7 – 25.2 |
| | | MAN T1 | 0.209 | -5.00 | 0.78 | 23.9 / 21.3 | 19.9 – 28.0 | 21.5 – 26.3 |
| | | MAN T2 | 0.170 | -4.40 | 0.73 | 25.9 / 21.1 | 20.9 – 30.9 | 22.9 – 28.8 |

The acceptable temperature ranges were evaluated in accordance to the statistical assumptions underlying the PMV/PPD heat-balance model (ISO 7730, 2005). Accordingly, it was assumed that a mean TS of ±0.85 and ±0.50 corresponds to 80% and 90% general acceptability respectively. As demonstrated in figure 6-19, the indoor thermal conditions in all terminal buildings regularly did not meet the respective ranges (table 6-18).

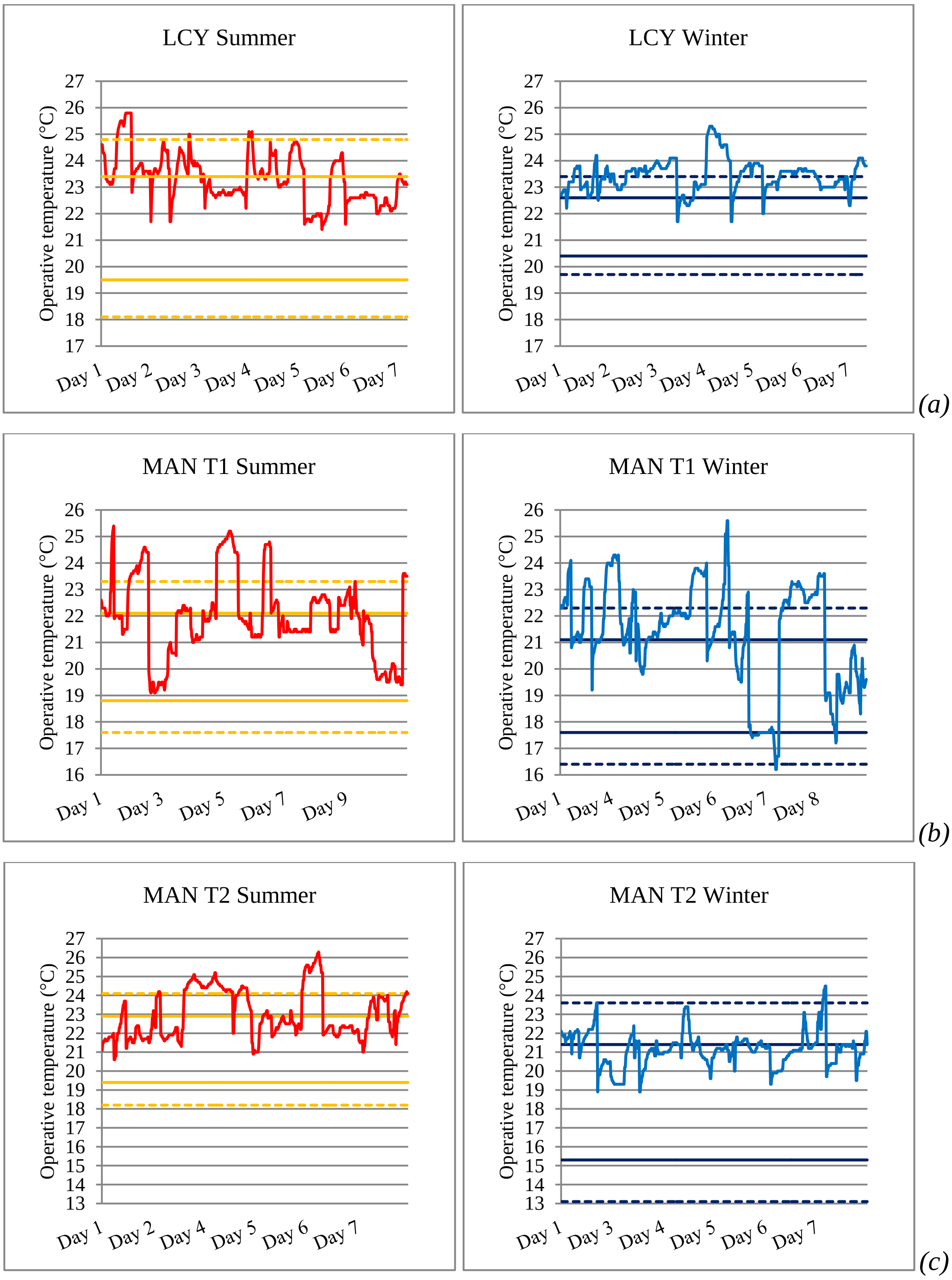



*Figure 6-19: Operative temperature, 80% (dotted lines) and 90% (continuous lines) acceptability temperature ranges in (a) LCY, (b) MAN T1 and (c) MAN T2.*

More specifically, operative temperature in summer lay within the 80% acceptability range for 94%, 82% and 73% of the monitoring time[10] in LCY, MAN T1 and MAN T2 respectively. This was also the case during winter in MAN T2 (99% of time), whereas in LCY and MAN T1 the temperature remained within that range for only 48% and 66% of time, stressing periods of overheating that are also apparent from the frequency distribution of TS (figure 6-10). The narrower 90% acceptability ranges were accomplished for significantly shorter periods of time; 59% of time in MAN T1, and 57% of time in LCY and MAN T2 in summer and for even shorter intervals in winter, 9% in LCY, 34% in MAN T1 and 69% in MAN T2.

#### 6.5.4.2 Preferred temperature

In order to quantify the temperatures people preferred in the terminal buildings, the 5-point thermal preference variable was transformed into a 3-point variable. Accordingly, preference for a "much warmer" and "a bit warmer" environment are represented by "prefer warmer" and those for a "much cooler" and "a bit cooler" environment by "prefer cooler", as shown in figure 6-20.

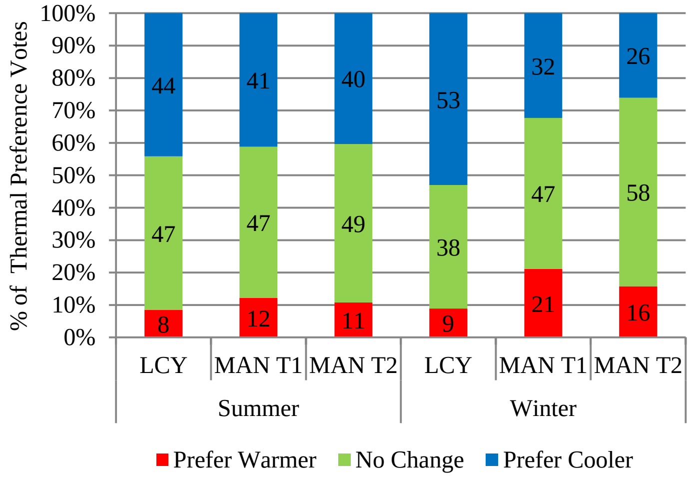



*Figure 6-20: Percentage of binned thermal preference votes.*

Weighted linear regressions were then fitted separately between the "prefer warmer" and "prefer cooler" percentages and operative temperature. Preferred temperature was obtained from the intersection of the two regression lines (figure 6-21).

[10] Having excluded the data collected while only environmental but not human monitoring was taking place, the percentage of monitoring time here equals the percentage of the questionnaires completed.

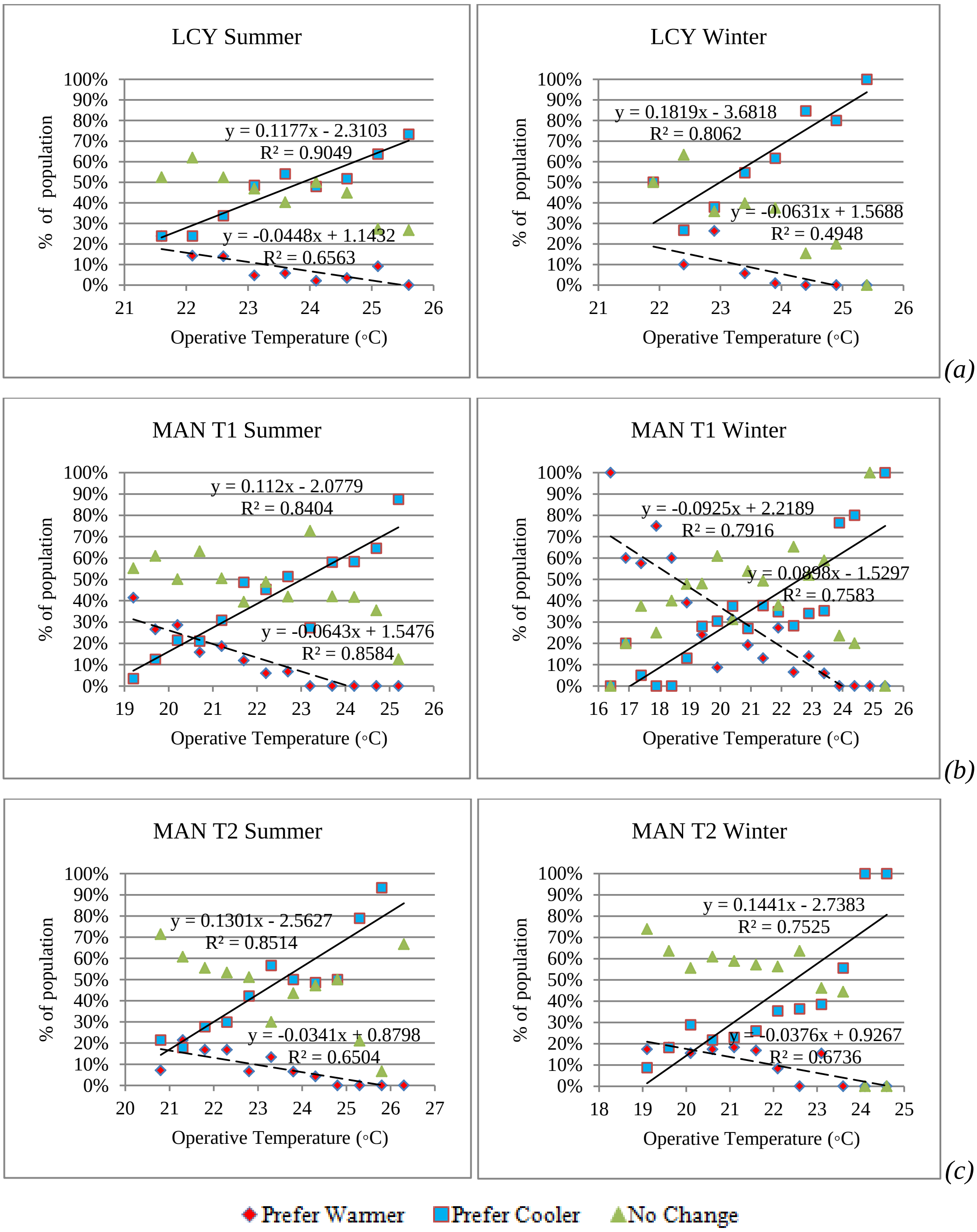



*Figure 6-21: Calculation of preferred temperatures in (a) LCY, (b) MAN T1 and (c) MAN T2 in summer and winter.*

The profile of preferred temperatures was found to follow that of neutral temperatures, with the two almost coinciding in most cases. The results (table 6-19) are uniform among the case studies and demonstrate people's preference for cooler temperatures than those experienced in the terminal buildings in both summer and winter. More specifically, in LCY, preferred temperature lay 2.0 ºC below the mean temperature in both seasons and in complete alignment with neutral temperature highlights the overheating conditions in the terminal. People in MAN T1 and MAN T2 preferred the thermal environment to be cooler by 1.4 ºC and 2.0 ºC respectively in summer, and cooler by nearly 1.0 ºC in both terminals during winter.

Furthermore, the results provide evidence of tolerance under cooler conditions. In MAN T1 and MAN T2 where the lowest indoor temperatures occurred during the winter surveys, the preferred temperature was 20.6 ºC and 20.2 ºC, with the respective neutral temperatures – 19.4 ºC in MAN T1and 18.3 ºC in MAN T2 – showing that people were still comfortable at temperatures lower than the ones preferred.

*Table 6-19: Summary of mean, neutral and preferred operative temperatures.*

| | Summer | | | Winter | | |
|---|---|---|---|---|---|---|
| (ºC) | LCY | MAN T1 | MAN T2 | LCY | MAN T1 | MAN T2 |
| $T_{mean}$ | 23.3 | 22.0 | 23.0 | 23.4 | 21.3 | 21.1 |
| $T_{neutral}$ | 21.4 | 20.4 | 21.1 | 21.5 | 19.4 | 18.3 |
| $T_{preferred}$ | 21.3 | 20.6 | 21.0 | 21.3 | 20.6 | 20.2 |
| $T_{mean}$ - $T_{preferred}$ | 2.0 | 1.4 | 2.0 | 2.1 | 0.7 | 0.9 |
| $T_{neutral}$ - $T_{preferred}$ | 0.1 | -0.2 | 0.1 | 0.2 | -1.2 | -1.9 |

### 6.5.5 The lighting environment

This section examines how the terminal population evaluated the lighting environment in the terminal buildings. Perception and preference over lighting are addressed along with the relationship between the two and illuminance, while further analysis reveals that bright rather dim conditions were preferred. Subsequently, the subjective assessments of daylight demonstrate people’s desire for natural light, with the respective preference being associated with the time of the day.

#### 6.5.5.1 Assessment of overall lighting conditions

The relationship between lighting sensation and illuminance is significant at the $p<0.01$ level in all cases, with the Pearson correlation coefficient being 0.18 for LCY, 0.29 for MAN T1 and 0.25 for MAN T2. The corresponding coefficient describing the relationship between lighting levels and preference over the lighting environment is -0.17 ($p<0.01$) in LCY and MAN T1 and -0.09 ($p<0.05$) in MAN T2.

Overall, the average perception of lighting in LCY and MAN T1 was “neither bright nor dim” and rounds up to “slightly bright” for MAN T2. The percentage distribution of lighting sensation is representative of the luminous environment in each terminal, with “daylight” being the differentiating parameter between the cases studies. More specifically, the distribution for the uniform spaces of LCY (figure 6-22a) is dominated by the middle three categories. “Slightly dim" and "slightly bright" represent nearly 25% of the population each and "neither bright nor dim" received the highest response, about 35%. These categories also represent the majority of responses (80%) in MAN T1 where more people, however, found it "slightly dim". On the contrary, more than half of the population in MAN T2 voted on the bright side of the 7-point sensation scale, with particularly 25% and 30% of interviewees finding the lighting environment "slightly bright" and "bright" respectively, reflecting the abundance of daylight in the terminal.

Unlike lighting sensation, the profile of preference votes is very similar between the case studies. In all terminals, the majority of people (60-67%) found lighting levels "just right", while widespread was the preference for brighter conditions among those requiring a change (figure 6-22b).

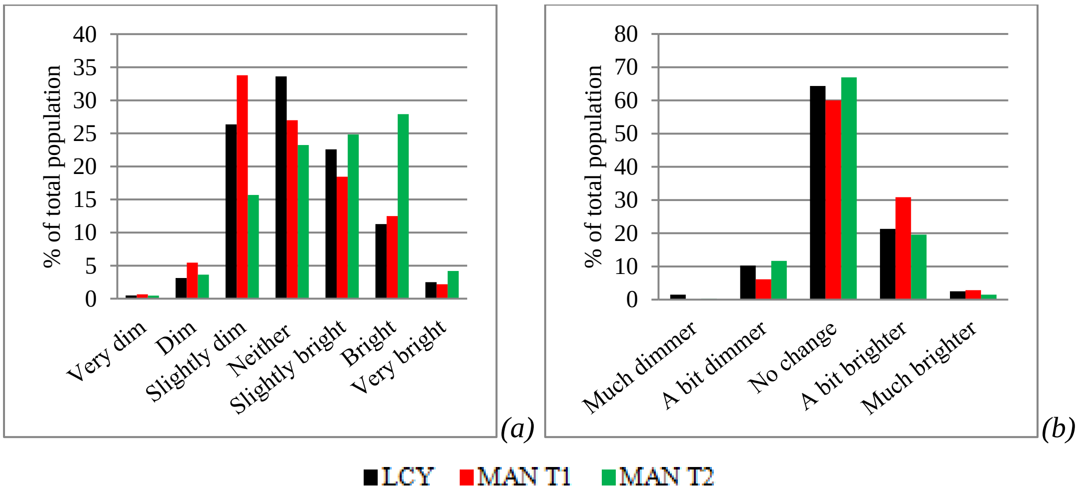



*Figure 6-22: Percentage distribution of (a) lighting sensation and (b) lighting preference votes.*

To investigate the relationship between the subjective assessments of lighting and illuminance, the latter was binned into increments of 200 lux and the mean sensation and preference scores were calculated for each bin (table F-5, appendix F). The plot of mean lighting sensation and illuminance reveals a logarithmic relationship between the two in all cases (figure 6-23a). At lighting levels of up to 1000 lux and 2000 lux in MAN T1 and MAN T2 respectively, the mean lighting sensation is well clustered around the line describing the relationship. Beyond these levels however, it presents significant variance indicating that the assessment of lighting environment becomes diversified at higher illuminances. On the other hand, lighting levels in most of the spaces at LCY did not exceed 1200 lux. Higher illuminances were recorded only in the retail facilities which are characteristic of the intensive spot lighting. These are the apparent "outliers" in the respective figures for LCY and correspond to assessments of retail staff.

Mean lighting preference is also logarithmically related to illuminance (figure 6-23b). With only few points denoting a preference for "a bit dimmer" environment at higher illuminances, the mean lighting preference scores remain on the “no change” line demonstrating people’s preference for a bright environment in all terminals.

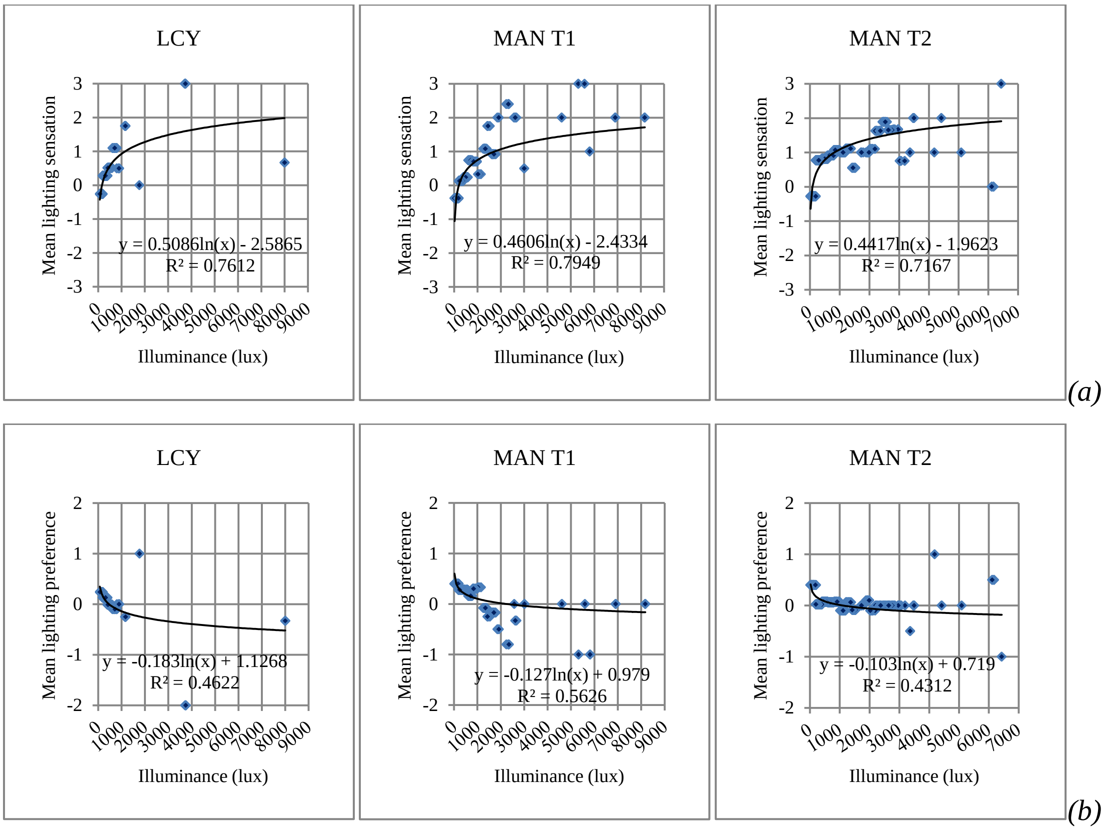



*Figure 6-23: Relationship between (a) mean lighting sensation, (b) mean lighting preference and illuminance.*

Further to this point, mean lighting preference was examined against lighting sensation irrespective of illuminance. Accordingly, figure 6-24 illustrates the mean lighting preference scores corresponding to each of the seven points on the lighting sensation scale. The developed pattern is uniform among the cases studies: the line representing the mean preference shows that people preferred a brighter environment when lighting was deemed to be “very dim”, “dim” and “slightly dim”, required “no change” when it was assessed as “neither bright nor dim” as well as “slightly bright” and “bright”, and preferred “a bit dimmer” only when lighting was perceived as “very bright”. Therefore, these results demonstrate from a different approach that a bright rather than a dim lighting environment was preferred in all buildings.

As seen in figure 6-23a, there is no clear distinction between “slightly bright”, “bright” and “very bright” in terms of illuminance levels. This suggests that satisfaction with the lighting environment (as expressed via the preference for no change), when this was deemed to be “slightly bright” and “bright” in particular, depended more on the perceived rather than the actual illuminance.

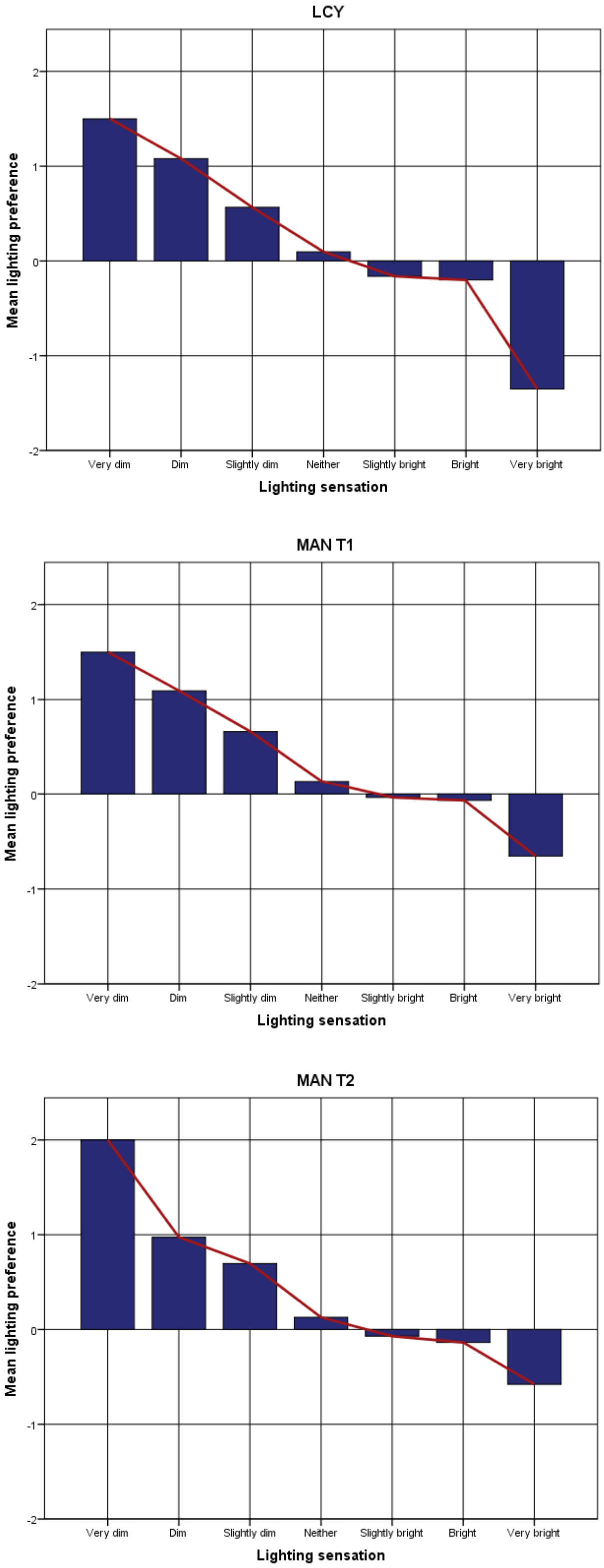



*Figure 6-24: Mean lighting preference (red line, from much dimmer = -2 to much brighter = 2) as a function of lighting sensation. Bars represent the mean illuminance corresponding to each sensation vote.*

Moreover, the vast majority of people (70-90%) in the three terminals found the light well distributed and a similar percentage of interviewees (nearly 90%) reported no discomfort glare. However, the assessment of light distribution from passengers and staff as well as their responses regarding the experience of discomfort glare reveal interesting differences between the two groups, discussed in section 6.6.3.

#### 6.5.5.2 Daylight

People's perception over the amount of natural light (figure 6-25a) describes the overall daylight profile of the three terminals. The majority of people in MAN T1 found it "little" or "very little" in the space they were interviewed, with the "sufficient" votes coming predominantly from the few spaces of the terminal that have large sources of natural light; departures lounge 1 and the two piers (gates). On the other hand, the extensive sources of daylight in the spaces of MAN T2 is reflected in the majority's assessment as "sufficient", while in LCY the assessment is equally distributed between "very little", "little" and "sufficient".

The corresponding preference votes (figure 6-25b) confirm people's desire for natural light, as this has been reported in a number of studies in other building types (Veitch and Gifford, 1996). More specifically, the majority of interviewees in LCY (70%) and MAN T1 (65%) expressed a preference for more daylight. This desire is further highlighted by the respective figures from MAN T2. The majority acknowledged the sufficiency of natural light in the building ("sufficient", "much" and "very much" account for 62% of responses), yet nearly half the population would prefer even more and almost no one less.

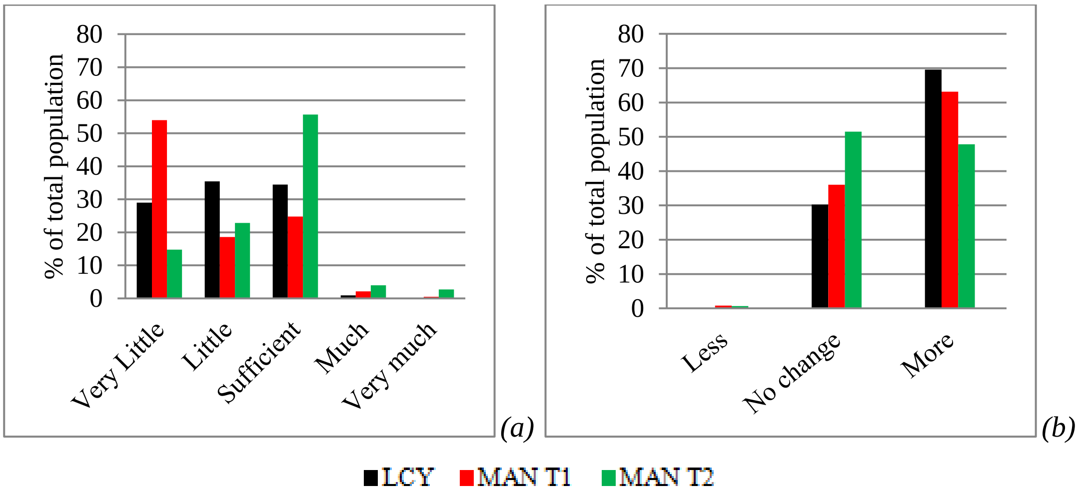



*Figure 6-25: Subjective assessment of daylight and relevant preference for change.*

Investigating a potential link with environmental variables, preference for daylight was evaluated against time of the day. Correlation analysis revealed a significant relationship between time and preference over daylight. In all cases, the relationship suggests that preference scores declined the later the time in the day was (table 6-20). To examine further this point, the mean preference score was calculated for each hour of the daytime (averaged for all days of each survey) and plotted against time separately for summer and winter. The data used in this analysis were collected between the representative sunrise and sunset times shown in table 6-20, in spaces with at least some basic source of natural light. The specific dataset represents approximately 80% of the total sample population in each terminal (78% in LCY, 83% in MAN T1 and 82% in MAN T2). It should be also noted that the time-variable taken into consideration was the start time of each questionnaire, from which the digit representing hours was extracted to label a certain interview. Accordingly, questionnaires conducted from 6:00 am to 6:59 am were regarded as 6 o'clock cases, from 7:00 am to 7:59 am as 7 o'clock cases and so on.

*Table 6-20: Sunrise/sunset times during the seasonal surveys and Pearson correlation coefficients between time and daylight preference votes.*

| | Correlation coefficients | | Sunrise / sunset times** | |
|---|---|---|---|---|
| | Summer | Winter | Summer | Winter |
| LCY | -0.11* | -0.17 | 4:50 / 21:08 | 7:39 / 16:50 |
| MAN T1 | -0.25 | -0.13* | 6:06 / 20:14 | 8:10 / 15:50 |
| MAN T2 | -0.23 | -0.15 | 6:20 / 19:55 | 8:19 / 15:50 |

* Significant at 0.05, all other at 0.01
** Representative times from the median day of the surveys, data from www.sunrisesunsetmap.com

In all terminals the mean preference ranged between “1=more” and “0=no change” and never approached “-1= less”, highlighting the desire for natural light. The plots (figure 6-26) demonstrate a strong preference for more daylight in the morning hours, which later on declines and turns into a preference for “no change” towards the sunset. This seems to suggest that preference for natural light follows the endogenous clock associated to the light-dark cycle. The same figure illustrates the regression lines for summer and winter (a linear relationship was assumed), with $R^2$ values showing that time explains about 80% of the variance in people’s mean preference over natural light during the daytime hours.

While this trend is uniform between the case studies, the change rate of preference varies. Consequently, the cut-off point of time beyond which the preference for “no change” prevails also differs. In winter for instance, preference for more daylight in LCY declined gradually during the day and crossed the line at 0.5 (therefore becomes a preference for “no change”) at 2pm – 3 hours before the sunset. In MAN T1 this occurred 2 hours prior to nightfall, whereas in MAN T2 “no change” prevailed 7 hours before the sunset, since 9am. Similarly in summer, people’s preference for more daylight was eliminated one hour before the sunset in LCY and MAN T1 whilst for MAN T2 this was 6 hours. The sharper drop of mean preference votes and therefore the earlier appearance of “no change” preference in MAN T2 in both summer and winter can be attributed to the abundance of natural light across the terminal’s spaces.

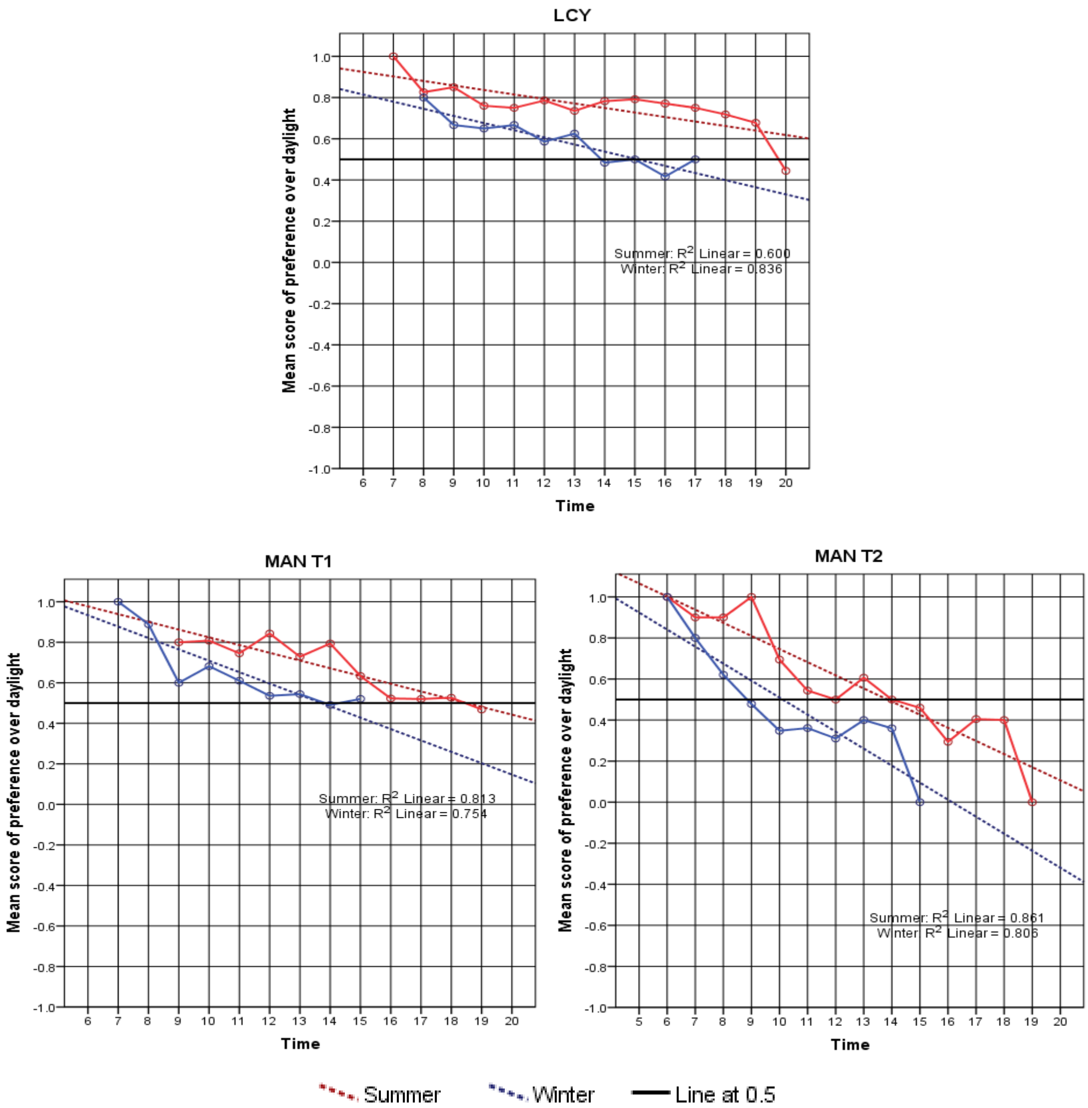



*Figure 6-26: Mean score of preference over the natural light (-1 = prefer less, 0 = no change, 1 = prefer more) in summer and winter. Dotted lines are linear regression lines. Points between 0 and 0.5 denote "no change", while points between 0.5 and 1 denote a mean preference for more natural light.*

### 6.5.6 Importance of indoor environmental conditions

This section places the results presented into the broader context of overall comfort in airport terminals. At first, the investigation focuses on the impact of the environmental parameters on overall comfort by means of the subjective assessments. Subsequently, the second part provides an indirect assessment of perceived importance of the indoor environmental conditions through the terminal aspects people liked or disliked the most.

#### 6.5.6.1 Environmental parameters influencing overall comfort

Where a linear relationship could be generally assumed, correlation analysis was also used as a means to inquire into the relationship between comfort and the subjective assessments, thus revealing the impact of perceived conditions on overall comfort. The assessment of air freshness appears to have a strong influence on comfort in all terminals (0.26 for LCY, 0.21 for MAN T1 and 0.30 for MAN T2, $p<0.01$). The correlation between the binary variable "glare" (question 16) and overall comfort associates the experience of discomfort glare with lower comfort levels (0.11 for LCY and MAN T1, and 0.10 for MAN T2, $p<0.01$). A relationship also exists with the binary variable "lighting distribution" (-0.18 for LCY and -0.17 MAN T1, $p<0.01$); comfort levels tended to drop when lighting was not deemed to be well distributed. Moreover, the correlation with the assessments of natural light denote increased comfort with lower scores of daylight preference (-0.15 for MAN T1 and -0.11 for MAN T2, $p<0.01$), as well as with perceived increasing daylight levels (0.15 for LCY and MAN T2, $p<0.01$).

As far as the subjective evaluation of the thermal environment is concerned, a linear relationship with overall comfort would not be reasonable. This is because comfort levels are normally expected to decrease the farer away from the "neither cold nor hot" the sensation is, at both sides of the ASHRAE scale. Indeed, the plots of the percentage of comfortable people at each TS category reveal a bell-shaped distribution and a quadratic relation between TS and comfort (figure 6-27a). In addition, these plots demonstrate that the difference in the comfort levels between interviewees with TS = 0 and TS = ±1 is very small in all cases. This reflects from a different perspective the finding discussed in section 6.5.2, i.e. neutral is not the desired thermal state for a significant percentage (over 50%) of the population in each terminal building. Similar is also the relationship between TP and overall comfort (figure 6-27b), demonstrating that comfort levels decreased the farer away from "no change" the preference vote was.

Interestingly, overall comfort is also associated with the time people spend in the terminals, with the relationship between the two suggesting less comfort the longer the dwell time was (-0.14 for LCY, -0.16 for MAN T1 and -0.17 for MAN T2, $p<0.01$). Given that most of the relationships between the subjective assessments of the indoor environment and overall comfort are weak and that there is a number of other, environmental, and more importantly non-environmental factors influencing comfort in airport terminals, the increase of overall discomfort with dwell time was rather not environmentally-dependent.

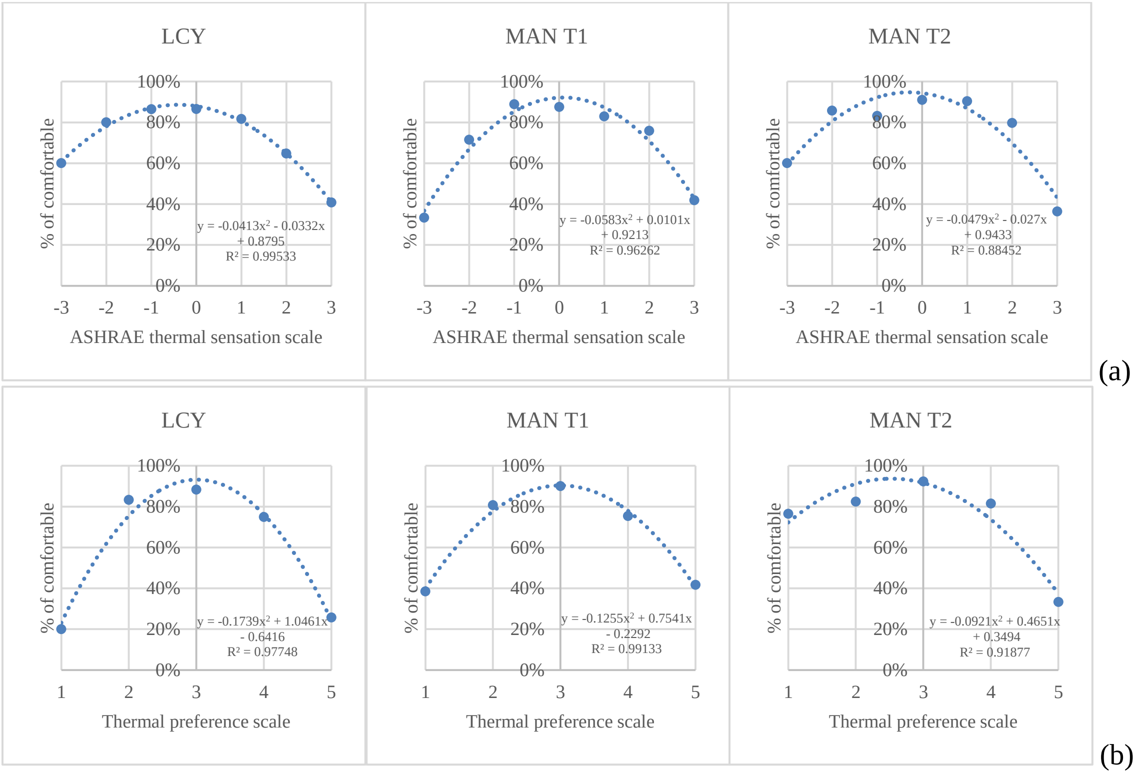



*Figure 6-27: Percentage of comfortable at each (a) thermal sensation and (b) thermal preference category (from 1=much warmer to 5=much cooler).*

Responses with respect to the most important factor in the terminal – among air temperature, air freshness, daylight, air movement and humidity – are remarkably uniform between the case studies. While the assessment of air freshness presented the strongest relationship with comfort, terminal users considered air freshness as the second most important (environmental) factor in the terminal buildings. More specifically, nearly half of the terminal users acknowledged temperature to be more important, followed by air freshness which was identified by approximately 25% of terminal users (figure 6-28). Air movement humidity and daylight share the remaining 25% of votes, with the latter being raised by a marginally higher percentage of people.

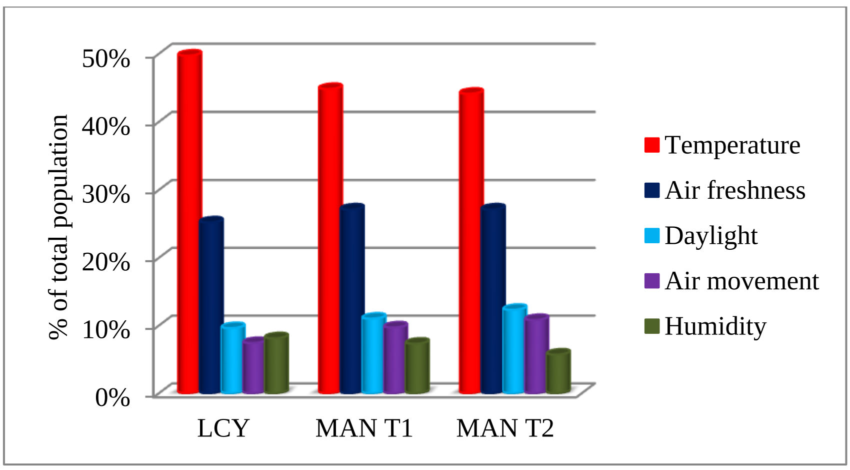



*Figure 6-28: Terminal users evaluating the most important (environmental) factor in the terminal buildings.*

#### 6.5.6.2 Environmental vs. non-environmental factors

There is wide range of issues people were concerned with in the terminal buildings and to some extent this reflects the complexity of providing comfort for all in such facilities. This is the general conclusion drawn from the data regarding the mostly liked and disliked aspects of the terminal buildings. The question then is how important for people are the environmental conditions compared to all other non-environmental "concerns" in terminals. To address this question, it was assumed that a person who reports to like or dislike a certain condition the most views that condition as important (not necessarily the most important).

Accordingly, the raw data from questions 20 and 21 was primarily classified into "environmental" and "non-environmental", thus allowing the relevant evaluation of the two in terms of perceived importance. "Environmental" comprise statements associated to the thermal, lighting and acoustic environment as well as air quality, while all other consist the "non-environmental" category.

In addition, a third category – "nothing particularly" – represents the considerable fraction of people in all terminals who viewed no certain condition as particularly negative or positive. In fact, "nothing particularly" expressed nearly 25% of interviewees in LCY, half the population in MAN T1 and approximately 40% of people in MAN T2, when asked about the aspect they liked the most. Similarly, 30% of interviewees in LCY and MAN T1 found nothing particularly negative, similarly to almost 45% of people in MAN T2.

The results (figure 6-29) are uniform between the case studies and demonstrate that the factors monopolising people's impressions from a positive as well as from a negative point of view were non-environmental. Interestingly, the fraction of people concerned with the environmental conditions was significantly higher in the "dislike" than in the "like" statements. This suggests that the negative impact of the indoor environment on people's terminal experience was stronger than the positive one.

More specifically, 70% of interviewees in LCY and approximately 40% of people in MAN T1 and MAN T2 pointed out non-environmental matters regarding the best aspect. On the other hand, only a small fraction of people (6%, 7% and 15% of interviewees in LCY, MAN T1 and MAN T2 respectively) acknowledged an environmental condition. When the question comes to the aspect disliked the most, the majority of issues raised were also non-environmental, yet the percentage of people highlighting environmental conditions was significantly higher; 23% in LCY and 20% in MAN T1. Exception was MAN T2, where positive and negative responses about the environmental conditions accounted for the same percentage (15%). The origin of the relatively high fraction of people in MAN T2 who reported to like the most a dimension of the indoor environment is revealed in the following analysis.

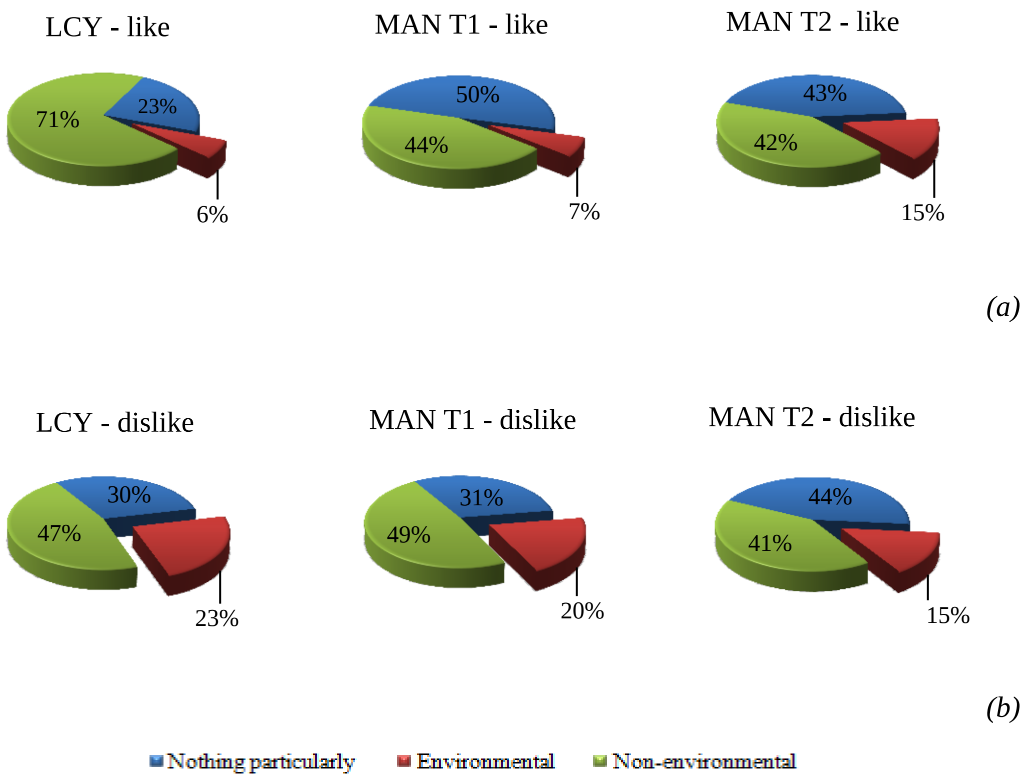



*Figure 6-29: Aspects of the terminal buildings people (a) like the most and (b) dislike the most, classified into nothing particularly, environmental and non-environmental.*

In order to investigate the relevant importance of the four dimensions representing the indoor environment, statements regarding the thermal, lighting and acoustic environment, and air quality were ranked separately (figure 6-30). Along with temperature, the category "thermal environment" comprises responses regarding the air movement and humidity, while "lighting environment" includes comments on both natural and artificial lighting. A number of statements were as simple as "it is too hot", "air-conditioning seems not to be working", "it is bright and airy" and "air feels still". Others associated their response with an explanatory condition, such as "it is stuffy with so many people around", "gets often hot when crowded", "small space, there is no fresh air" and "bright, large windows".

Similarly, the non-environmental responses were classified into ten sub-groups. Representative statements include: "seats are (un)comfortable", "there is not enough seating", "fast check-in", "long queues", "it is spacious", "low ceiling, feels claustrophobic" and "open layout". The category "other" represents a number of unmatched (non-environmental) parameters with significantly lower frequency. For instance, the positive statements "other" refer to topics such staff's friendliness and the quick and/or easy access to the airport (that is relatively high for the case of LCY due to its location and access via DLR). "Other" negative statements comprise issues such as "I dislike the security screening", "staff's behaviour" and the lack of certain facilities (e.g. the lack of a business lounge was a frequent point among the business passengers at LCY).

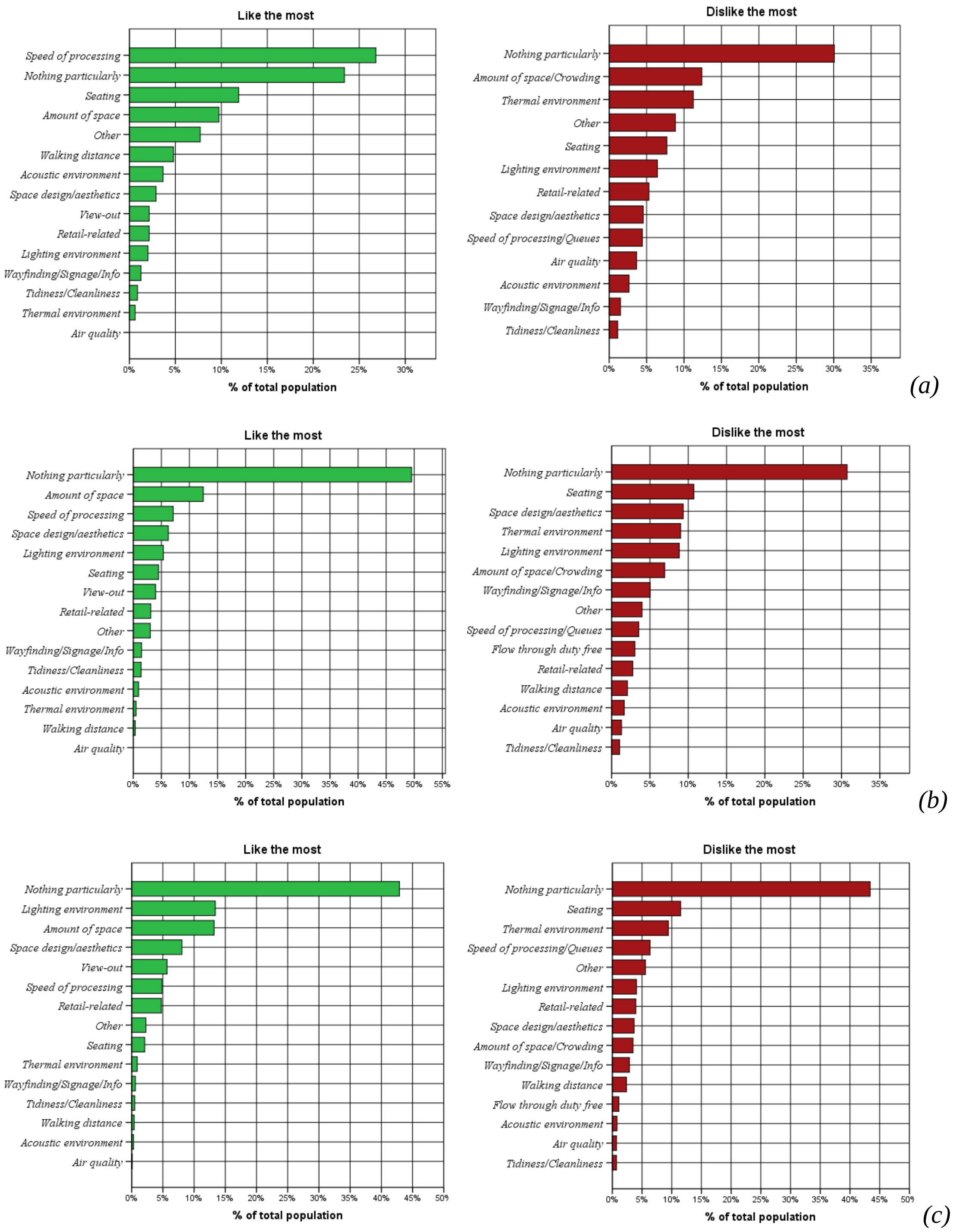



*Figure 6-30: Aspects of the terminal buildings people liked and disliked the most in (a) LCY, (b) MAN T1 and (c) MAN T2.*

The relatively high percentage of people found mostly pleased with the indoor environment in MAN T2 (highlighted in figure 6-29a), was predominantly due to “lighting” and particularly due to the abundance of natural light in most spaces. In fact, MAN T2 is the only building where an environmental factor viewed positively receives such a high rank, exceeding also the non-environmental parameters. Lighting was also the most popular aspect among the environmental conditions in MAN T1, however with significantly lower frequency (ranked 4$^{th}$ overall), and with most of the relevant statements being received in two certain spaces. In LCY, it was the acoustic component of the indoor environment that was mostly appreciated (with the lack of announcements being the most frequently reason reported), yet receiving also a low response (ranked 6$^{th}$ overall).

The inferior ranking of the indoor environmental conditions as compared to the non-environmental ones could be an expected outcome. As shown from the percentage distributions of the “like the most” variable, people in such facilities are mostly concerned with issues such as time (in terms of processing speed), seating and space availability. This is also the case with the “dislike the most” responses. For example, “speed of processing” was the mostly appreciated aspect in LCY (accounting for a percentage higher even than the “nothing particularly” response), while the worst one was the “amount of space/crowding”. Similarly, “amount of space” was ranked 1$^{st}$ among the positively perceived conditions in MAN T1 and MAN T2, with “seating” being the aspect deemed as the worst in both terminals.

On the other hand, environmental conditions were among the foremost issues raised negatively, with the results demonstrating the higher perceived importance of the thermal environment as compared to the other three dimensions of indoor comfort. More specifically, “thermal environment” was highlighted by nearly 10% of the interviewees in all terminals and ranked 2$^{nd}$ among the worst aspects of LCY and MAN T2 and 3$^{rd}$ in MAN T1.

Further to this point, figure 6-31 focuses on the people with TS = ±2, ±3. In this case, “thermal environment” is ranked first among all other environmental and non-environmental factors in all terminal buildings. The fact that only a small fraction of people who experienced unacceptable TS considered the thermal environment as the worst terminal aspect – 30% in LCY, 20% in MAN T1 and 25% in MAN T2 (as shown in figure 6-31) – could also be viewed as a form of adaptation. Overall, the results show that thermal conditions were not considered important unless people’s expectations were not met and the conditions were deemed to be unsatisfactory.

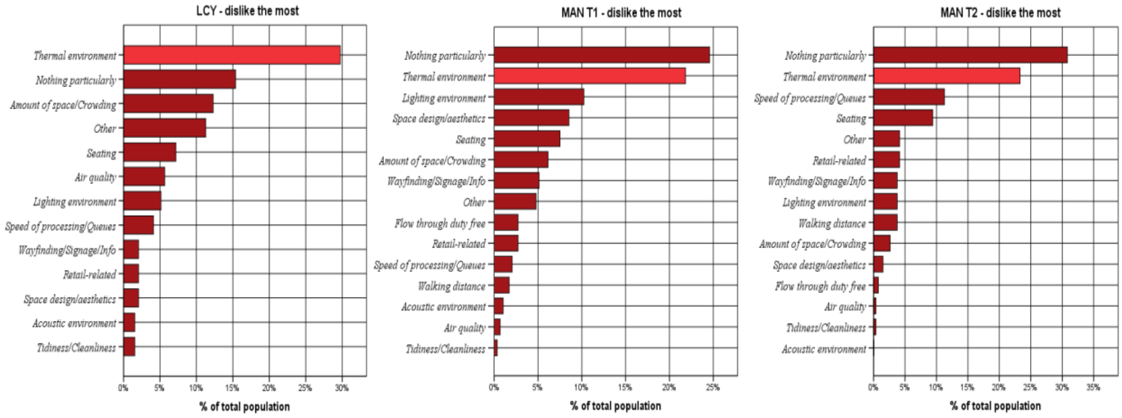



*Figure 6-31: The thermal environment becomes the most important issue for people who experience unacceptable TS.*

## 6.6 The comfort gap between passengers and staff

This section focuses on the evaluation of indoor comfort conditions separately for passengers and staff. Provided the satisfaction gap revealed in section 6.4.2, the hypothesis is that the two groups have different comfort requirements.

### 6.6.1 Assessment of thermal environment

Preliminary evidence for the hypothesis provides the investigation of TS and TP profiles, revealing significant differences between the two groups in all terminal buildings.

#### 6.6.1.1 Thermal sensation

The profile of TS is representative of the different way the two groups experienced the thermal environment (figure 6-32). The extensive majority of passengers handled in LCY (90%) reported acceptable TS in summer, when “neutral” (41%) and “slightly warm” (35%) were the most frequently experienced sensations. The same percentage shifted towards warmer votes in winter, with only 20% of passengers feeling “neutral” and the bulk of sensations referring to “slightly warm” (42%) and “warm” (28%).These three categories expressed also the majority of passengers in MAN T1 and MAN T2 (nearly 80%) in both summer and winter, when “slightly warm” had the lead in most cases and represented the thermal condition of at least one out of three passengers.

In all terminals, the fraction of passengers reporting “cool” and “cold” TS was negligible. On the contrary, the percentage of passengers experiencing unacceptable TS on the warm side of the ASHRAE scale was considerable in both seasons. This was the case with 20% of passengers in MAN T1 and MAN T2 in summer, rising to 25% in winter, and with 30% of passengers using LCY in winter.

Employees, however, experienced more unacceptable sensations than passengers in summer and winter. This is demonstrated from the wider distribution of TS for staff and is validated statistically from the higher standard deviation of staff's mean TS in all cases. More specifically, unacceptable TS expressed at least one out of three employees in each terminal, increasing to almost half (47%) in LCY during summer (table 6-21). On the contrary, such sensations were experienced from 10-31% of passengers with the highest percentages found in winter, predominantly from "warm" votes.

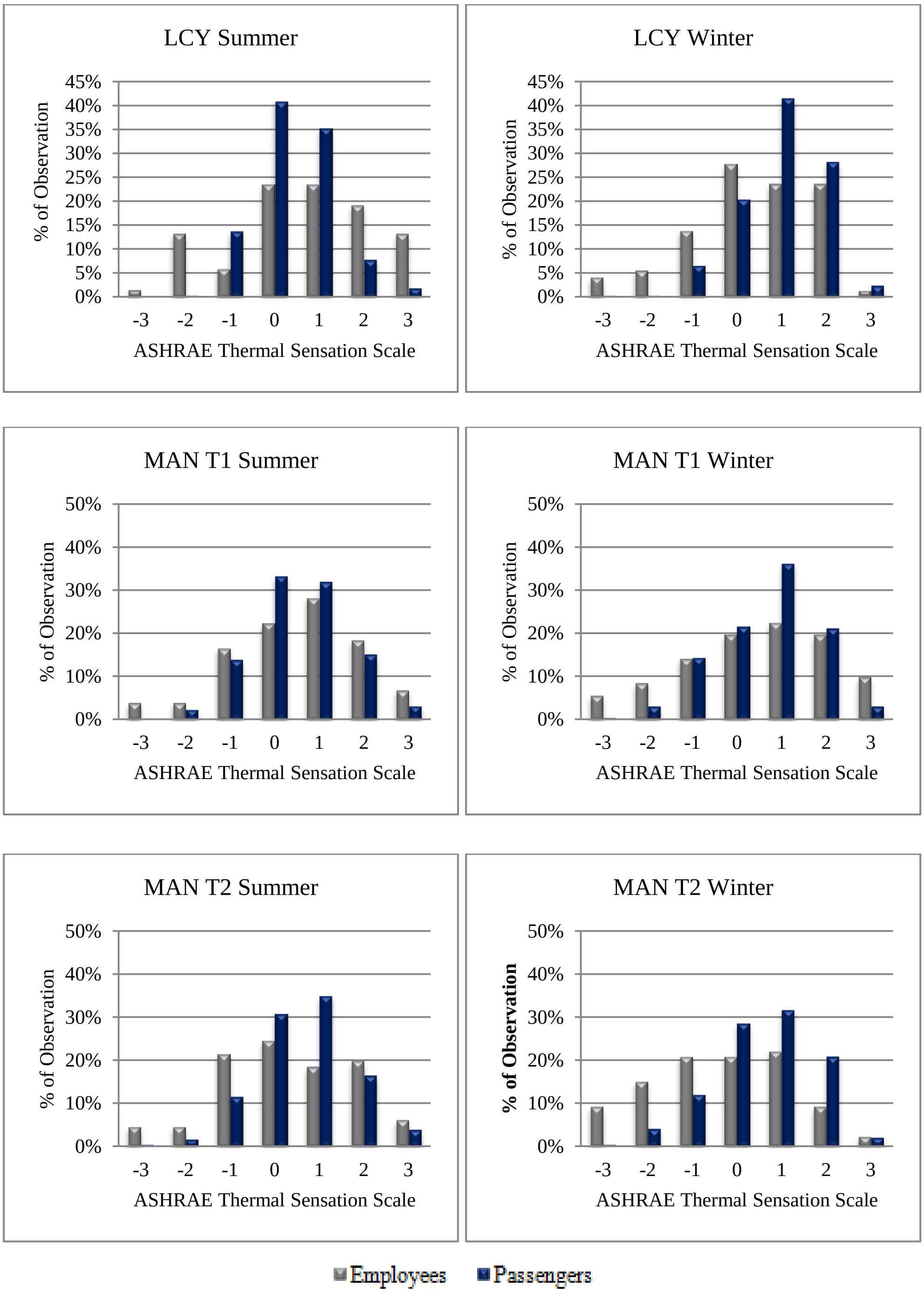



*Figure 6-32: Percentage distribution of thermal sensation for passengers and staff in summer and winter.*

Similarly to passengers, most of the unacceptable TS votes reported by employees lie on the warm side of the ASHRAE scale. In particular, "warm" and "hot" represented together the TS of 12-32% of staff, with the highest percentage found for LCY staff in summer. On the other hand, and unlike passengers, the frequency of "cool" and "cold" sensations was considerably higher among employees. While no more than 5% of passengers experienced such sensation in the three terminals, the corresponding percentage for employees varied between the case studies and ranged from 8% to 25%, with the latter found in MAN T2 during winter.

A seasonal difference is also revealed in respect to the mean TS of the two population groups. Staff in all three terminals presented lower mean TS in winter than in summer, with the most significant seasonal difference – 1 unit on the ASHRAE scale – found in MAN T2 (table 6-21). On the contrary, passengers' mean TS increased in winter (with the exception of T2), due to the higher clothing insulation worn, particularly at LCY and MAN T1 (table 6-6).

*Table 6-21: 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% |

#### 6.6.1.2 Thermal preference

The mean scores of TP for passengers and staff were very close in most cases (table 6-22). Exceptions are LCY and MAN T2 in winter, where passengers' mean score was 0.6 and 0.5 units higher than employees' with the difference being statistically significant at $p<0.001$. These were also the two cases with the largest difference in the mean TS score of the two groups (table 6-21).

*Table 6-22: Mean score and standard deviation of thermal preference for staff and passengers.*

| | | Employees | | Passengers | |
|---|---|---|---|---|---|
| | | Mean TP* | SD | Mean TP* | SD |
| Summer | LCY | 3.5 | 0.87 | 3.4 | 0.67 |
| | MAN T1 | 3.3 | 0.95 | 3.4 | 0.71 |
| | MAN T2 | 3.4 | 0.98 | 3.3 | 0.72 |
| Winter | LCY | 3.0 | 0.96 | 3.6 | 0.65 |
| | MAN T1 | 3.1 | 1.07 | 3.2 | 0.73 |
| | MAN T2 | 2.7 | 1.00 | 3.2 | 0.66 |

* Thermal preference: from 1=much warmer to 5=much cooler

Figure 6-33 illustrates the percentage distribution of TP votes for passengers and staff. Reflecting the proportionally more unacceptable votes experienced by employees, the distribution for staff is wider than passengers' in summer and winter, in all terminals. Statistically, this is confirmed by the higher standard deviations associated to staff's TP votes (table 6-22).

Common between employees in the three terminal buildings was the preference for a change in the thermal environment, as expressed by approximately 70% of staff in each terminal in both summer and winter. Among those requiring a change, the majority preferred cooler conditions in most cases. Exception is MAN T2 where nearly 40% of employees preferred a warmer thermal environment in winter. In MAN T1, the majority of staff desiring a change preferred to be cooler in both seasons. However, the fraction of employees preferring warmer conditions was significantly increased in winter (31%), thus highlighting the cool conditions prevailing in this period of time in certain spaces of the terminal.

Passengers' TP profile was rather consistent among the case studies in summer; nearly half were satisfied with the thermal conditions, whilst the vast majority of those requiring a change preferred a cooler environment. On the other hand, the profile for passengers varied between the terminals in winter. In LCY nearly 60% of passengers preferred to be cooler, underlying the overheating problem highlighted in sections 6.5.2 and 6.5.4 for this terminal. However, this is the case with only one out of three employees in LCY during winter, with the other two thirds being equally distributed between the preferences for no change and for a warmer environment. This suggests that overheating in winter was an issue for the passenger rather than the staff population. Almost half the passengers in MAN T1 found the thermal environment 'just right' in winter, while widespread among those requiring a change was the preference for a cooler environment. With over 60% of passengers preferring "no change" in winter, MAN T2 presented the highest thermal satisfaction rate for passengers in both seasons.

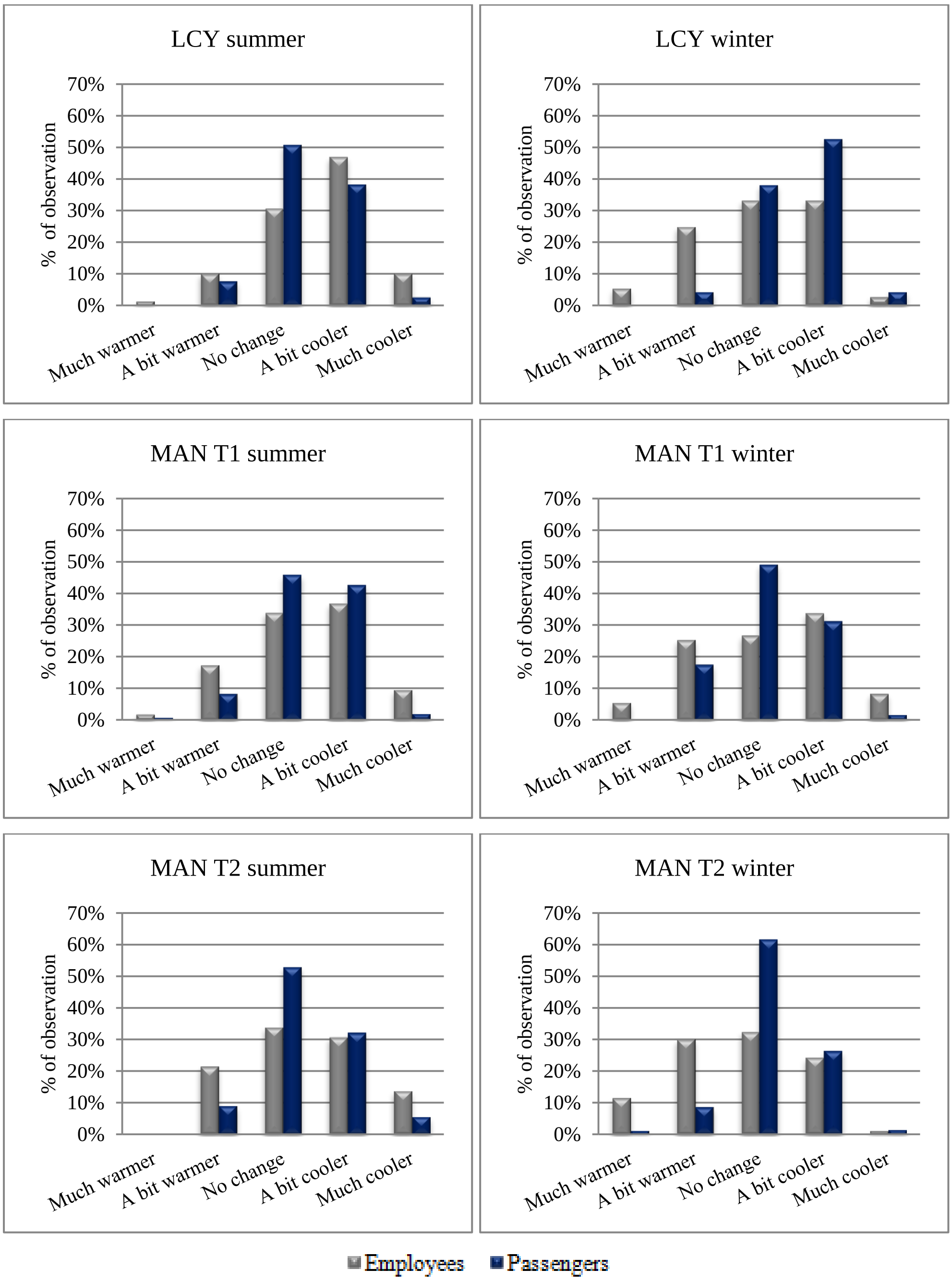



*Figure 6-33: Percentage distribution of thermal preference votes for passengers and staff.*

The analysis for the total population demonstrated that neutral was not the desired TS for the majority of people (figure 6-13). To investigate whether this was the case with passengers and staff, TS and TP were cross-examined separately for each group (figure 6-34). Under the assumption of equality between the preference for no change and thermal satisfaction, the results show that 51%, 64% and 62% of passengers satisfied with the thermal environment in LCY, MAN T1 and MAN T2 had reported TS other than neutral. Similarly, 53%, 57% and 61% of employees in LCY, MAN T1 and MAN T2 who required no change in the thermal conditions were in a non-neutral thermal state.

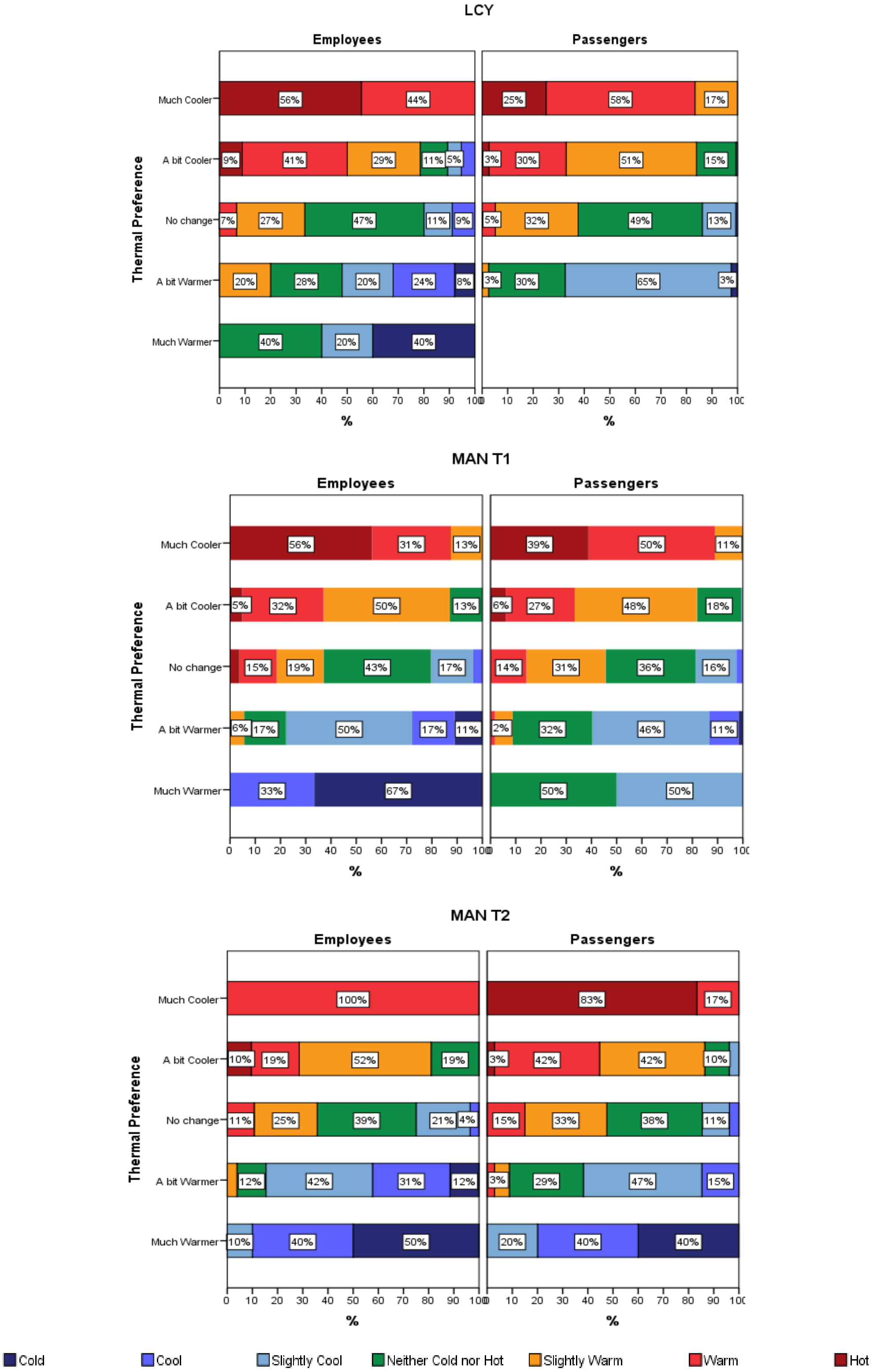



*Figure 6-34: Breakdown of passengers' and staff's thermal sensation votes for each thermal preference category.*

### 6.6.2 Quantifying the thermal conflict

The calculation of neutral and preferred temperatures is the focus of this section. The results show that passengers require cooler temperatures than staff, are more tolerant of the thermal conditions and have a wider acceptability temperature range in all cases.

#### 6.6.2.1 Neutral temperature

Aimed at quantifying the thermal requirements for the two main population groups, neutral temperatures and acceptability temperature ranges were calculated separately for passengers and staff. Working with weighted linear regressions, the mean TS of each group was determined for each half-degree (ºC) increment of operative temperature (tables F-6 to F-11 in appendix F). The mean TS was regressed against operative temperature and neutral temperatures were subsequently obtained by solving the regression equations for TS = 0. Similar process was followed to produce PMV-based regression models. All presented models are significant at the 99% level.

The gradient of the regression models (figure 6-35) indicate that employees were on average 1.6 times more sensitive to temperature changes than passengers in both seasons. Consequently, the TS change rate differed significantly between the two groups, with employees' rate being lower in all cases. More specifically, 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 during summer, whilst passengers' TS would not be altered with temperature changes below 4.1 °C, 3.5 °C and 3.7 °C respectively. Similarly in winter, the TS change rate for staff working in MAN T1 and MAN T2 was one unit for every 2.9 ºC and 2.7 ºC temperature change, whereas for passengers that was 3.3 ºC and 4.5 ºC. In LCY, both population groups presented higher thermal sensitivity in winter, when a temperature rise of only 1.3 ºC was sufficient to increase employees' TS by one unit, rising to 2.5 ºC for passengers.

The results (table 6-23) demonstrate that neutrality for staff was achieved in most cases at temperatures cooler than the mean indoor temperature, with the respective difference being nearly 1.0 °C. More specifically, neutral temperature for employees in summer was lower than the mean temperature by 1.2 °C in LCY, 0.9 °C in MAN T1 and by 0.6 °C in MAN T2. Essentially unchanged are the results for winter, when staff's neutrality lay 0.9 °C and 0.7 °C below the mean temperature in LCY and MAN T1 respectively. However, an exception in this pattern is MAN T2 where employees' neutral temperature in winter was 1.2 °C higher than the mean indoor temperature. This is a result of the operational particularity of this terminal in winter, when periods of very low passenger traffic dominated the occupancy profile subsequent to the daily main occupancy peak early in the morning. Consequently, there were prolonged periods of time with low temperatures prevailing across the different spaces of the terminal; characteristically, MAN T2 presented the lowest mean indoor temperature in winter. Along with the reduced activity levels of staff during these periods, this resulted in a comfortable temperature "warmer" than the mean temperature.

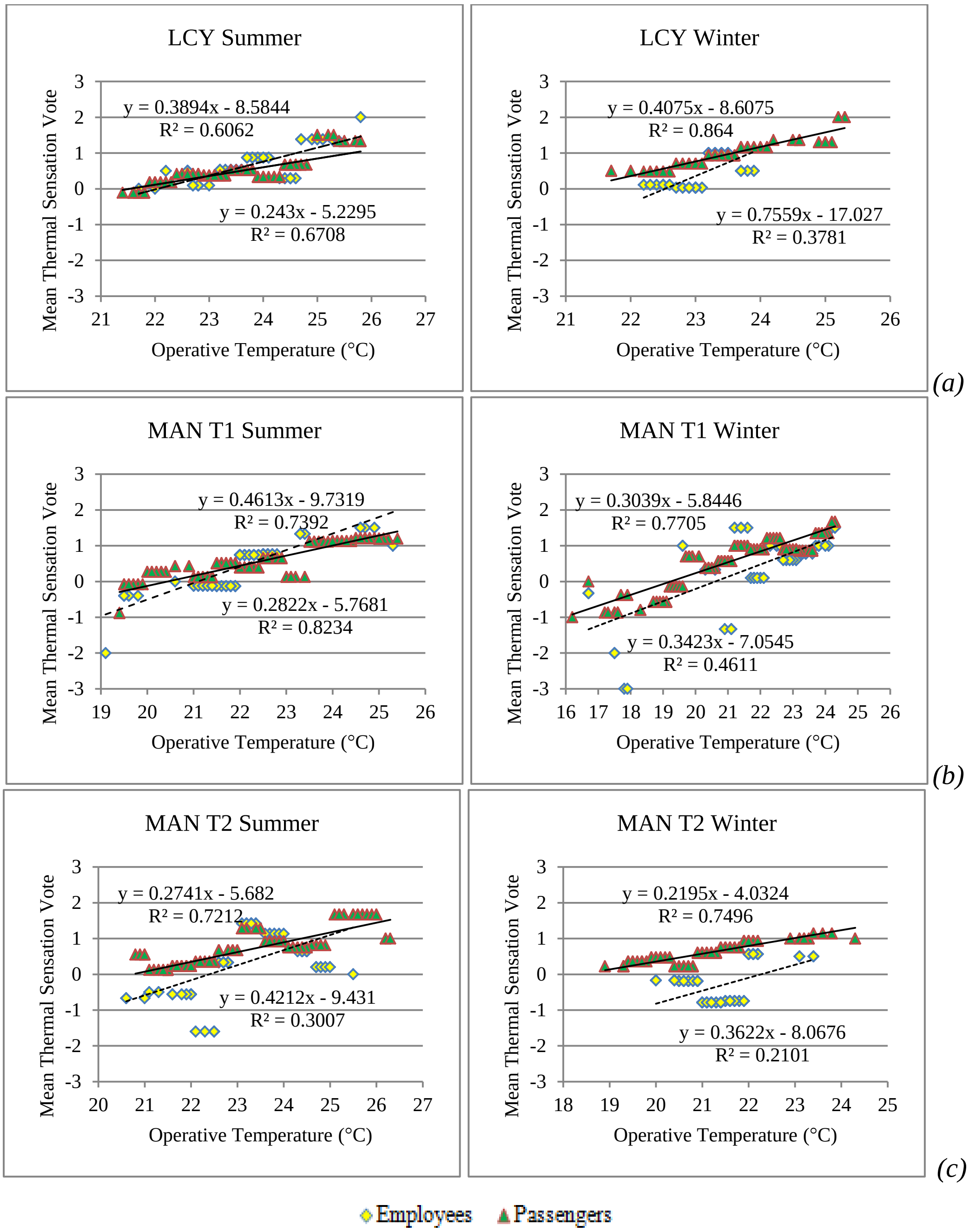



*Figure 6-35: Relationship between thermal sensation and operative temperature for passengers and staff in (a) LCY, (b) MAN T1 and (c) MAN T2.*

Likewise employees, passengers in all terminals were comfortable at cooler temperatures than the mean temperature in summer and winter. More specifically, in summer, the difference between mean indoor temperature and passengers' neutral temperature was 1.8 °C in LCY, 1.5 °C in MAN T1 and 2.3 °C in MAN T2, rising to 2.3 °C in LCY, 2.1 °C in MAN T1 and 2.7 °C in MAN T2 in winter.

*Table 6-23: TS regression models, neutral temperatures (°C) and acceptability ranges (°C) in summer and winter.*

| Season | Group | Terminal | Gradient | $R^2$ | $T_{neutral}$ (°C) | 80% accept. (°C) | 90% accept. (°C) |
|---|---|---|---|---|---|---|---|
| Summer | Employees | LCY | 0.389 | 0.61 | 22.1 | 19.9 - 24.3 | 20.8 - 23.4 |
| | | MAN T1 | 0.461 | 0.74 | 21.1 | 19.3 - 23.0 | 20.0 - 22.2 |
| | | MAN T2 | 0.421 | 0.30 | 22.4 | 20.4 - 24.4 | 21.2 - 23.6 |
| | Passengers | LCY | 0.243 | 0.67 | 21.5 | 18.0 - 25.0 | 19.5 - 23.6 |
| | | MAN T1 | 0.282 | 0.82 | 20.5 | 17.4 - 23.5 | 18.7 - 22.2 |
| | | MAN T2 | 0.274 | 0.72 | 20.7 | 17.6 - 23.8 | 18.9 - 22.6 |
| Winter | Employees | LCY | 0.756 | 0.38 | 22.5 | 21.4 - 23.6 | 21.9 - 23.2 |
| | | MAN T1 | 0.342 | 0.46 | 20.6 | 18.1 - 23.1 | 19.2 - 22.1 |
| | | MAN T2 | 0.362 | 0.21 | 22.3 | 19.9 - 24.6 | 20.9 - 23.7 |
| | Passengers | LCY | 0.407 | 0.86 | 21.1 | 19.1 - 23.2 | 19.9 - 22.4 |
| | | MAN T1 | 0.304 | 0.77 | 19.2 | 16.4 - 22.0 | 17.6 - 20.9 |
| | | MAN T2 | 0.219 | 0.75 | 18.4 | 14.5 - 22.3 | 16.1 - 20.7 |

These results provide solid evidence for the discrete thermal requirements between passengers and staff. Both populations achieved neutrality at temperatures lower than the mean indoor temperature, but were comfortable at different temperatures in summer and winter. Neutral temperature for staff was "warmer" than passengers' in all cases, with the difference between the two being lower in summer and notably higher in winter when "clothing insulation" was a differentiating factor. Accordingly, neutral temperature for employees in LCY and MAN T1 was higher by 0.6 °C than passengers' in summer, while the difference rose to 1.4 °C in winter. The corresponding difference was greater in MAN T2, where staff achieved neutrality at temperatures higher by 1.7 °C in summer and by 3.9 °C in winter, despite the similar clothing insulation worn by the two groups in that terminal in both seasons.

Additionally, the results demonstrate that in all terminals comfortable temperature for staff was closer to the mean indoor temperature. In fact, this reflects employees' long-term adaptation to the terminals' indoor environment developed from the long dwell times and continuous experience with it. The diverse thermal requirements for passengers and staff are further highlighted from the temperature ranges the two groups find acceptable (table 6-23). In all terminals, employees presented a narrower acceptability range in summer as well as in winter. The 80% acceptability range was on average 4.0 °C wide for staff and 6.0 °C wide for passengers, shrank to 2.4 °C and 3.5 °C for employees and passengers respectively when considering the 90% acceptability range.

On the other hand, the figures derived from the PMV regression models (table 6-24) are far from those obtained by TS regression models. A graphical comparison to TS-based models is provided in appendix E. The PMV-based results suggest that both groups were comfortable at higher temperatures than the mean indoor temperature in both seasons and in most cases implies higher neutral temperatures for passengers. In fact, the predicted neutral temperature for employees and passengers is on average 3.5 °C and 5.3 °C higher than the corresponding actual neutral temperature, resulting also in acceptability temperature ranges that are inconsistent to mechanically ventilated environments in a mild climatic zone.

*Table 6-24: PMV regression models, neutral temperatures (°C) and acceptability ranges (°C) in summer and winter.*

| | | | Gradient | $R^2$ | $T_{neutral}$ (°C) | 80% Accept. (°C) | 90% Accept. (°C) |
|---|---|---|---|---|---|---|---|
| Summer | Employees | LCY | 0.218 | 0.76 | 24.8 | 20.9 - 28.7 | 22.5 - 27.1 |
| | | MAN T1 | 0.285 | 0.84 | 25.2 | 22.3 - 28.2 | 23.5 - 27.0 |
| | | MAN T2 | 0.282 | 0.83 | 25.7 | 22.6 - 28.7 | 23.9 - 27.4 |
| | Passengers | LCY | 0.102 | 0.31 | 28.6 | 20.2 - 36.9 | 23.7 - 33.5 |
| | | MAN T1 | 0.227 | 0.78 | 26.8 | 23.1 - 30.5 | 24.6 - 29.0 |
| | | MAN T2 | 0.347 | 0.94 | 26.0 | 23.6 - 28.5 | 24.6 - 27.5 |
| Winter | Employees | LCY | 0.088 | 0.07 | 24.1 | 14.4 - 33.8 | 18.4 - 29.8 |
| | | MAN T1 | 0.172 | 0.66 | 25.9 | 20.9 - 30.8 | 23.0 - 28.8 |
| | | MAN T2 | 0.168 | 0.45 | 26.0 | 21.0 - 31.1 | 23.1 - 29.0 |
| | Passengers | LCY | 0.150 | 0.67 | 22.1 | 16.4 - 27.8 | 18.8 - 25.4 |
| | | MAN T1 | 0.259 | 0.79 | 23.3 | 20.0 - 26.6 | 21.4 - 25.2 |
| | | MAN T2 | 0.164 | 0.69 | 26.3 | 21.2 - 31.5 | 23.3 - 29.4 |

#### 6.6.2.2 Preferred temperature

Similarly to the methodology adopted for the total sample population, preferred temperatures were calculated separately for passengers and staff by means of weighted linear regressions. Thermal preference was transformed into a 3-point variable by merging the preferences “a bit warmer” and “much warmer” into “prefer warmer” and the votes for “a bit cooler” and “much cooler” into “prefer cooler” (figure 6-36).

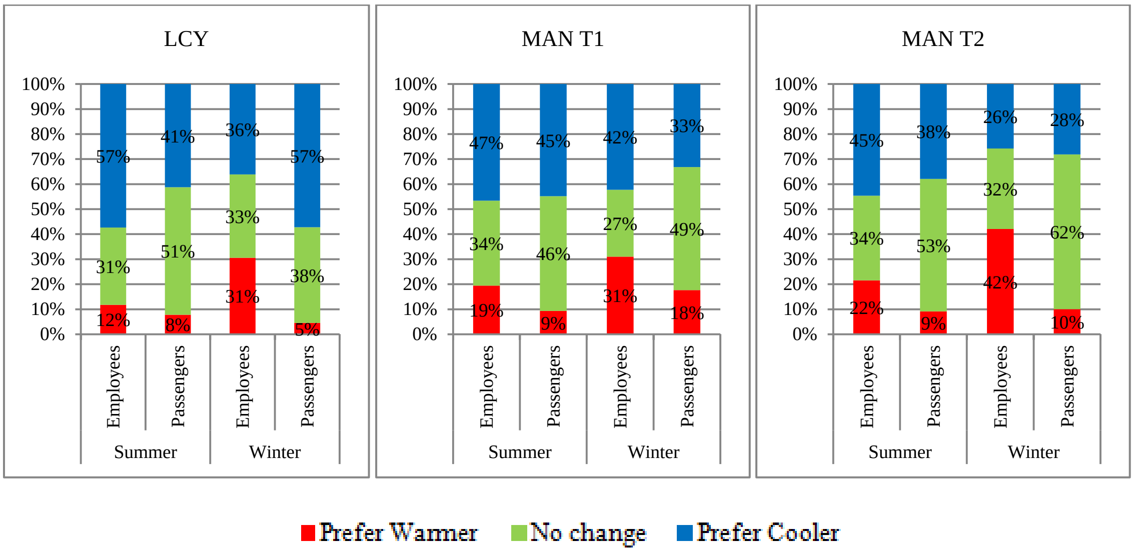
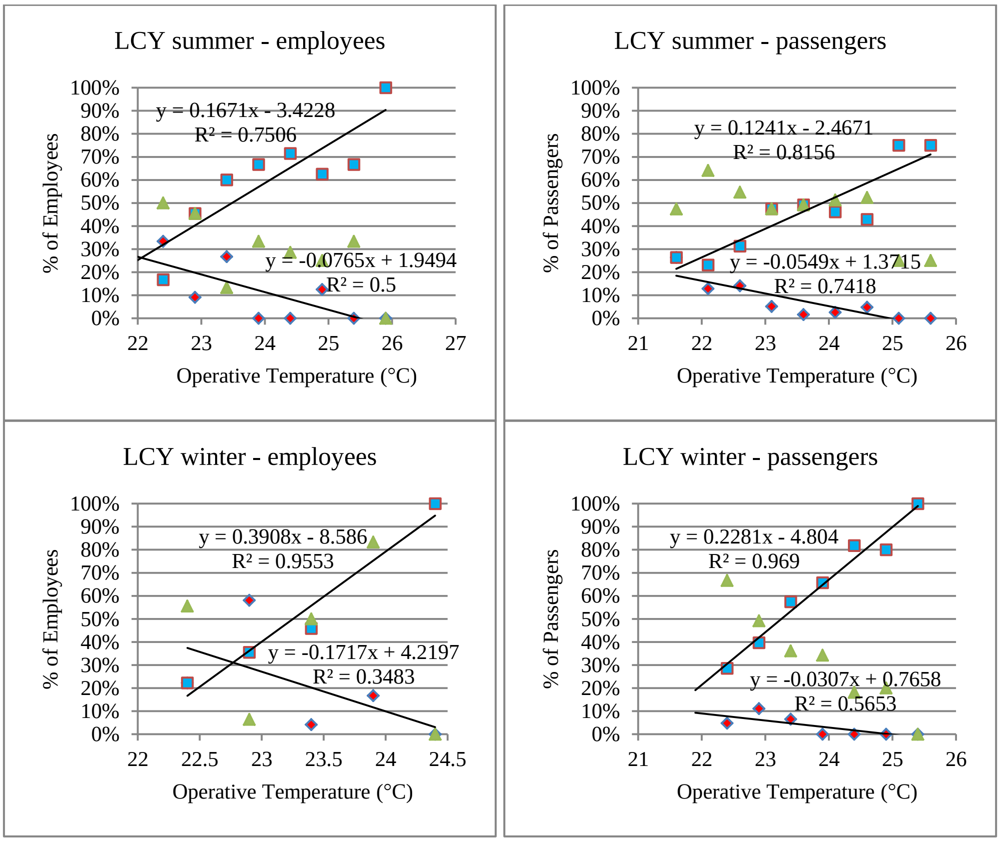



*Figure 6-36: Percentage distribution of binned thermal preference votes for passengers and staff.*

The percentages of "prefer cooler" and "prefer warmer" votes were calculated for each half-degree (ºC) increment while using the sample size of each bin as weighting factor. The "prefer cooler" and "prefer warmer" percentages were then regressed separately against operative temperature, with the intersection of the two regression lines marking the preferred operative temperatures as shown in figure 6-37.



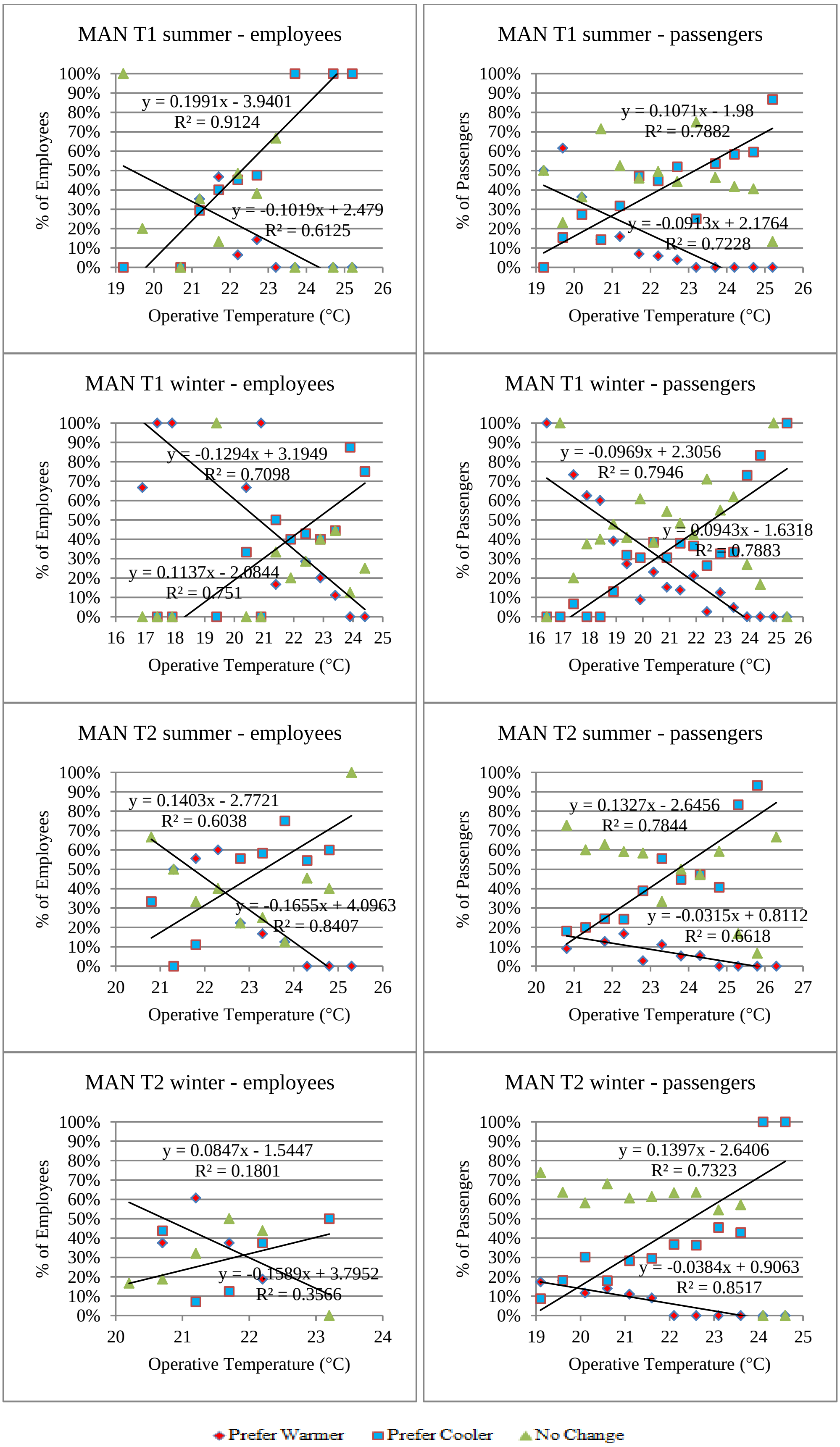



*Figure 6-37: Calculation of operative temperatures preferred by passengers and staff.*

The results (table 6-25) demonstrate that passengers in all terminals preferred lower temperatures than the mean temperature experienced in both seasons. For instance, passengers' preferred temperature in MAN T1 lay 1.1 °C and 0.7 °C below the indoor temperature in summer and winter respectively. Passengers in MAN T2 preferred the thermal environment to be cooler by 1.2 °C in winter and by 1.9 °C in summer. The latter was the highest difference found between preferred and mean temperature and was also the case with LCY passengers, whose preferred temperature was lower than the terminal's mean indoor temperature by 1.9 °C in both summer and winter.

*Table 6-25: Preferred temperatures for passengers and staff compared to neutral and mean indoor temperatures.*

| | | | $T_{mean}$ (°C) | $T_{neutral}$ (°C) | $T_{pref.}$ (°C) |
|---|---|---|---|---|---|
| LCY | Summer | Employees | 23.3 | 22.1 | 22.1 |
| | | Passengers | | 21.5 | 21.4 |
| | Winter | Employees | 23.4 | 22.5 | 22.8 |
| | | Passengers | | 21.1 | 21.5 |
| MAN T1 | Summer | Employees | 22.0 | 21.1 | 21.3 |
| | | Passengers | | 20.5 | 20.9 |
| | Winter | Employees | 21.3 | 20.6 | 21.7 |
| | | Passengers | | 19.2 | 20.6 |
| MAN T2 | Summer | Employees | 23.0 | 22.4 | 22.5 |
| | | Passengers | | 20.7 | 21.1 |
| | Winter | Employees | 21.1 | 22.3 | 21.9 |
| | | Passengers | | 18.4 | 19.9 |

Preferred temperatures for passengers confirm the profile of their neutral temperatures with the two being very close in most cases. More specifically, preferred temperature was only 0.4 °C higher than neutral temperature in MAN T1 and MAN T2 during summer, similarly to LCY in winter, while the two almost coincided in LCY during summer. Exceptions however are the cases of MAN T1 and MAN T2 in winter where the lowest operative temperatures were observed, and as a result passengers preferred temperatures 1.4 °C and 1.5 °C higher than the their neutral temperature. This demonstrates passengers' tolerance over cooler conditions, while a comparison with the respective figures for staff in these two terminals in winter suggests that passengers were significantly more tolerant of cooler conditions than staff. More specifically, in

MAN T1 where the mean indoor temperature was 21.3 °C in winter, staff achieved neutrality at 20.6 °C but preferred this to rise to 21.7 °C (slightly higher than the mean temperature). On the other hand, passengers achieved neutrality at 19.2 ºC and preferred this to rise to 20.6 ºC. Similarly, in MAN T2 the mean temperature was 21.1 ºC in winter when employees preferred it to be 21.9 ºC (also higher than the mean temperature) and achieved neutrality at 22.3 ºC. However, passengers preferred 19.9 ºC and were still comfortable at (the neutral temperature of) 18.4 ºC, thus demonstrating higher levels of tolerance of cooler temperatures.

Beyond the two cases of MAN T1 and MAN T2 in winter where staff's preferred temperature was higher than the mean indoor temperature by 0.4 ºC and 0.8 ºC, the results show that in all other cases, and similarly to passengers, employees preferred temperatures cooler than the mean temperature experienced. More precisely, preferred temperature for staff was 1.2 ºC, 0.7 ºC and 0.5 ºC below the mean temperature in LCY, MAN T1 and MAN T2 respectively in summer and by 0.6 ºC in LCY during winter. Similarly to passengers, neutral and preferred temperatures for staff were very close to each other with the respective difference being - in absolute values - in the range of 0.0-0.4 ºC. This applies to all cases except from that of MAN T1 in winter where employees' preferred temperature was 1.1 ºC higher than their neutral temperature.

Overall, the results demonstrate that passengers (in all cases) and staff (with the exception of MAN T1 and MAN T2 in winter) prefer a cooler thermal environment than the one experienced. However, in all terminals passengers prefer lower temperatures than staff in both seasons. The preferred temperatures for the two groups differed by 0.4 ºC - 2.0 ºC, with the wider differences encountered in all case studies during winter. One of the highest differences, 1.3 ºC, was in LCY where the warm conditions in winter were an issue for passengers but not for staff. The most significant difference, however, was found in MAN T2 where staff preferred warmer – by 1.4 ºC in summer and by 2.0 ºC winter – temperatures than passengers. In accordance with the profile of neutral temperatures for the two groups, employees' preferred temperature was constantly closer to the mean indoor temperature, thus reflecting their long-term acclimatisation with the thermal environment in the terminal buildings.

### 6.6.3 The lighting environment

Figure 6-38a illustrates the percentage distribution of lighting sensation as derived from both summer and winter data. Rounded up to the nearest integer, the overall mean lighting sensation for passengers and staff was "neither bright nor dim" for LCY and MAN T1 and "slightly bright" for MAN T2.

Correlation analysis shows that the relationship between illuminance and respective sensation is of similar strength for among employees (0.22 in LCY, 0.25 in MAN T1 and MAN T2, $p<0.01$), as well as between passengers in the three terminals (0.34 in LCY, 0.33 in MAN T1 and 0.35 in MAN T2, $p<0.01$). Statistically, the relationship is weak for staff and moderate for passengers. The higher correlation coefficients for passengers and the consistency of that difference between the case studies imply that employees' assessment was more dependent on other issues, while for passengers was more objective towards the actual illuminance.

The overall mean lighting preference rounds up to "no change" for both groups in all terminals. However, the respective percentage distributions differ significantly (figure 6-38b). The majority of passengers - nearly 70% in all cases - found the lighting environment "just right", with most preferences for a change referring to a brighter environment. On the other hand, the distribution for staff is wider in all cases; only a narrow majority (55%) of employees in MAN T2 were satisfied with the lighting environment, while such an assessment did not represent more than 45% of staff in LCY and MAN T1.

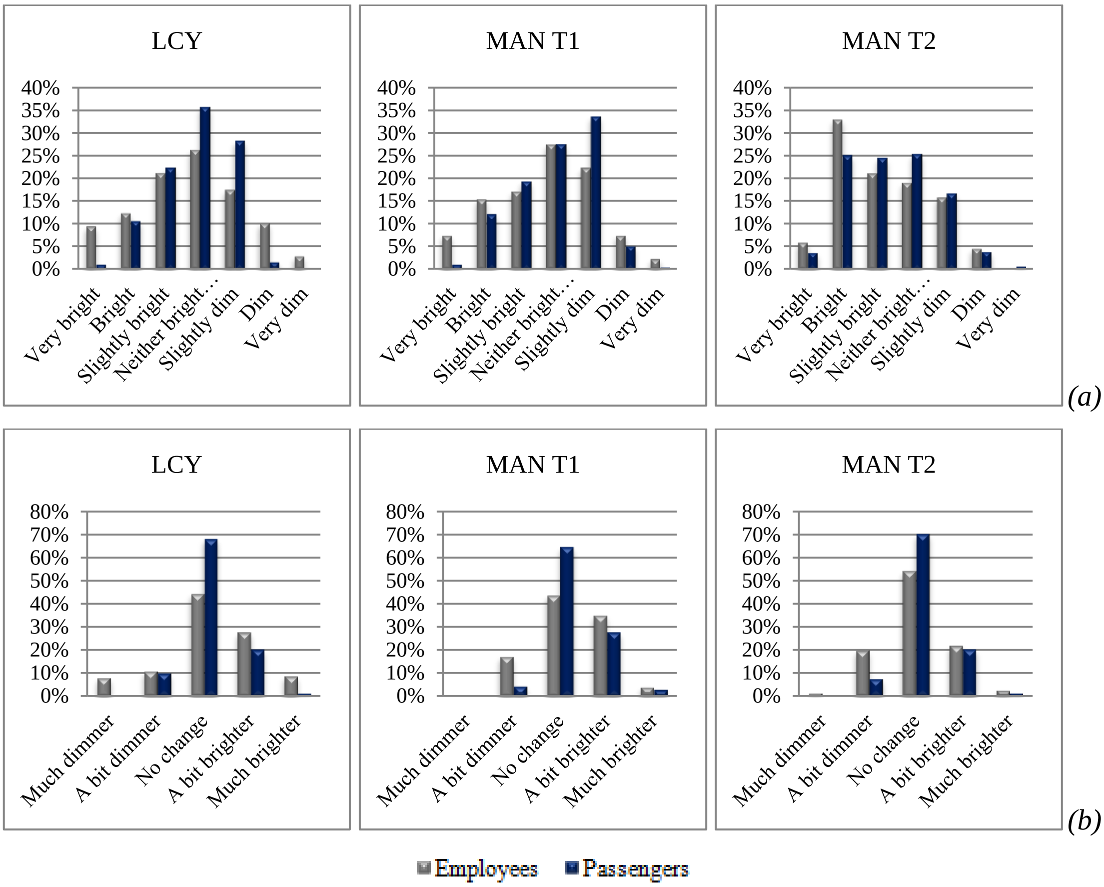



*Figure 6-38: Percentage distribution of (a) lighting sensation and (b) lighting preference for passengers and staff.*

Unlike passengers, there was a significant percentage of employees (about 20% in all terminals) who preferred a dimmer environment. Such preference was expressed in a range of terminal areas but the bulk comes from certain spaces. These include the departures lounges 1 and 2 in LCY, the daylit departures lounge 1 in MAN T1, the check-in and arrivals halls in MAN T2 as well as all the retail areas which were among the brightest (artificially lit) spaces. Along with the fluctuation of the mean lighting sensation and preference across the different terminal spaces (figure 6-39), this reflects the different lighting requirements between the various types of staff within a terminal building.

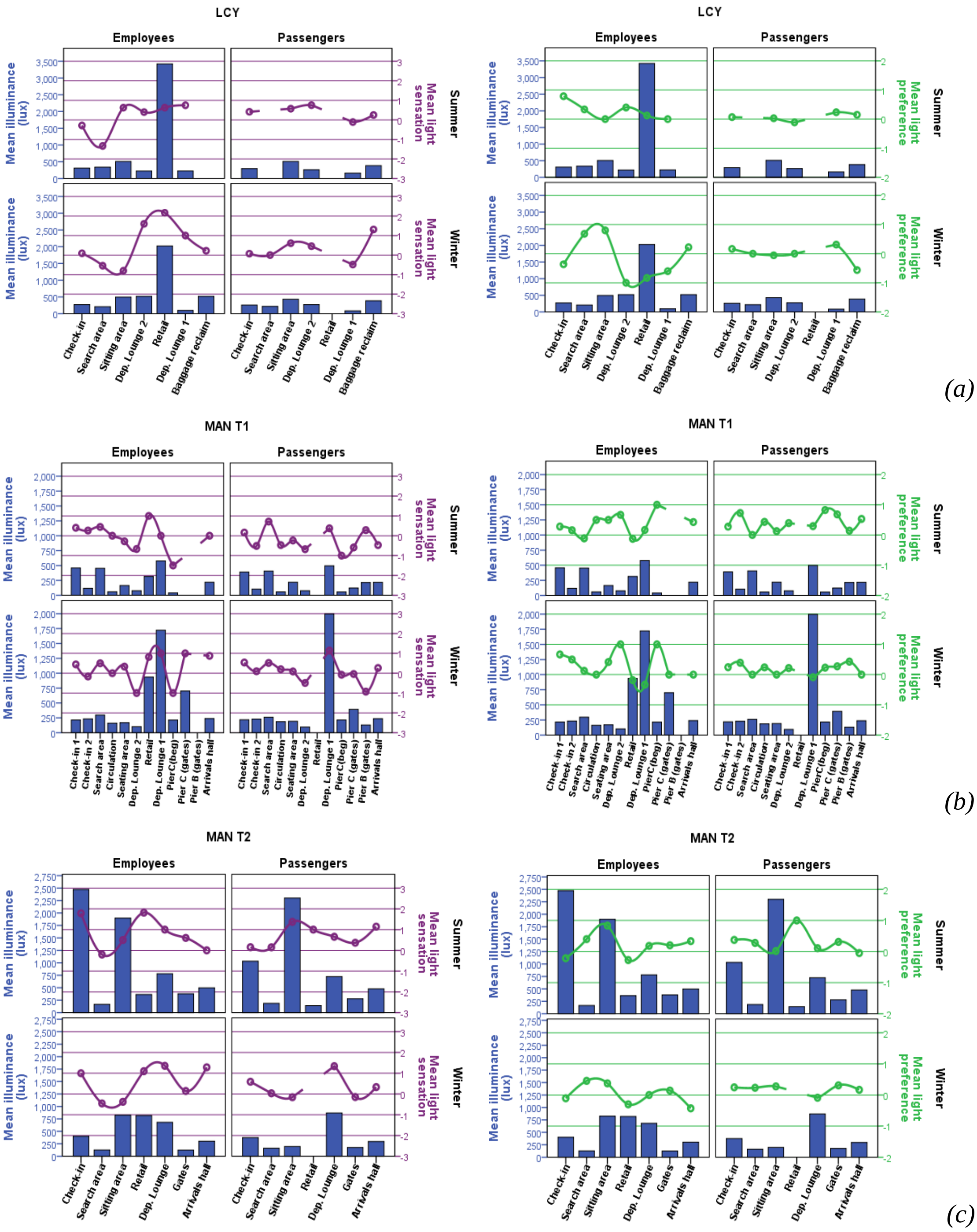



*Figure 6-39: Mean lighting sensation (left) and mean lighting preference (right) for passengers and staff across the terminal spaces in (a) LCY, (b) MAN T1 and (c) MAN T2.*

Moreover, figure 6-39 demonstrates that underneath the consensus of passengers and staff in terms of overall lighting sensation (LS) and preference (LP)[11], the two groups assessed differently the lighting environment in the terminal spaces. Characteristic are the cases in LCY during the winter surveys. Employees (mean LS = -0.8, mean LP = 0.8) found the seating area (about 480 lux) slightly dim and preferred it a bit brighter, whereas passengers (mean LS = 0.6, mean LP = -0.1) assessed it as slightly bright and were satisfied with it.

The similar lighting environment in the nearby departures lounge 2 was deemed to be bright by employees (mean LS = 1.6, mean LP = -1.0) and neither bright not dim by passengers (mean LS = 0.5, mean LP = 0.0), with the former preferring a bit dimmer environment and the latter requiring no change. In the dimmer departures lounge 1, the mean LS and LP for passengers (mean LS = -0.5, mean LP = 0.3) rounds up to “neither bright nor dim” and “no change”, whilst for staff these are “slightly bright” and “a bit dimmer” respectively. Furthermore, 0.7 units separate the mean LS for the two groups in the check-in of LCY in summer, where staff preferred a bit brighter and once again passengers required no change.

Similar cases are derived from MAN T1 and MAN T2. During the summer surveys, staff (mean LS = 0.3, mean LP = 0.2) working in the small check-in 2 of MAN T1 found the space “neither bright nor dim” and was satisfied with it, whereas passengers (mean LS = -0.5, mean LP = 0.7) assessed it as slightly dim and preferred “a bit brighter” environment. In the same terminal, the departures lounge 2 in winter was deemed to be “slightly dim” by employees and “neither bright nor dim” by passengers. In the seating area of MAN T2 in summer, passengers found it just right whilst staff preferred “a bit brighter” environment.

The divergent assessments addressed are only few among those achieved statistical significance (at $p<0.05$) while controlling for illuminance. The particular examples were selected to represent cases where illuminance was on average nearly identical during the interviews with both groups in a certain space, thus highlighting the different perspective of passengers and staff towards lighting. The underlying reasons are difficult to identify due to the number of parameters involved. But beyond the personal, contributing factors can be assumed to be the different tasks performed by the two groups and the prolonged dwell time of staff in a certain space as opposed to the short dwell time for passengers and their transition from one space to another.

The different perspective of passengers and staff towards the lighting environment is further highlighted from the assessment of light distribution as well as from the responses regarding the experience of discomfort due to glare. More specifically, light was deemed not to be well distributed by 21%, 25% and 11% of passengers in LCY, MAN T1 and MAN T2, whilst such

[11] LS and LP stand for lighting sensation and lighting preference respectively.

perception was expressed by more than 40% of staff in LCY and MAN T1 and by nearly 25% of employees in MAN T2 (figure 6-40a). Moreover, there is a significant difference in the percentage of passengers and staff who reported to have experienced glare discomfort. While the vast majority of passengers (at least 90%) responded negatively, nearly 40% of employees in all terminals reported to have experienced such discomfort (figure 6-40b). The most frequently sources of glare reported are associated to artificial lighting, large electronic advertisement boards and computer monitors.

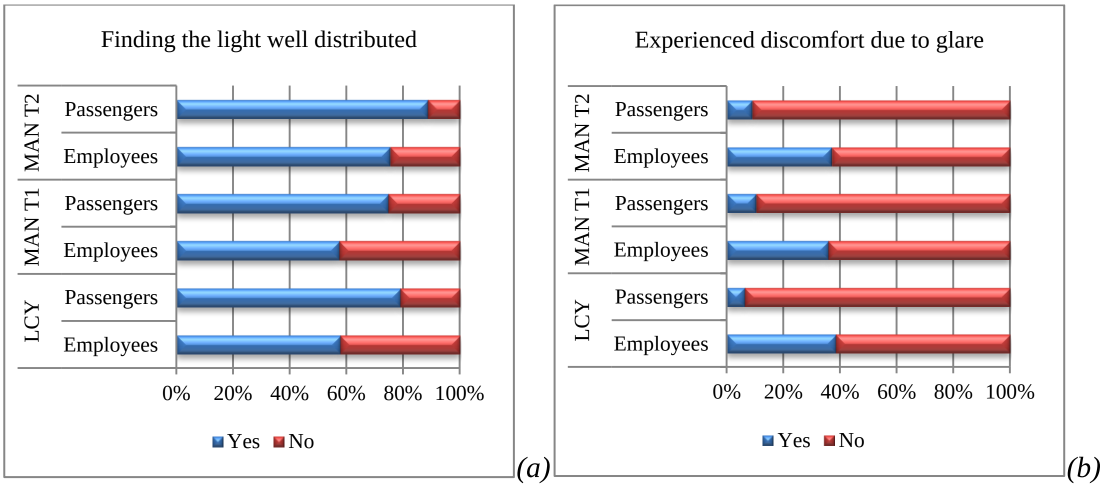



*Figure 6-40: Percentage distribution of passengers' and staff's responses about (a) the distribution of light and (b) the experience of discomfort glare.*

Common ground between passengers and staff was the subject of daylight in most cases. The majority of both groups (about 60%) in LCY described the amount natural light as "little" and "very little". These are also the categories expressing the majority of passengers (70%) and staff (80%) in MAN T1, where only 28% of passengers and 17% of employees found it sufficient. On the contrary, the results for MAN T2 reveal a different perception between the two groups; while the majority of passengers (60%) found it sufficient, the same opinion shared only 40% of employees whose majority (60%) assessed it "little" and "very little" (figure 6-41a).

Moreover, figure 6-41b shows that the preference for more daylight, as this was demonstrated in section 6.5.5.2 for the total population, expresses the majority of both groups in LCY and MAN T1 and that of employees in MAN T2, with the highest figure being the 80% of staff in MAN T1. As a result of the wide acceptance of daylight from passengers in MAN T2, the narrow majority (55%) preferred no change, yet a significant fraction of passengers (44%) preferred more demonstrating people's desire for daylight.

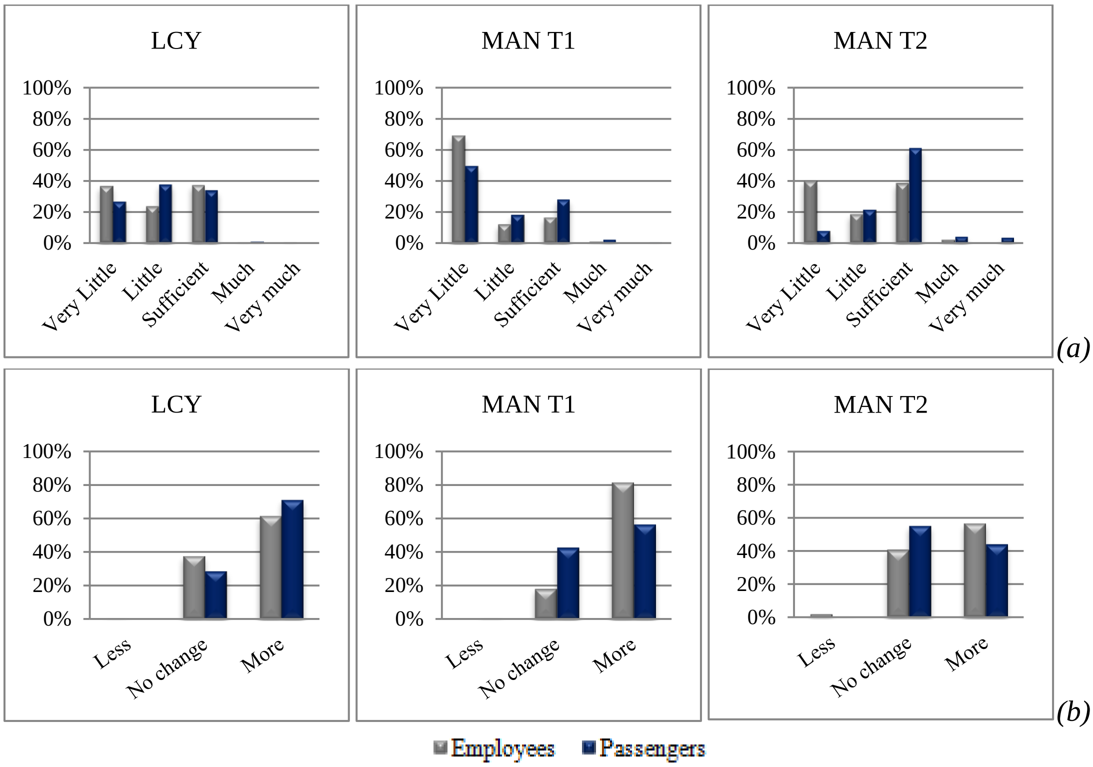



*Figure 6-41: (a) Subjective assessment of daylight sufficiency and (b) relevant preference for change from passengers and staff.*

### 6.6.4 The significance of indoor environment for passengers and staff

A similar analysis to that in section 6.5.6.2 for the total population was conducted with passengers and staff in the spotlight. The analysis aimed to evaluate the relative importance of the indoor environment, and particularly of the thermal conditions, for the two groups. Prior to the results a qualitative difference should be highlighted. With the exception of passengers flying very frequently from a certain terminal (such as many of the business passengers in LCY), passengers' response was stemmed from their terminal experience in the day. On the contrary, staff responses were largely based on their long term experience in the terminal.

Both passengers and staff raised issues other than environmental when asked about the terminal aspect they liked the most (figure 6-42). The relatively higher fraction of employees and passengers in MAN T2 who pointed out an environmental condition is mainly associated to lighting and particularly to the natural light in the terminal. Unlike passengers however, half of employees in all buildings found nothing particularly positive to report. The category "nothing particularly" has a qualitative difference between passengers and staff, with the former most often replying "nothing really, it is just an airport" and with the latter replying "nothing" or "nothing at all".

Regarding the mostly disliked aspects, the percentage of passengers concerned with the indoor environment was higher in LCY and MAN T1 and lower in MAN T2, although a small fraction in all cases (figure 6-43b). On the contrary, the respective percentage distribution for employees (figure 6-43a) demonstrates that the majority of staff – 62% in LCY and MAN T1 and 54% in MAN T2 – was concerned the most with the indoor environment.

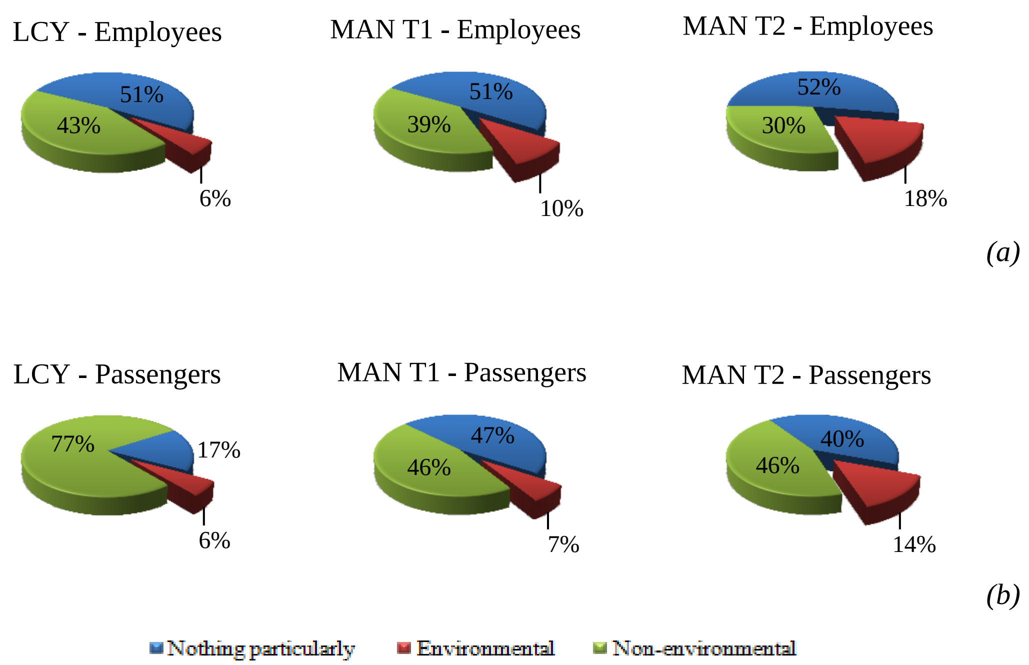



*Figure 6-42: Aspects of the terminal buildings (a) employees and (b) passengers like the most, classified into nothing particularly, environmental and non-environmental.*

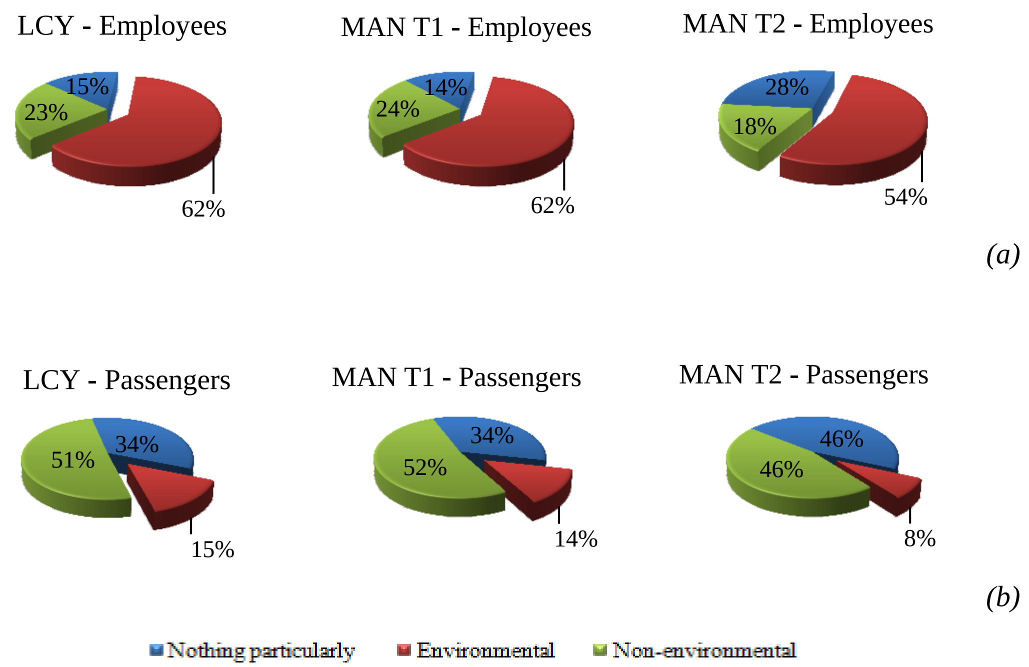



*Figure 6-43: Aspects of the terminal buildings (a) employees and (b) passengers dislike the most, classified into nothing particularly, environmental and non-environmental.*

The results show that the conclusion drawn (in section 6.5.6.2) for the total population – that the indoor environmental conditions get a higher rank when perceived as negative – applies to both staff and passengers (with the exception of passengers in MAN T2). Therefore, the next step was to look in further detail at the negative statements of the two groups in order to find out which feature of the indoor environment staff was mainly concerned with and to what extent the environmental conditions were unimportant from passengers' perspective. Figure 6-44 reveals that the top issue among staff in all terminals was the thermal environment, concerning the most 34% of employees in LCY and nearly 40% of employees in MAN T1 and MAN T2.

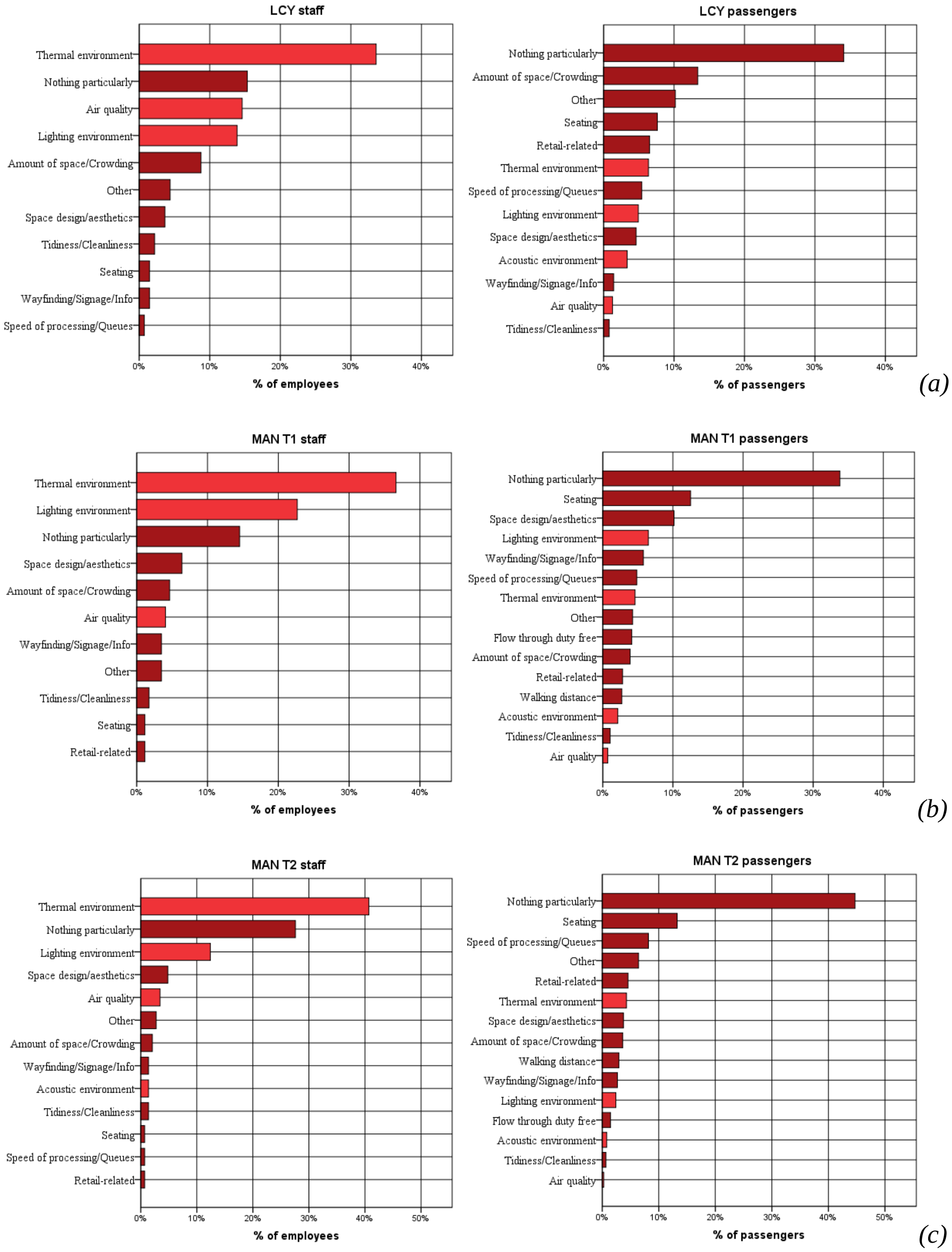



*Figure 6-44: Aspects of the terminal buildings passengers and staff dislike the most in (a) LCY, (b) MAN T1 and (c) MAN T2.*

These figures explain that the relatively high rank (2nd for LCY and MAN T2, 3rd for MAN T1, but with low percentage response in all cases) of the thermal conditions in the respective analysis for the total population (figure 6-30) was due to employees. In fact, passengers ranked thermal environment 5th among the worst aspects of LCY and MAN T2 and 6th for MAN T1, with only 4-6% of passengers in each terminal raising a thermal issue.

Beyond the thermal conditions, lighting was also an important parameter for staff in the terminal buildings, concerning a respectful fraction; 14% in LCY, 23% in MAN T1 and 12% in MAN T2. Accordingly, lighting was ranked 3rd by employees in LCY (behind air quality) and 2nd in MAN T1 and MAN T2. For passengers, thermal conditions were the most important among the four different features of the indoor environment in LCY and MAN T2, while for passengers in the thermally diverse MAN T1 lighting was on top!

Additionally, the results show that thermal conditions were becoming the top issue for passengers only when they experienced unacceptable TS (figure 6-45). However, the percentage of passengers who considered the thermal environment as the worst aspect of their in-terminal experience while experiencing unacceptable TS is unexpectedly low - 21% in LCY and 15% in MAN T1 and MAN T2 - suggesting a great extent of tolerance of “uncomfortable” thermal conditions. Interestingly, the perceived importance of thermal conditions in this case is still comparable to that of other non-environmental issues, such as the “amount of space/crowding” in LCY, “space design/aesthetics” and “seating” in MAN T1 and “speed of processing/queues” in MAN T2.

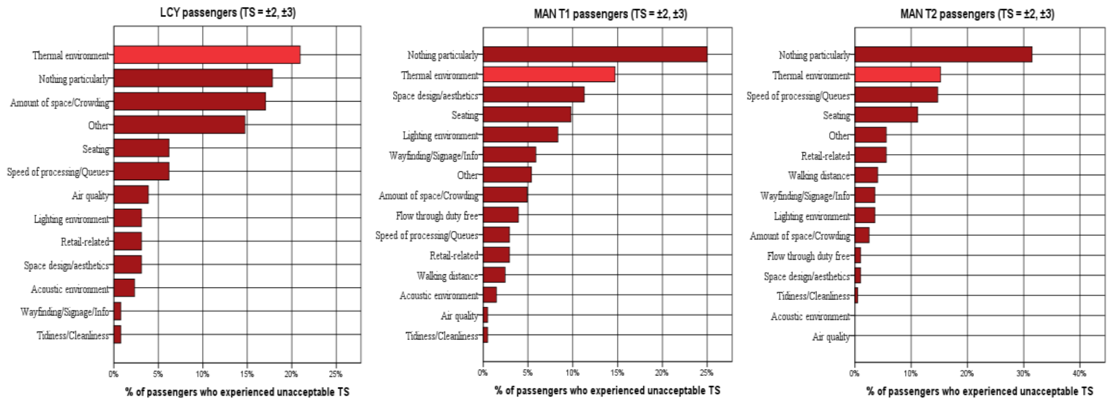



*Figure 6-45: The thermal conditions become the most important issue among passengers who experience unacceptable TS.*

Further input on the significance of the indoor environmental conditions for employees, was derived from staff’s responses regarding the environmentally-related problems they had noticed in the terminals (question 24). Free from the comparative notion imposed through the “like/dislike the most” restriction and focused on the indoor environment, this question allowed employees to highlight any issues they were aware of or concerned with[12].

With only 30% of staff in MAN T1 and 20% of staff in LCY and MAN T2 reporting no problem, the results show that the vast majority was concerned with one or more aspects of the indoor environment (figure 6-46). In fact, a respectful percentage of staff (29% in LCY, 13% in MAN T1 and 23% in MAN T2) raised at least two issues of different nature (e.g. thermal and air quality). For this reason, the different categories in figure 6-46 are not mutually excluding and therefore their sum is not equal to 100%.

Thermal issues were raised by 66%, 61% and 80% of staff in LCY, MAN T1 and MAN T2 respectively, highlighting again the high importance of thermal conditions for employees. Representative responses included: “air-conditioning is always wrong”, “it is cold in summer and hot in winter”, “temperature is never right” and “it is winter and air-conditioning is on”. These percentages are significantly higher – nearly double – than the percentage of staff considering the thermal conditions as the worst aspect (34%, 37% and 41% of staff in LCY, MAN T1 and MAN T2, figure 6-44).

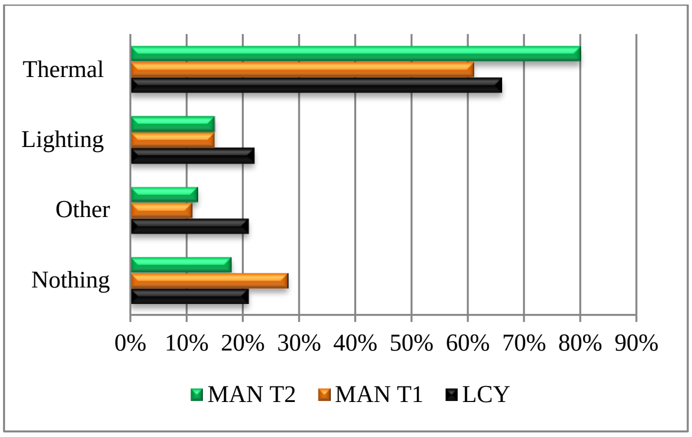


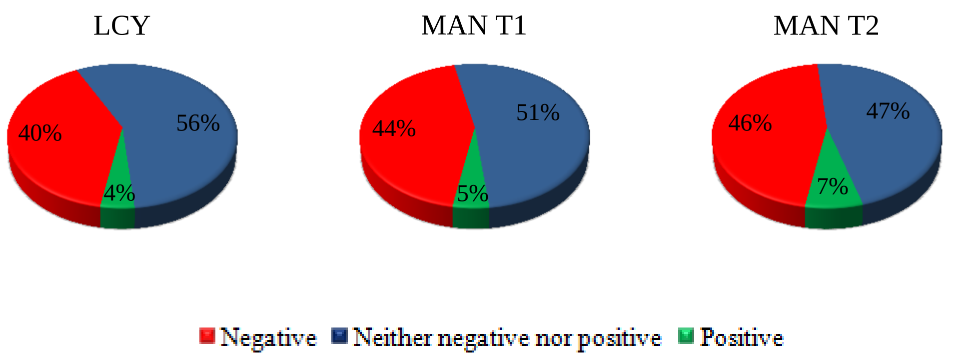

*Figure 6-46: Nature of issues related to the indoor environmental conditions raised by staff in the three terminals.*

From a different perspective, the results also confirm that lighting was deemed as the second most important feature of the indoor environment; relevant issues were reported by 22% of staff in LCY and by 15% of staff in MAN T1 and MAN T2. “Other” matters were raised by 21% of staff in LCY, 11% of staff in MAN T1 and 12% of staff in MAN T2. These include predominantly air quality issues in certain terminal spaces and secondarily problems indirectly related to the thermal environment. For instance, 42% of security staff in the search area of MAN T2 reported lack of fresh air, associating it most often with the busy times. Similarly, the majority of staff (67%) interviewed in the baggage reclaim area of LCY reported poor air

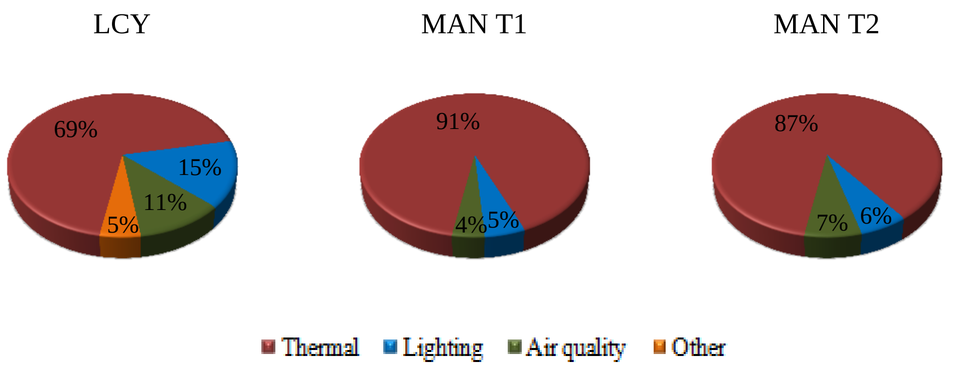
[12] While the question was for the entire terminal in general, the majority of employees raised issues concerning their workspace.

quality due to aircraft fumes entering the space through the baggage conveyors when the aircraft stands adjacent to the space are in use. Moreover, 25% of the security staff raised the issue of static shocks as a result of the dry conditions in the search area.

A very similar profile was revealed from employees' response regarding the impact of the environmental conditions on their productivity. A respectful percentage (40-46%) acknowledged a negative effect while the narrow majority (47-56%) reported that the indoor environment does not affect its productivity in either a negative of positive manner (figure 6-47a). For the vast majority among those who reported a negative effect, this was attributed to thermal conditions (figure 6-47b).




*(a)*




*(b)*

*Figure 6-47: Employees (a) assessing the effect of indoor environmental conditions on their productivity and (b) specifying the cause if the effect is negative.*

The data collected from three questionnaire items (questions 25, 26 and 27) are representative of the rigid working conditions for terminal staff. A considerable percentage of employees – nearly 40% in LCY and 30% in MAN T1 and MAN T2 – rated the clothing policy as inflexible in maintaining their thermal comfort. The classification of responses according to the types of staff show that flexibility with dressing codes varies between the different staff groups in a terminal as well as between the same staff group between the terminals. For instance, the type of staff appearing to have the most inflexible clothing policy in LCY and MAN T2 was the security staff, while in MAN T2 this was the retail and airport staff.

More importantly, the vast majority of employees in each terminal (86% in LCY and MAN T1 and 94% in MAN T2) reported no control over the thermal and visual environment. The very small number of staff who responded positively acknowledged in all cases controls over the thermal environment. These included personal heating units and small standing fans, as well as the control of individual AC units and the use of thermostats in few retail facilities. The satisfaction rates, however, were low in most cases with the control being deemed as satisfactory by 53%, 33% and 22% of employees who held one in LCY, MAN T1 and MAN T2.

## 6.7 Spatial analysis of thermal conditions

Building size, spatial design, outdoor weather, occupancy and operational profile were among the parameters influencing and often differentiating the thermal conditions in the mechanically ventilated facilities housed in the three terminal buildings. Aimed at understanding thermal comfort conditions in the different terminal areas, this section investigates the thermal environment of the terminal spaces, addresses the overall TS profiles and locates the different thermal requirements between passengers and staff.

### 6.7.1 A comparison to CIBSE comfort criteria

The space-to-space temperature profile is summarised in table 6-26, where spaces are listed in the order met by a passenger. Descriptive statistics of all other environmental quantities for each space are provided in appendix D.

CIBSE's comfort criteria (table 3-4) allow for a comparison to the basic terminal spaces. These include the check-in halls, departures lounges, the baggage reclaim area of LCY, as well as the search areas which are regarded as "concourse (no seats)" areas. From those listed in table 6-26, the spaces comprising the broader departures lounge area of each terminal are "seating area", "departures lounge 1" and "departures lounge 2" for LCY, "seating area", "departures lounge 1", "departures lounge 2" and "Pier C (beg.)" for MAN T1 and "departures lounge" for MAN T2.

*Table 6-26: Summary of minimum, maximum and mean operative temperature (°C) for each terminal space.*

| | | Summer | | | | Winter | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | **Mean** $T_{op}$ (°C) | **SD** | **Min - Max** $T_{op}$ (°C) | **Range** | **Mean** $T_{op}$ (°C) | **SD** | **Min - Max** $T_{op}$ (°C) | **Range** |
| **LCY** | **Check-in** | 22.7 | 0.6 | 21.4 - 25.0 | 3.6 | 23.4 | 0.4 | 21.7 - 23.9 | 2.2 |
| | **Search area*** | 23.4 | 0.3 | 23.2 - 23.7 | 0.5 | 23.0 | 0.2 | 22.2 - 23.2 | 1.0 |
| | **Seating area** | 23.2 | 0.8 | 22.0 - 24.6 | 2.6 | 23.1 | 0.4 | 22.0 - 23.8 | 1.8 |
| | **Dep. Lounge 2** | 23.1 | 0.5 | 21.7 - 24.2 | 2.5 | 22.9 | 0.4 | 21.7 - 23.3 | 1.6 |
| | **Retail*** | 24.6 | 0.7 | 23.2 - 25.1 | 1.9 | 23.5 | 0.5 | 22.8 - 24.2 | 1.4 |
| | **Dep. Lounge 1** | 23.9 | 1.0 | 21.6 - 25.8 | 4.2 | 23.9 | 0.7 | 22.3 - 25.3 | 3.0 |
| | **Gates (west pier)**** | 25.1 | 0.4 | 24.4 - 25.6 | 1.2 | 18.1 | 1.9 | 12.7 - 21.1 | 8.4 |
| | **Baggage reclaim** | 23.9 | 0.3 | 23.2 - 24.3 | 1.1 | 23.2 | 0.6 | 22.3 - 24.1 | 1.8 |
| **MAN T1** | **Check-in 1** | 22.3 | 1.1 | 21.2 - 24.6 | 3.4 | 21.7 | 0.5 | 20.1 - 22.2 | 2.1 |
| | **Check-in 2** | 22.4 | 0.5 | 21.3 - 22.8 | 1.5 | 22.8 | 0.4 | 21.8 - 23.3 | 1.5 |
| | **Search area** | 22.4 | 0.2 | 22.1 - 22.6 | 0.5 | 23.4 | 0.6 | 21.4 - 24.0 | 2.6 |
| | **Circulation** | 22.0 | 0.3 | 21.5 - 22.4 | 0.9 | 23.2 | 0.5 | 22.3 - 23.9 | 1.6 |
| | **Seating area** | 21.5 | 0.5 | 21.0 - 22.6 | 1.6 | 23.6 | 0.7 | 22.4 - 24.3 | 1.9 |
| | **Dep. Lounge 2** | 22.0 | 0.3 | 21.7 - 22.6 | 0.9 | 21.2 | 0.6 | 19.2 - 23.3 | 4.1 |
| | **Retail*** | 22.6 | 0.5 | 22.1 - 23.3 | 1.2 | 22.2 | 0.9 | 20.6 - 23.0 | 2.4 |
| | **Dep. Lounge 1** | 24.5 | 0.5 | 22.9 - 25.4 | 2.5 | 21.9 | 1.5 | 19.5 - 25.6 | 6.1 |
| | **Pier C (beg.)** | 22.6 | 0.2 | 22.4 - 23.1 | 0.7 | 19.8 | 0.5 | 19.2 - 21.1 | 1.9 |
| | **Pier C (gates)** | 21.6 | 0.8 | 20.3 - 22.6 | 2.3 | 18.9 | 0.7 | 17.2 - 20.4 | 3.2 |
| | **Pier B (gates)** | 21.1 | 0.2 | 20.9 - 21.3 | 0.4 | 20.2 | 0.5 | 19.4 - 20.9 | 1.5 |
| | **Arrivals hall** | 19.8 | 0.5 | 19.1 - 21.0 | 1.9 | 17.4 | 0.4 | 16.2 - 17.9 | 1.7 |
| **MAN T2** | **Check-in** | 24.6 | 0.3 | 23.4 - 25.2 | 1.8 | 21.0 | 0.6 | 18.9 - 21.8 | 2.9 |
| | **Search area** | 23.7 | 0.7 | 21.4 - 24.5 | 3.1 | 21.3 | 1.3 | 18.9 - 23.4 | 4.5 |
| | **Seating area** | 21.9 | 0.6 | 20.9 - 22.9 | 2.0 | 20.0 | 0.7 | 19.3 - 22.1 | 2.8 |
| | **Retail*** | 22.4 | 0.6 | 21.3 - 23.2 | 1.9 | 21.4 | 0.8 | 20.0 - 23.1 | 3.1 |
| | **Dep. Lounge** | 22.7 | 1.5 | 20.6 - 26.3 | 5.7 | 21.6 | 0.8 | 19.6 - 24.5 | 4.9 |
| | **Gates** | 23.0 | 1.3 | 21.0 - 25.6 | 4.6 | 21.1 | 0.6 | 19.5 - 22.6 | 3.1 |
| | **Arrivals hall** | 22.2 | 0.2 | 21.8 - 22.5 | 0.7 | 21.1 | 0.2 | 20.6 - 21.6 | 1.0 |

* Based on staff responses predominantly
** Environmental monitoring without questionnaires

In summer, the mean temperature in all check-in areas and departure lounges was within or very close to the recommended range (figure 6-48). Exception was the check-in area in MAN T2, where the mean temperature exceeded the range by 1.5 °C. Within the range was also the temperature in the baggage reclaim area of LCY and in the search areas of all three terminals. Similarly to summer, the temperature in all search areas lay within the respective range in winter. On the contrary, the majority of all other spaces presented a significantly warmer environment beyond the range, with the maximum "deviations" derived from overheated spaces in LCY (figure 6-49). More specifically, the large check-in areas of MAN T2 and MAN T1 (check-in 1) presented 1.0 °C and 1.7 °C higher mean temperature. Considerably warmer were the smaller-sized check-in halls in LCY and MAN T1 (check-in 2); 3.4 °C and 2.8 °C higher than the recommended range.

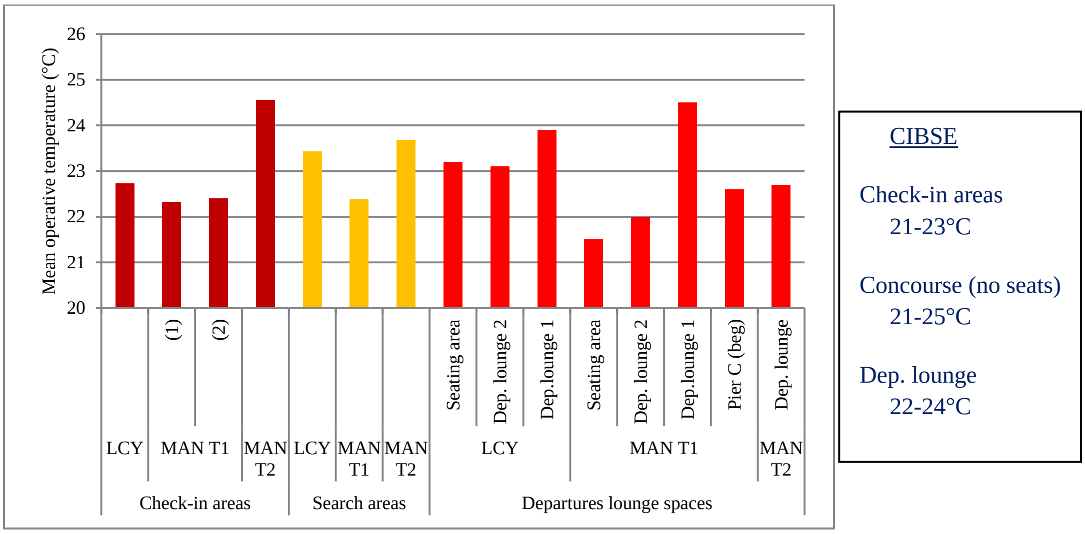



*Figure 6-48: Summer mean operative temperature in check-in halls, search areas and dep. lounges compared to CIBSE's comfort criteria.*

As far as the departures lounges are concerned, all three related spaces in LCY presented significantly higher mean temperature in winter; the seating area by 2.1 °C, the departures lounge 2 by 1.9 °C and the departures lounge 1 by 2.9 °C. The respective difference for the departures lounge in MAN T2 was lower at 0.6 °C, while two out of four spaces comprising the departures lounge in MAN T1 – pier C (beg.) and departures lounge 2 were within the CIBSE range. On the other hand, the mean temperature in the departures lounge 1 and the seating area of MAN T1 exceeded the range by 0.9 °C and 2.6 °C respectively. Moreover, the thermal environment was significantly warmer in the baggage reclaim area of LCY, where the mean temperature was found 4.2 °C beyond the CIBSE range.

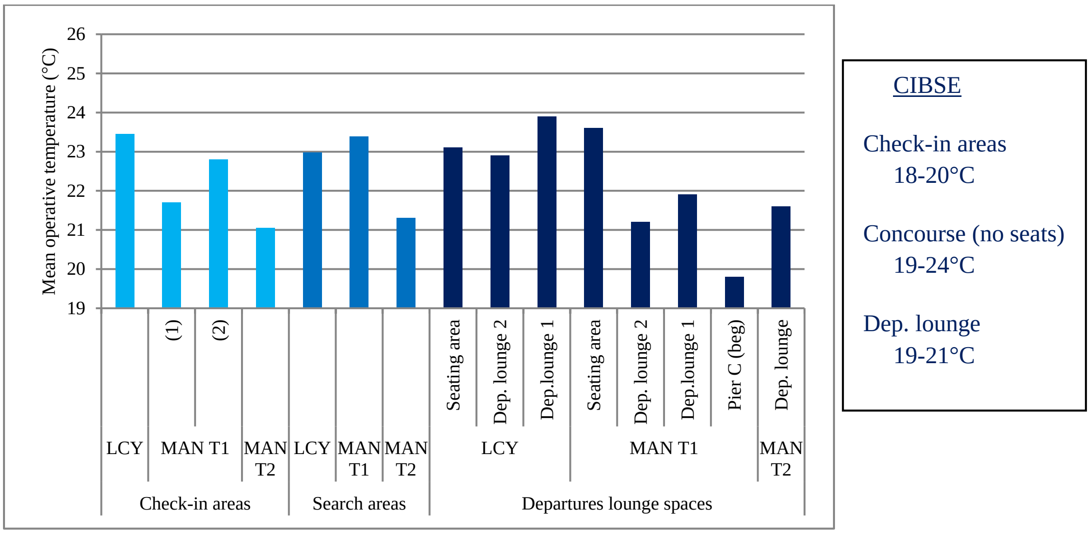



*Figure 6-49: Winter mean operative temperature in check-in halls, search areas and dep. lounges compared to CIBSE's comfort criteria.*

### 6.7.2 London City

LCY is a compact terminal and characteristic of homogenous spaces. As a result, its areas presented the highest thermal uniformity among the case studies (table 6-26). The greatest mean temperature difference between its spaces was only 1.2 ºC; between the departures lounge 1 and check-in hall in summer and between the departures lounges 1 and 2 in winter. Beyond the uniformity within-the-season, the figures indicate between-the-seasons uniformity with the temperature in most spaces remaining at very similar levels in summer and winter.

Exceptions in the nearly flat thermal profile were the gate lounges and retail area. In the latter, the extensive spot lighting from the ceiling and the very low floor-to-ceiling height (figure 6-50a) often resulted in higher temperatures. Representative is the particularly high mean temperature in summer (24.6 ºC). On the other hand, it was the outdoor weather determining the distinct thermal profile in the gate lounges (figure 6-50b), where the summer (25.1 ºC) and winter (18.1 ºC) mean temperatures are characteristic of the free-running conditions.

*(a)* *(b)*

*Figure 6-50: (a) Extensive lighting in retail facilities and (b) free-running conditions in gate lounges, LCY.*

Beyond the spatial homogeneity, occupancy levels had a great impact on the indoor thermal environment. Due to the small volume of spaces and the proportionally large numbers of passengers passing through, occupancy was the major parameter responsible for temperature fluctuations. The overall effect was illustrated in figure 6-5 and highlighted in section 6.4.1, where correlation analysis revealed a significant relationship between $CO_2$ and operative temperature, demonstrating that occupancy levels explain 30-40% of the temperature variance.

The impact was significant in most spaces but statistically more evident where occupancy fluctuated more frequently in the day. Such are the cases of the seating area, baggage reclaim and particularly of the departures lounge 1 (figure 6-51). As a result, the latter was the space with the widest temperature range (4.2 ºC in summer and 3.0 ºC in winter) and the highest maximum temperatures (25.8 ºC in summer and 25.3 ºC in winter) in both seasons.

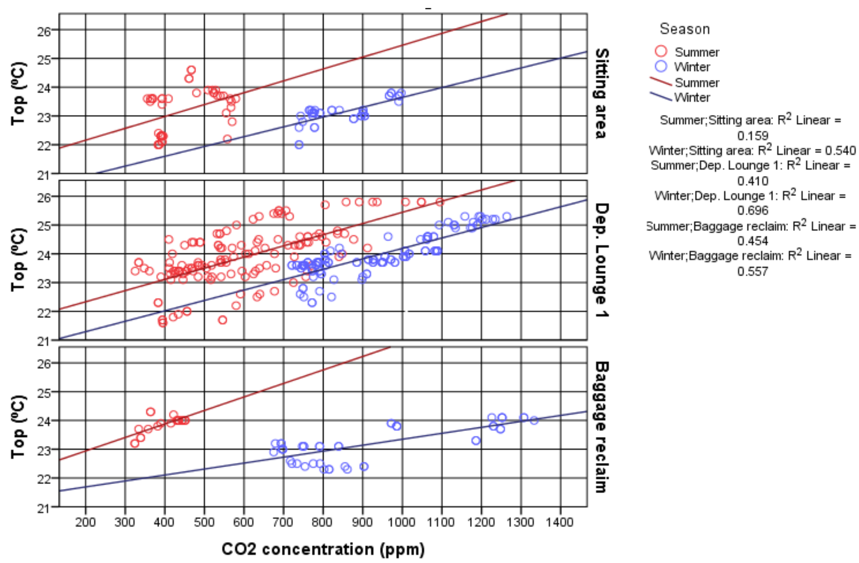



*Figure 6-51: Relationship between operative temperature and $CO_2$ concentration (occupancy) in the seating area, dep. lounge 1 and baggage reclaim area of LCY.*

This explains why these three were among the terminal areas where overheating was more profound in winter, when congestion was more frequent due to adverse weather conditions. More specifically, the temperature in the seating area lay above the upper limit of the 80% acceptability range for 22% of the time it was monitored, similarly to the 35% and 65% of the monitoring time in the baggage reclaim are and check-in hall respectively. In the departures lounge 1, the temperature exceeded this boundary for nearly all the time in winter (84% of the time it was monitored). The overall increasing trend of TS in overcrowded conditions (figure 6-11) was particularly strong in the departures lounge 1 (figure 6-52).

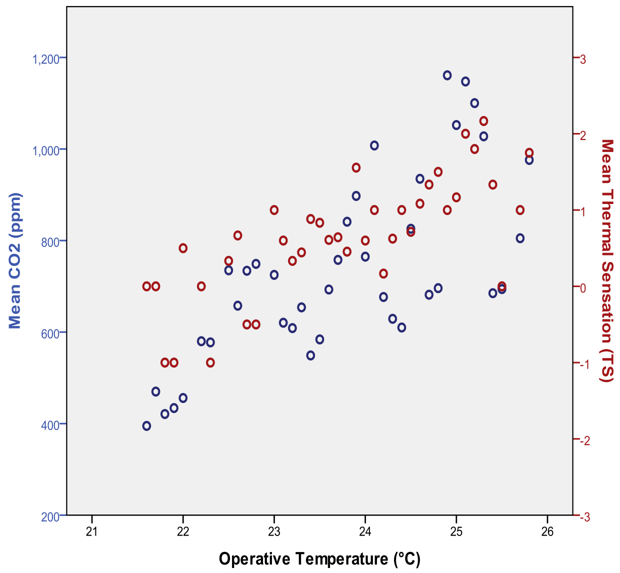



*Figure 6-52: Relationship between operative temperature, mean $CO_2$ levels (occupancy) and mean TS in the departures lounge 1 in LCY (summer & winter data).*

The mean TS follows the temperature profile in most cases and suggests a nearly stable thermal experience within the terminal's spaces (figure 6-53). For summer, the overall mean TS rounds up to "neither cold nor hot" in the check-in area, seating area, departures lounge 2 and retail area and to "slightly warm" in the departures lounge 1 and baggage reclaim area. The highest difference was 0.6 units[13], between the seating area (mean $T_{op}$ = 23.2 ºC, mean TS = 0.1) and the departures lounge 1 (mean $T_{op}$ = 23.9 ºC, mean TS = 0.7).

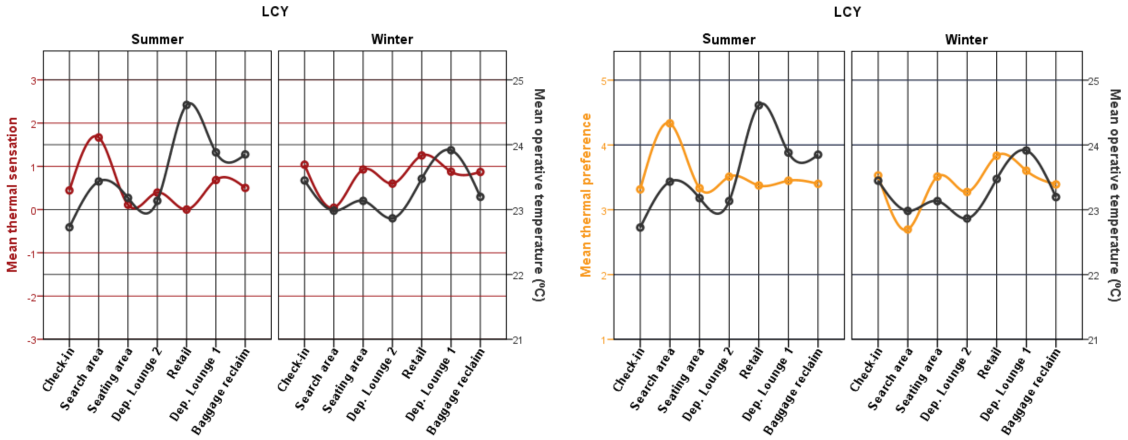



*Figure 6-53: Mean thermal sensation (left) and mean thermal preference (right), plotted against mean operative temperature for the different terminal spaces in LCY.*

Exceptions are the retail and search area where only a very small number of staff was interviewed during the summer surveys. Therefore, the TS figures derived from the two spaces in summer may be indicative but are statistically insignificant. The high mean TS (1.7 units) in the search area is representative of staff's high activity levels during busy times. In the retail area, employees' neutral TS and preference for no change reflects their long-term adaptation to the frequently warm conditions experienced in their workspace. The profile of TS was stable also in winter, and along with the profile of TP reflects the overheating conditions experienced. With the exception of the search area where the mean TS was "neither cold nor hot", people in all other spaces reported on average a "slightly warm" TS and preferred "a bit cooler" environment in most of cases.

The consistency of the overall TS and TP profile is, however, the result of passengers' votes who dominated the sample population. As it is evident in figure 6-54, the two groups experienced differently the uniform conditions. Employees' TS and TP profile fluctuated significantly across the terminal spaces whilst passengers presented more stable profiles. This highlights the wider adaptive capacity of passengers as opposed to the rigid working conditions for the vast majority of staff.

[13] For all terminals, the numerical differences in thermal sensation addressed are statistically significant at $p<0.05$.

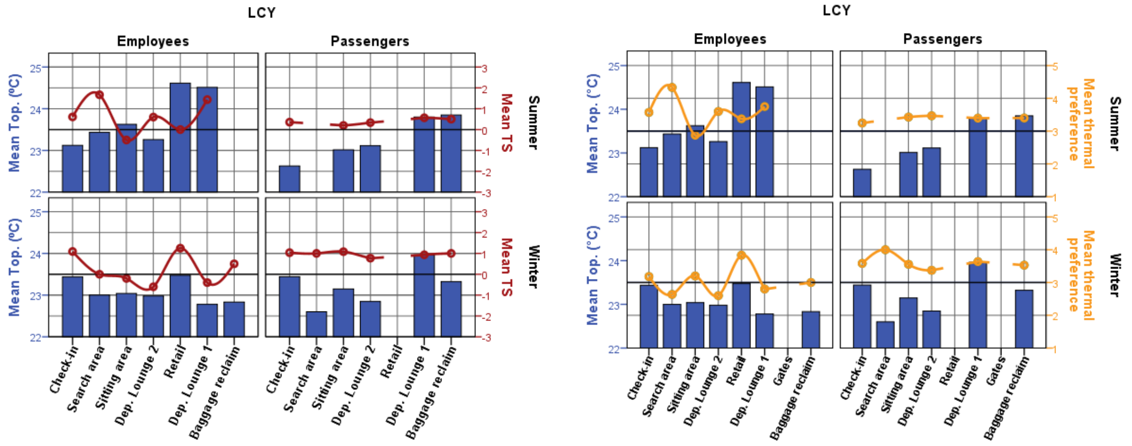



*Figure 6-54: Mean thermal sensation (left) and mean thermal preference (right), for passengers and staff in the spaces of LCY.*

Characteristic of the thermal conflict is the case of departures lounge 1. This is an important space for both groups, as it is the main waiting area for passengers and the space where a number of employees spend their entire working day. In summer (23.9 ºC), passengers' mean TS (0.6 units) was 0.8 units lower than employees' (1.4 units), despite that the mean clothing insulation for both was on average same at 0.60 clo[14]. Additionally, the majority of staff (about 70%) preferred to be cooler whereas passengers were equally split between "prefer cooler" and "no change" (figure 6-55a). The figures in winter (23.9 ºC) were reversed and suggestive of overheating for passengers but not for staff. As a result of the higher clothing insulation, passengers (mean TS = 0.9, mean clo = 1.1) reported on average 1.3 units warmer TS than staff (mean TS = -0.4, mean clo = 0.9). While nearly 60% of passengers preferred cooler conditions, an equivalent fraction of staff required no change.

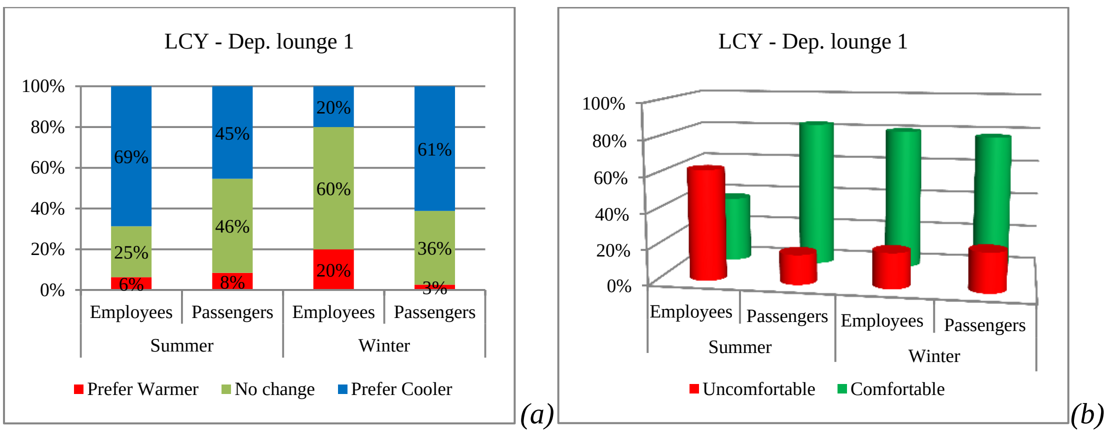



*Figure 6-55: Percentage distribution of (a) thermal preference and (b) overall comfort for passengers and staff in departures lounge 1, LCY.*

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[14] The mean clothing insulation for passengers and staff in the different terminal spaces is provided in table D-7, appendix D.

The wider adaptive capacity for passengers in the particular space attests the fact the mean temperature in summer and winter was closer to employees' neutral and preferred temperature (table 6-25). Furthermore, the results demonstrate the larger impact of thermal conditions on staff's overall comfort. The widely accepted conditions in winter and the unsatisfactory conditions in summer, as denoted by staff's TP votes, were associated to an overall discomfort rate of 20% and 63% respectively. On the contrary, discomfort among passengers was low in both seasons; 17% in summer and only 22% in winter when passengers experienced overheating (figure 6-55b).

Results derived from departures lounge 2 highlight further the divergent thermal requirements between the two groups. In winter (22.9 ºC), passengers (mean TS = 0.8 units, mean clo = 0.9) reported 1.4 units higher mean TS than staff (mean TS = -0.6 units, mean clo = 0.7). About 60% of passengers found the temperature "just right", while the same percentage of employees preferred warmer conditions (figure 6-56a). In spite of the respectful fraction of passengers requiring cooler conditions (40%) overall discomfort was very low (9%), contrarily to the significantly higher levels among staff (40%), (figure 6-56b).

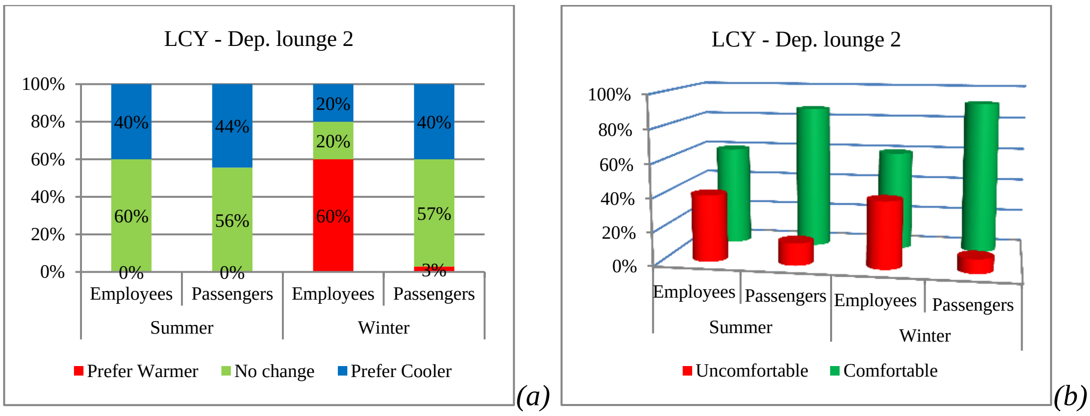



*Figure 6-56: Percentage distribution of (a) thermal preference and (b) overall comfort for passengers and staff in departures lounge 2, LCY.*

On the contrary, the same space in summer was one of the few cases where the two groups assessed similarly the thermal environment. The mean TS (0.6 for staff and 0.3 for passengers, mean clo = 0.6 for both) may indicate different TS when rounded up to the nearest integer but the difference is statistically insignificant. While the TP profiles were also nearly identical, overall comfort levels were higher among passengers (87%) than staff (60%).

In other spaces the two groups reported similar TS, yet they expressed conflicting TP. Such is the case of the check-in area, where in summer (22.7 ºC) the mean TS difference between passengers (mean TS = 0.4, mean clo = 0.7) and staff (mean TS = 0.6, mean clo = 0.6) was statistically insignificant. Staff's preference for cooler conditions, as expressed by 60% of employees, shared only a third of passengers whose narrow majority required no change.

Similarly in winter, passengers (mean TS = 1.0, mean clo = 1.2) and staff (mean TS = 1.1, mean clo = 0.9) reported on average the same TS. As a result of the indoor-outdoor temperature difference and the higher clothing and activity levels, the majority (about 60%) of passengers entering the check-in hall preferred to be cooler. On the contrary, “slightly warm” was the desired thermal state for staff as more than 70% required no change (figure 6-57a).

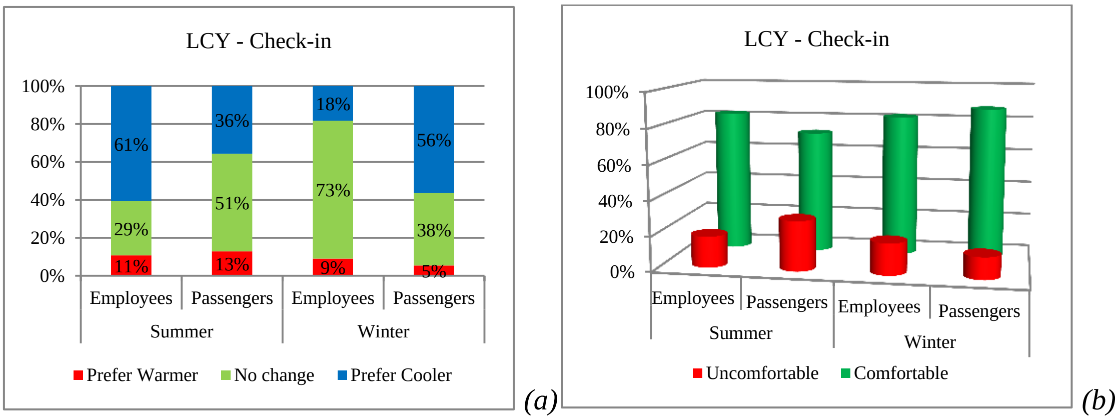


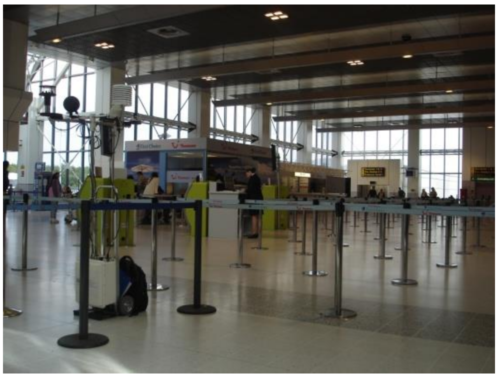

*Figure 6-57: Percentage distribution of (a) thermal preference and (b) overall comfort for passengers and staff in the check-in hall, LCY.*

The check-in hall is the only space in LCY, and one of the few in the three terminals, where staff presented high levels of overall comfort (over 80%) analogous to passengers. Unlike in other spaces where control over the thermal environment is absent, most employees interviewed in this space were airline staff, who reported the frequent use of small fans or personal heaters behind the check-in desks. The unusual high overall comfort levels among staff in this space underlines the importance of thermal controls for occupant comfort.

### 6.7.3 Manchester Terminal 2

Uniformity characterizes the thermal environment in MAN T2 to a great extent. Unlike LCY however, the terminal presented a distinct thermal profile in the two seasons, with the temperature in all spaces being 1.1-3.6 °C lower in winter. More specifically, thermal uniformity in summer was found between the airside spaces (i.e. beyond the search area) of the terminal where the greatest difference – only 1.1 °C – was encountered between the seating area and gates (table 6-26). Higher temperatures in summer prevailed landside; in the check-in hall and search area. As addressed in section 4.5.2, prior to its refurbishment, the space currently used as search area consisted of distinct office rooms. Their overhaul into a single open-plan area found the vents unevenly distributed, resulting in hot and cold spots and consequently in the insufficient conditioning of the space. As a result, passengers and staff experienced a higher mean temperature of 23.7 °C during the busy summer period.

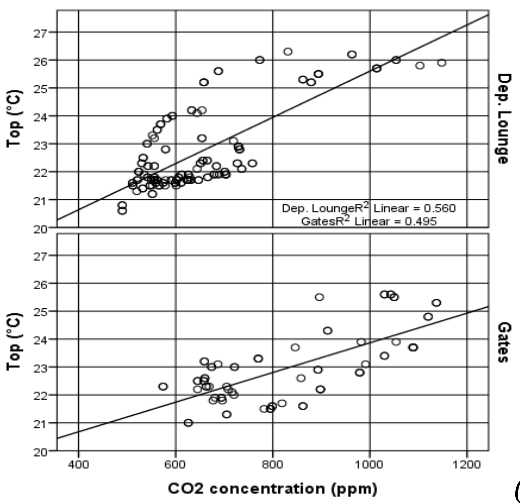
However, the warmest on average space in summer was the check-in area, 24.6 °C, with the temperature remaining close to this level for most of the time (as reflected in the respective standard deviation). The check-in area is the largest of all spaces in MAN T2 and therefore occupancy density does not have a substantial effect on its thermal environment. The particularly high temperature in summer reflects the impact of external heat gains on its thermal environment, as a result of the extensive use of glazing (glazed façade and a number of skyroofs across the space; figure 6-58).


*(a)*

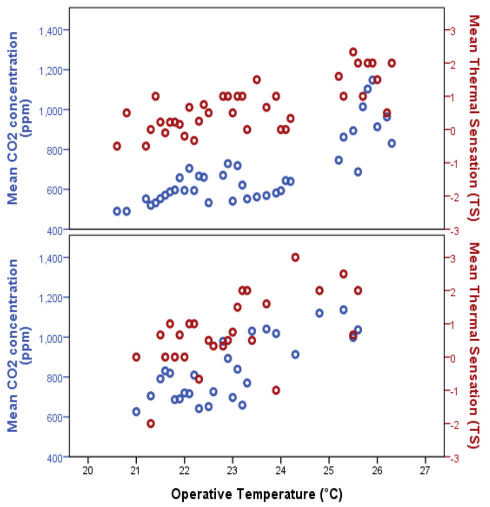
*(b)*

*Figure 6-58: (a) Extensive glazed façade and (b) representative skyroof in check-in hall, MAN T2.*

On the contrary, occupancy changes explain nearly 50% of the temperature variance in the departures lounge and gates (figure 6-59a), where the widest temperature ranges were encountered (5.7 °C in the dep. lounge and 4.6 °C in the gates). The overall trend of increased TS with occupancy (figure 6-11b) was statistically evident only in summer (as discussed in section 6.4.1), finding its strongest expression in the departures lounge and gates (figure 6-59b).



*(a)*



*(b)*

*Figure 6-59: (a) Relationship between operative temperature and $CO_2$ concentration (occupancy) and (b) between operative temperature, mean $CO_2$ levels and mean TS in the departures lounge and gates, summer, MAN T2.*

In winter, when the external heat gains have a minor effect, the mean temperature was very similar between the spaces and close to 21.0 °C (the temperature set-point). The highest difference (1.6 °C) occurred between the departures lounge and seating area. The latter was on average the coolest space in MAN T2 in both winter (20.0 °C) and summer (21.9 °C), due to a number of large jet nozzles (diffusers) discharging high volumes of cooled air at different angles (figure 6-60). The uniform temperatures in winter are also associated with the terminal's operational profile at this time of the year. MAN T2 serves mainly holiday destinations and therefore it experienced a significantly smaller volume of passengers in winter. After the main occupancy peak in the morning and the secondary peak in the midday the terminal handled sparse passenger traffic. Consequently, there were prolonged periods of time with very low occupancy resulting in uniformly lower temperatures very close to the winter temperature set-point.


*Figure 6-60: Air-conditioning nozzles positioned immediately beneath the roof in the seating area, MAN T2.*

Despite the distinct temperature patterns in summer and winter, the overall mean TS and TP was almost identical (figure 6-61). Juxtaposing the overall profiles with those for passengers and staff (figure 6-62) it can be seen that this was due to the votes of both groups. Therefore, this indicates that the relatively small increase (as compared to LCY and MAN T1) of clothing levels in winter balanced sufficiently the cooler temperatures.

On the other hand, in spite of the seasonal thermal uniformity, the overall mean TS presented consecutive changes across the spaces. For both seasons, the mean TS rounds up to "slightly warm" in the check-in hall and search area, to "neutral" in the seating area and to "slightly cool" in the retail area ahead. Thereafter, it rises to "neutral" again in the departures lounge and further to "slightly warm" in the gates. The only differentiation point was the arrivals hall; "neutral" in summer and "slightly warm" in winter. On the contrary, the overall TP profile was more stable with the rounded mean scores denoting a preference for no change in most spaces.

Exceptions were only the gates in summer and the search area in both seasons where "a bit cooler" environment was preferred.

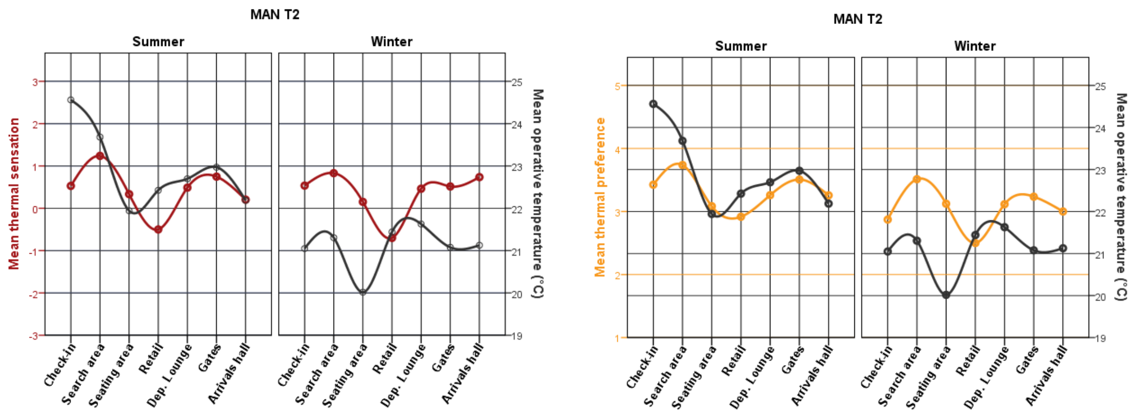



*Figure 6-61: Mean thermal sensation (left) and mean thermal preference (right), plotted against mean operative temperature for the different terminal spaces in MAN T2.*

Another outcome from figure 6-61 is that the TS does not always follow the temperature profile; i.e. people in spaces with lower temperature may report higher TS than in warmer spaces. In summer for instance, people experienced 23.7 °C on average in the search area and reported a mean TS of 1.2 units, whereas in the warmer check-in hall (24.6 °C) a mean TS of 0.5 units. This reflects the diverse factors influencing TS in different spaces and highlights the impact of spatial characteristics and function.

The high mean TS in the search area can be attributed to a combination of parameters. These include the unquantifiable impact of passengers' stress on their TS as a result of the screening process, the very frequent congestion which was shown to increase TS and the higher activity levels performed by security staff (than by check-in staff). In fact, the search area had the highest mean TS (0.8 units) also in winter while the mean temperature was essentially the same to other spaces. On the other hand, the lower TS in the check-in hall can be attributed to people's notion that the particularly warm environment was a natural consequence of the inflowing sunlight through the extensive and perceptible - across the space - glazed areas. This is also reflected in the TP votes; over 60% of people in the search area expressed a preference for cooler conditions, whereas a similar percentage in the significantly warmer check-in area required no change.

Similarly to LCY, the spatial analysis for MAN T2 revealed the different thermal comfort requirements between passengers and staff. An overview of figure 6-62 shows that (departing) passengers reported a mean TS in the range of 0.2 - 1.1, extended to 1.3 when accounting for the arrived passengers in the arrivals hall. On the contrary, the respective range for employees was 3 units wide; from -1.3 in the arrivals hall in summer to 1.7 in the search area also in summer.

Contrarily to passengers, the mean TS for staff was found to lie on the cool side of the ASHRAE scale in half of the spaces in summer and in most of the spaces in winter, reflecting the significantly higher frequency of cool sensations among employees.

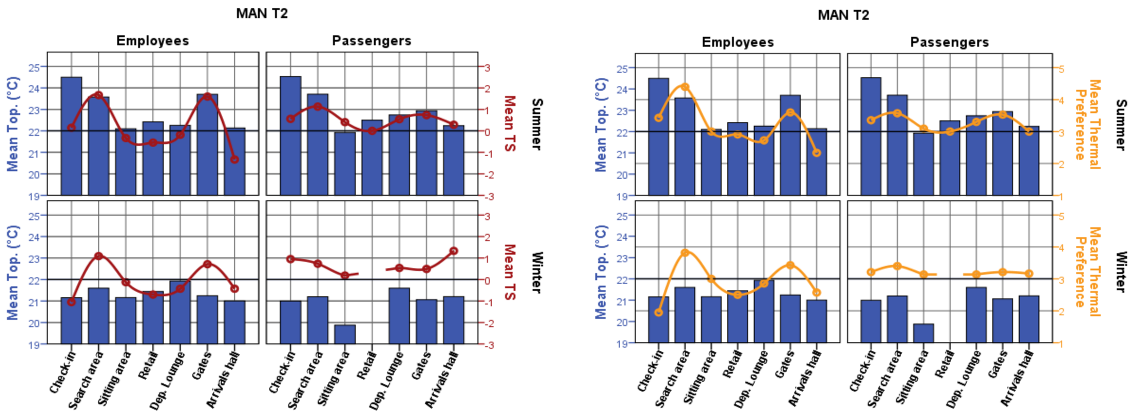



*Figure 6-62: Mean thermal sensation (left) and mean thermal preference (right), for passengers and staff in the spaces of MAN T2.*

Representative of the thermal conflict is the case of the check-in hall, where passengers (mean TS = 0.6, mean clo = 0.5) in summer reported 0.5 units higher mean TS than employees (mean TS = 0.6, mean clo = 0.7) in spite of their lower clothing levels. This result highlights the different activity levels performed. The majority of employees are engaged in sedentary activities. On the contrary, passengers arrive either by car and have a short walk to the hall or by train and walk about 10 minutes via the Skylink bridge, most often while carrying luggage in both cases.

Further differentiated however, was the thermal experience of the two groups in the check-in area in winter when the TS gap measured 2.1 units. More specifically, passengers and staff experienced a mean temperature of 21.0 °C, with the former reporting a mean TS of 1.0 and the latter a mean TS of -1.1. Beyond the different activity levels, additional contributing factors in winter become the wider indoor-outdoor temperature difference passengers experienced as well as passengers' higher clothing levels tailored to outdoor weather (1.0 clo for passengers and 0.8 clo for staff). The distribution of TP widens further the thermal conflict. No change of the prevailing conditions preferred nearly 60% of passengers and only 40% of staff whose other 60% preferred to be warmer (figure 6-63a). On the contrary, the majority of passengers who required a change preferred cooler conditions. Similarly to LCY, the check-in hall in MAN T2 is one of terminal's few spaces where staff reported high overall comfort levels (79%) close to passengers' (93%), (figure 6-63b).

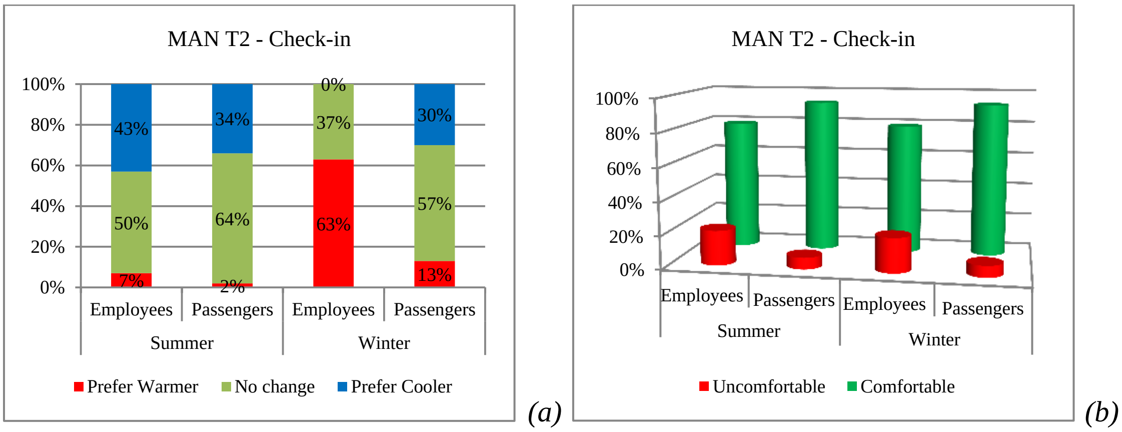



*Figure 6-63: Percentage distribution of (a) thermal preference and (b) overall comfort for passengers and staff in the check-in hall, MAN T2.*

Apparently, this was not the case with the search area, where in both summer and winter passengers and staff reported the highest discomfort levels and the warmest mean TS than in any other of terminal's spaces. But similarly to check-in, the figures depict a thermal conflict. Clothing insulation was very similar for the two groups at 0.5 clo in summer and 0.9 clo in winter.

In summer (23.7 °C), staff's mean TS was 1.7 and nearly all (93%) preferred cooler conditions (figure 6-64a). The particularly high mean score of TP (4.4) is suggestive of the frequently expressed preference for "much cooler". On the other hand, passengers' mean TS (1.1 units) was 0.6 units lower. With just over half the passengers preferring to be cooler and a respectful percentage (43%) requiring no change, the results demonstrate passengers' higher tolerance of warm conditions. This is also reflected in the significantly lower overall discomfort among passengers (20%) as opposed to 87% of uncomfortable employees (figure 6-64b).

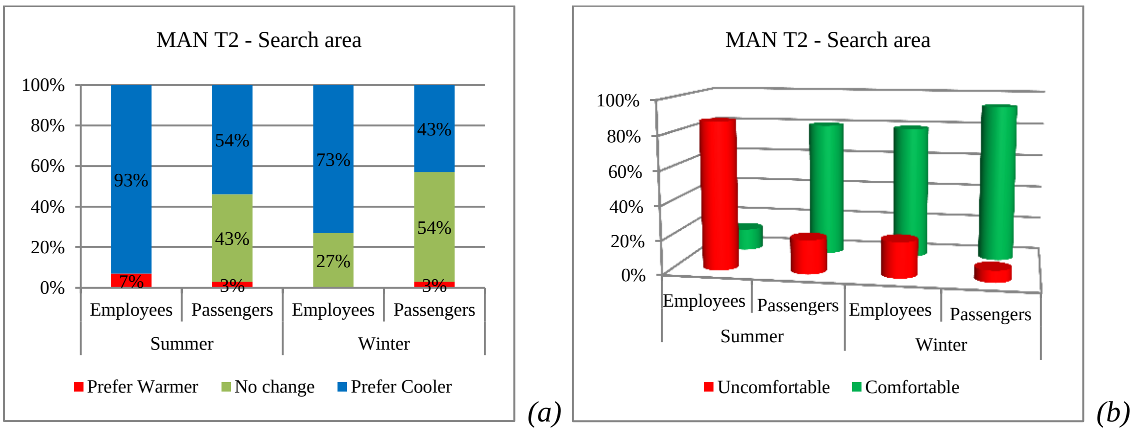



*Figure 6-64: Percentage distribution of (a) thermal preference and (b) overall comfort for passengers and staff in the search area, MAN T2.*

In winter (21.3 °C), the small difference in the mean TS of passengers (0.7) and employees (1.1) mean TS is statistically insignificant, but similarly to summer they expressed diversified TP. The majority of staff (73%) preferred a cooler environment whereas over half the passengers found the temperature “just right”. Even in this case, discomfort was higher among staff (three times higher in particular) reflecting the larger impact of thermal conditions on employees’ overall comfort.

The thermal conflict was not restricted in the landside spaces; a distinct thermal experience was revealed in the departures lounge. In this space there was a mixture of retail, airline and airport employees whose mean activity level (1.2 met) was slightly higher than passengers’ (1.0 met) who were mainly seated. Clothing for the two groups was similar (0.5 clo in summer and 0.8 clo in winter for passengers and 0.6 clo in both seasons for staff). However, the mean TS for passengers (0.5 in summer and winter) was constantly warmer than employees’ (-0.2 in summer and -0.4 in winter), accounting for a mean difference of 0.7 in summer and 0.9 units in winter.

Despite that staff’s mean TS was essentially “neutral”, the TP profile implies this was not the desired TS by almost half the staff in both seasons; nearly half preferred to be warmer in summer and the same percentage was equally split between “prefer cooler” and “prefer warmer” in winter (figure 6-65a). The considerable percentages of all three TP categories reflect the diverse preference between the different types of staff in this space. On the contrary, passengers vote was more solid, with 60% finding the temperature “just right” and the preference for cooler conditions being widespread among those who raised the need for a change in both seasons.

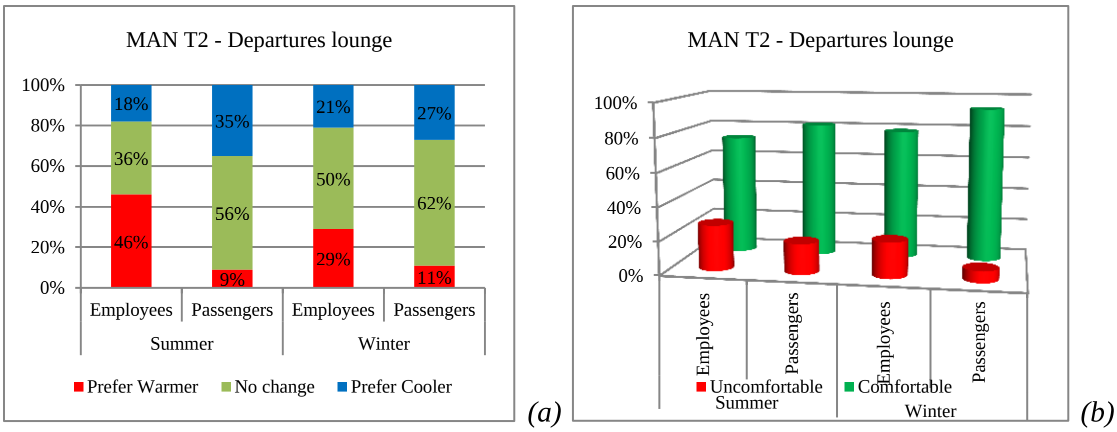



*Figure 6-65: Percentage distribution of (a) thermal preference and (b) overall comfort for passengers and staff in the departures lounge, MAN T2.*

Beyond the thermal conflict between passengers and staff, the results (figure 6-62) demonstrate the key role of activity levels as a differentiating factor between employees working in different terminal spaces. Representative is a comparison between the check-in hall, seating area and gates, all with the same mean temperature in winter (21.2 °C). The majority of employees in the check-in were airline staff with a mean clothing insulation of 1.0 clo. In the seating area, employees (mostly retail) were dressed on average in 0.9 clo. Having walked from the check-in hall to the gates, airline staff had removed 0.2 clo and presented a mean clothing insulation of 0.8 clo in the gates (table D-7, appendix D).

Despite the thermal uniformity, employees in these three spaces reported three distinct sensations in discordance to the clothing levels; -1.1 in the check-in where mostly sedentary tasks are performed, -0.1 in the seating area where staff is involved in standing light activities and 0.7 in the gates where walking succeeds standing light activity while boarding passengers. Comparable is also the retail area with just 0.2 °C higher mean temperature (21.4 °C). Retail staff dressed in 0.7 clo reported a mean TS of -0.7.

Similarly in summer, employees in the retail area (22.4 °C, 0.5 clo, 1.6 met) and airport staff in the arrivals (22.2 °C, 0.5 clo, 1.3 met) experienced a similar thermal environment but presented significantly different mean TS. Retail staff reported a mean TS of -0.5 whereas for employees in the arrivals hall this was -1.3, with the nature of work and therefore the activity level being a major differentiating factor.

The impact of activity is further highlighted in spaces with different thermal environment. In summer for instance, airline staff in the check-in hall (24.5 °C) experienced higher mean temperature than security staff in the search area (23.6 °C). The mean clothing insulation was 0.7 clo for the former and 0.5 clo for the latter. However, security staff reported (mean TS = 1.7) reported 1.6 units higher mean TS. In fact, security staff reported the highest mean TS in summer when the search area was the second warmest space on average, as well as in winter when temperature was nearly same to the other spaces.

### 6.7.4 Manchester Terminal 1

MAN T1 is a miscellany of spaces built years apart at varying standards and successively refurbished over the years. As a result, the terminal houses a variety of thermal environments with consecutive temperature changes and the highest temperature contrasts between its spaces.

Characteristic is the fluctuation of mean temperature across the spaces in winter. Having used the check-in 1 (21.7 °C), passengers experienced on average a temperature increase of nearly 2.0 °C while going through the search area (23.4 °C) to the seating area (23.6 °C), which was the warmest space at this time of the year. Keeping this as a reference point, the mean temperature in the main waiting areas ahead - departures lounge 2 (21.2 °C) and departures lounge 1 (21.9 °C) - drops by 2.4 °C and 1.7 °C respectively, while the corresponding mean temperature difference with the cooler gates in pier C and pier B was 3.4 °C and 4.7 °C.

Similar temperature variations occurred also in summer. The temperature from the check-in halls to the departures lounge 2 was around 22.0 °C. However, walking few meters away from the departures lounge 2 to the nearby departures lounge 1 (24.5 °C) people experienced a sharp temperature increase of 2.5 °C on average. Proceeding to gates in pier C (21.6 °C) or pier B (21.1 °C), people were subsequently coming across an average temperature drop of 2.9 °C and 3.4 °C respectively.

Representative of the influence of spatial design on the thermal environment is the temperature difference addressed above, between the neighboring departures lounge 2 and 1 in summer. As described in section 4.5.1, the two spaces are utterly different. Departures lounge 2 represents the older "boxed up" terminal spaces with small volume and complete lack of natural light (figure 6-66a). On the other hand, departures lounge 1 has about three times higher floor-to-ceiling height, covers nearly three times larger area and represents the large open plan spaces with glazed facades found often in modern terminal buildings (figure 6-66b). External heat gains are therefore the major differentiating factor in this case. In fact, departures lounge 1 is the only space in MAN T1 with extensive glazing and therefore was the warmest space in summer.

This is also the reason for the significant temperature difference between the departures lounge 1 and the nearby pier C (beg.). The latter is the continuity of departures lounge 1 and was originally designed as a gate lounge. However, it is predominantly used as an alternative waiting/seating area with children playground, where windows are shaded to prevent direct sun penetration. Along with its smaller volume, this was the reason that pier C (beg.) was regarded as a separate area (figure 6-66c). Indeed, the space was constantly cooler by 1.9 °C in summer and 2.1 °C in winter, functioning as a thermal transition space between the warm departures lounge 1 and the cooler gates in Pier C.


*(a)*

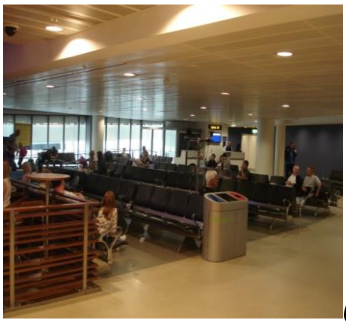
*(b)*

*(c)*

*Figure 6-66: (a) Dep. Lounge 2, (b) dep. Lounge 1 and (c) Pier C (beg.) are spaces with similar function but with different thermal profiles due to design dissimilarities.*

Other spaces of similar function but with different thermal conditions are the check-in halls 1 and 2. Check-in 2 is a level below check-in 1 and as a result of its significantly smaller volume – and particularly of its very low floor-to-ceiling height – it was on average 1.1 °C warmer in winter. Different thermal insulation rather than design features is a contributing factor for the temperature difference between piers C and B. The two have a very similar geometry but differ in terms of thermal insulation which is poorer in the older Pier C. The latter was on average 0.5 °C warmer in summer and 1.3 °C cooler in winter.

A comparison between the warmest and coolest terminal spaces is indicative of the wide temperature range in MAN T1. Being the coolest terminal area, arrivals hall was on average 4.7 °C cooler than the departure lounge 1 in summer and 6.2 °C cooler than the seating area in winter. While in most cases the temperature fluctuations across the spaces of MAN T1 are associated to changes in spatial characteristics, the distinct thermal environment in the arrivals hall was due to outdoor weather conditions. More specifically, the particularly low mean temperature in summer (19.8 °C) and winter (17.4 °C) was the result of its great exposure to outdoor weather through the north-orientated sliding doors. The doorway lacks of an appropriate protection, as the intermediate enclosure housing the doors in the respective facility at MAN T2 and the doors serving the check-in area at LCY.

The profiles of overall TS and TP (figure 6-67) reveal a wide-ranging thermal experience in accordance to the temperature fluctuations. Accordingly, the mean TS in summer was "slightly warm" in both check-in halls and search area, "neither cold nor hot" in the following four spaces and "slightly warm" again in the departures lounge 1. Subsequently, the average sensation for people in the pier B ahead was back to "neither cold nor hot", while for those diverted to pier C this was "neither cold nor hot" at its beginning (pier C beg.) and "slightly warm" TS in the gates. The fluctuations were wider in winter when TS ranged between "slightly cool" in the arrivals hall and "slightly warm" in the majority of other spaces.

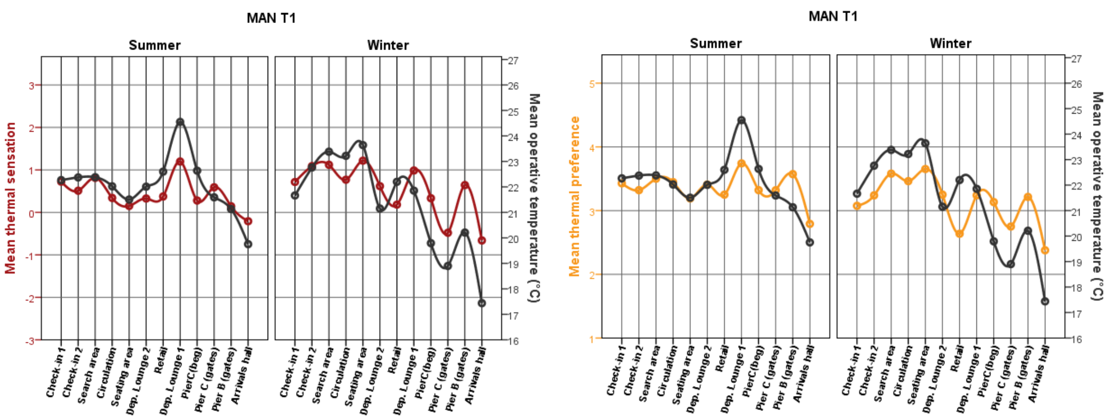



*Figure 6-67: Mean thermal sensation (left) and mean thermal preference (right), plotted against mean operative temperature for the different terminal spaces in MAN T1.*

A more thorough examination than that through the rounded TS scores associates the change of TS with the above-mentioned temperature fluctuations. The mean TS in the smaller and warmer check-in 2 (mean $T_{op}$ = 22.8 ºC, mean TS = 1.1) in winter was 0.4 units higher than in check-in

1 (mean $T_{op}$ = 21.7 ºC, mean TS = 0.7). Significantly wider, 1.1 units, was the mean TS difference between people in pier C (mean $T_{op}$ = 18.9 ºC, mean TS = -0.5) and pier B (mean $T_{op}$ = 20.2 ºC, mean TS = 0.6), also in winter. In summer, the mean TS in the departures lounge 1 (mean $T_{op}$ = 24.5 ºC, mean TS = 1.2) was on average 0.9 units higher than in the nearby pier C (beg.) (mean $T_{op}$ = 22.6 ºC, mean TS = 0.3) and the adjoining departures lounge 2 (mean $T_{op}$ = 22.0 ºC, mean TS = 0.3), as well as 1.0 unit higher than in the seating area (mean $T_{op}$ = 21.5 ºC, mean TS = 0.2). The arrivals hall was the only space where the mean TS lay on the cool side of the ASHRAE scale in both summer (-0.2) and winter (-0.7). It is characteristic that, compared to the warmest spaces of the terminal, the mean TS in this space was 1.4 and 1.9 units lower than in the departures lounge 1 in summer and in the seating area in winter respectively.

The spatial profiles of mean TS and TP for passengers and staff (figure 6-68) bear a strong resemblance to the respective profiles for LCY and MAN T2. Employees' profile fluctuates significantly even between spaces with similar temperature. Additionally, the figures are indicative of the different thermal comfort requirements and overall comfort levels between the two groups.

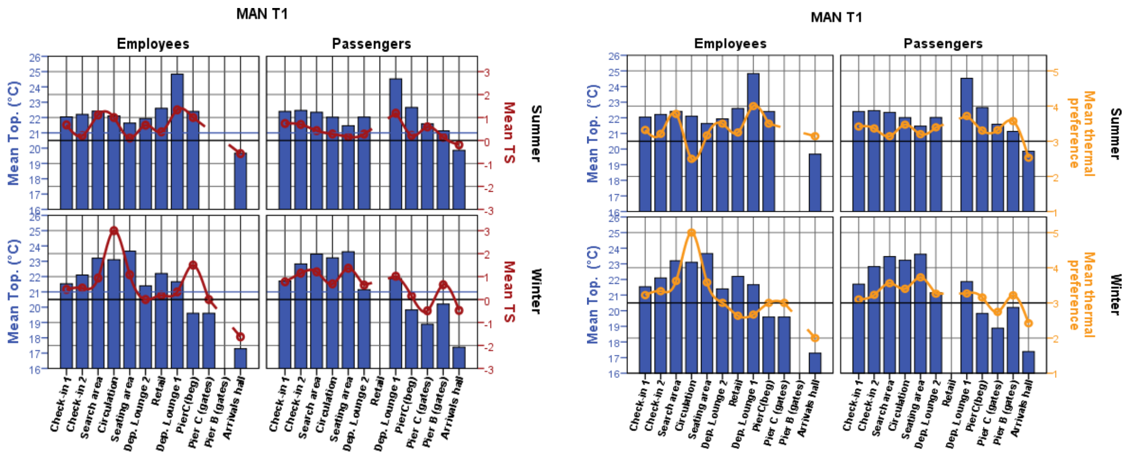
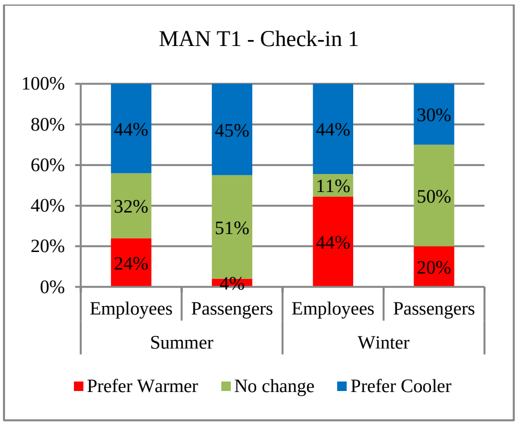


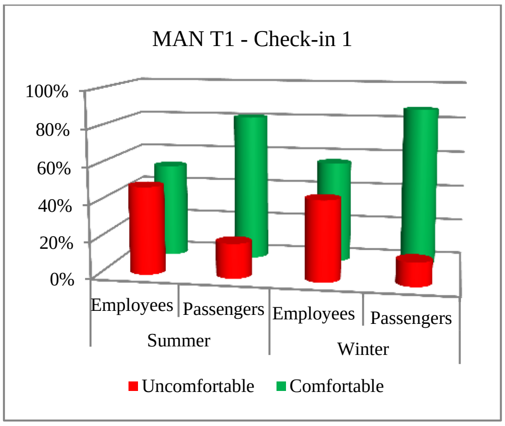

*Figure 6-68: Mean thermal sensation (left) and mean thermal preference (right), for passengers and staff in the spaces of MAN T1.*

Passengers in the check-in halls reported regularly higher mean TS than staff, as in MAN T2. Again, differentiating factors include primarily passenger mobility (to and within the space) and their transition from outdoors or semi-indoor environments (such as the air bridge) to indoors. Clothing was an additional parameter in winter when the mean values for the two groups differed widely.

In check in 1, passengers (mean TS = 0.8, mean clo = 1.0) reported 0.4 units higher mean TS than staff (mean TS = 0.4, mean clo = 0.8) in winter and similar TS at 0.7 in summer. In both seasons, however, TP differed significantly. Half the passengers required no change and preference for a cooler environment was dominant among the other half. On the contrary, the vast majority of employees preferred to be either cooler or warmer, with both categories expressing a considerable fraction (figure 6-69a). The particularly few employees finding the temperature right (only 11% in winter and 32% in summer) is reflected in the low levels (52-56%) of overall comfort reported (figure 6-69b).



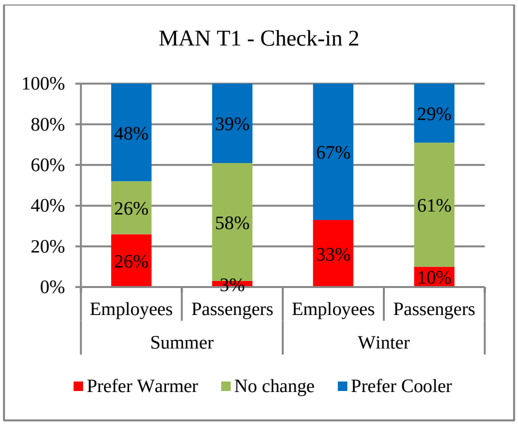
(a)



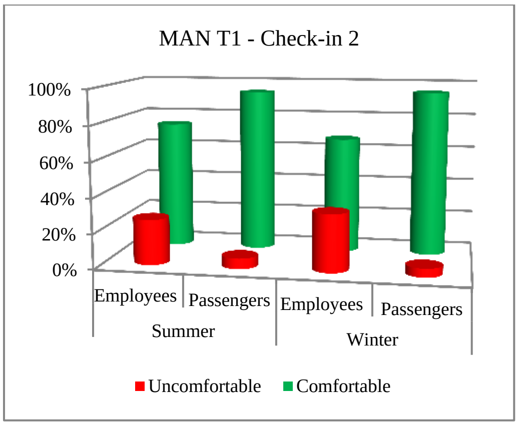
(b)

*Figure 6-69: Percentage distribution of (a) thermal preference and (b) overall comfort for passengers and staff in the check-in 1, MAN T1.*

In the smaller check-in 2, passengers' mean TS (0.7 in summer and 1.1 in winter) was consistently higher than staff's (0.2 in summer and 0.5 in winter). Nonetheless, about 60% of passengers required no change while the vast majority of employees preferred a different thermal environment (figure 6-70a). Similarly to check-in 1, and in spite of the sizeable percentage preferring to be cooler, the overwhelming majority of passengers was comfortable, while discomfort was reported by 26-33% of employees (figure 6-70b).



(a)



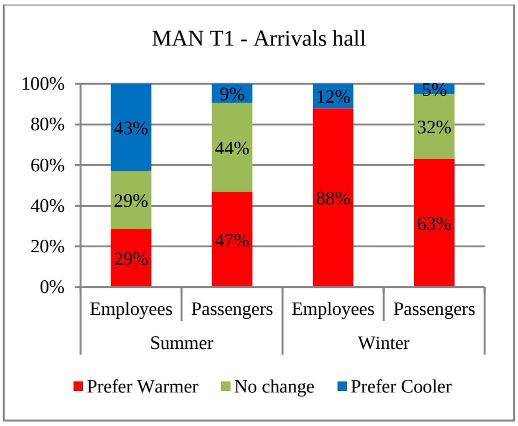
(b)

*Figure 6-70: Percentage distribution of (a) thermal preference and (b) overall comfort for passengers and staff in the check-in 2, MAN T1.*

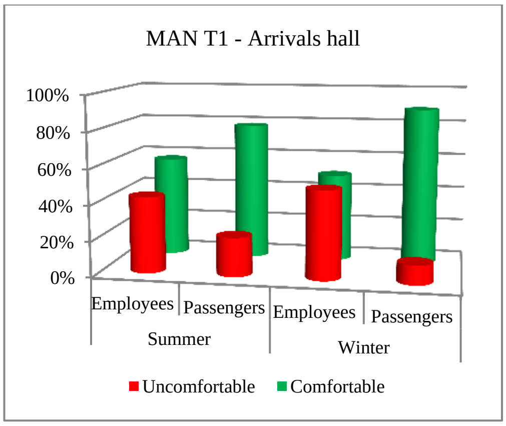
A different thermal experience was also revealed in the arrivals hall; in this case between arrived passengers and staff. In summer, passengers (mean clo = 0.6) and staff (mean clo = 0.8) experienced a mean TS of -0.2 and -0.6 respectively, with employees' TS being lower in spite of their higher clothing levels. The gap was wider in the cooler conditions in winter, when passengers (mean clo = 1.1) and staff (mean clo = 0.9) reported a mean TS of -0.5 and -1.6.

Contributing factors include the activity levels (seating for staff and walking with luggage for passengers), dwell time as well as and passengers' transition from different thermal environments (e.g. aircraft, circulation, baggage reclaim) before entering the arrivals hall. These characteristics are to a great extent common between passengers and the majority of people interviewed in the arrivals hall – meeters – and thus the two groups presented identical mean TS and TP scores. Similar pattern was found in the arrivals hall of MAN T2.

The duration of exposure to the indoor thermal conditions is undoubtedly a differentiating parameter between passengers and staff in all terminal spaces and a key factor in terms of tolerance. However, its role is far more profound in the arrivals hall where the difference in dwell time between passengers (most often few minutes) and staff is maximized. It is evident that the thermal conditions were not the preferred ones for both groups (figure 6-71a). However, the fraction of people requiring no change was significantly higher among passengers as a result of their short exposure to the specific conditions. In summer, "no change" represented 29% of staff and 44% of passengers. No employee expressed such preference in the particularly cooler conditions in winter, yet one out of three passengers required no change. The different impact on overall comfort is also evident; uncomfortable were nearly half the employees and 11-22% of passengers (figure 6-71b).



(a)



(b)

*Figure 6-71: Percentage distribution of (a) thermal preference and (b) overall comfort for arrived passengers and staff in the arrivals hall, MAN T1.*

Employees in the arrivals hall where dressed with higher clothing insulation than in any other of the terminal spaces in both seasons. This reflects their long-term experience and the respective expectation for cool conditions in the hall, which is also apparent from the constant use of a personal heater behind the information desk in winter. However, the TS and TP figures show that the particular interactive and reactive adjustments were insufficient to attenuate the effect of outdoor weather in the space.

Similarly to LCY and MAN T2, results for MAN T1 demonstrate that the nature of work – and therefore the respective metabolic rate – may differentiate the thermal requirements between employees. For example, airline staff in the check-in 2 experienced a mean temperature of 22.2 ºC in summer and reported a mean TS of 0.2. With the mean temperature being just 0.2 ºC higher in the search area and the mean clothing insulation being similar at 0.7 clo, security staff reported a mean TS of 1.1. In fact, the search area of MAN T1 was characteristic of the high TS reported regularly by both passengers and staff (1.1 in summer and 0.9 in winter for staff, 0.4 and 1.2 for passengers respectively) as well as for the low overall comfort levels (e.g. uncomfortable were 33% of staff and 47% of passengers in winter). This is fairly consistent with the figures for the respective areas of MAN T2 and LCY, suggesting that the particular function has an increasing effect on TS and decreasing effect on overall comfort due to staff's high activity levels and passenger stress.

### 6.8 Summary

The results shed light on the nature of comfort conditions in airport terminals with the thermal environment being the focus of the data analysis. Each of the buildings surveyed presented a distinct thermal character (section 6.7). Overall building size, spatial design, operational profile and outdoor weather were among the parameters influencing the thermal environment and overshadowing the HVAC systems in certain cases.

Formative factors for the thermal profile of LCY are its compactness, spatial homogeneity and occupancy levels. The first two were responsible for the very narrow temperature range (table 6-5) and the uniform thermal environment (table 6-26), where temperature fluctuations were predominantly occupancy-driven (figures 6-5 and 6-11a). Thermal uniformity was also found between the spaces of MAN T2, where the extensive use of glazing and the particular occupancy profile played a key role in summer and winter respectively. On the other hand, the diversity of spaces in MAN T1 resulted in a variety of thermal environments, characteristic for the wide temperature differences.

Temperature, clothing and activity levels comprise the set of variables identified to explain better thermal sensation (table 6-10). The examination of "clothing" variable showed that outdoor rather than indoor thermal conditions have a greater impact on people's outfits (figure 6-8). Metabolic rate was found to play a key role in the differentiated thermal sensation reported across the terminal areas and particularly in the warmer sensations experienced in spaces with intensive activity. Occupancy levels – expressed via $CO_2$ concentration – were also shown to impact thermal sensation, with the relationship between the two revealing an increasing trend of thermal sensation in overcrowded conditions (table 6-9, figure 6-11). Reflecting the diverse activity and clothing levels as well as the impact of space and function on thermal perception, a cross examination of thermal sensation and preference votes revealed that neutral was not the desired thermal state for over half the terminal occupants (figure 6-13).

In spite of the diverse thermal profiles, a regular discrepancy between occupant thermal requirements and thermal conditions encountered was common between the case studies. More than half the interviewees expressed a preference for a thermal environment other than the one experienced (figure 6-20). In all terminals, the thermal profile leaned closer to the upper boundary of the 80% and 90% acceptability temperature range and often surpassed it (figure 6-19). The average thermal sensation was constantly on the warm side of the ASHRAE scale (table 6-7) and preference for higher air movement (figure 6-14b) and cooler conditions was dominant among those requiring a change. In accordance, cooler temperatures by 0.7 - 2.1 °C were preferred, while thermal neutrality was found 1.6 - 2.8 °C lower than the mean indoor temperature (table 6-19).

These results demonstrate also that warm rather than cool conditions can be an issue for the terminal population in both summer and winter. On the other hand, the winter figures for MAN T1 and MAN T2 – where the lowest temperatures occurred – show that people were still comfortable at temperatures lower than the ones preferred, providing therefore evidence of tolerance under cooler conditions (table 6-19). Accordingly, the calculation of the 80% and 90% acceptability temperature ranges indicated that occupants in the terminals can accept wider temperature ranges than those recommended by CIBSE and ASHRAE.

Furthermore, the data analysis revealed a discrepancy in the comfort conditions between passengers and staff. The thermal requirements of the two groups differ significantly (table 6-25), resulting in thermal conflict across the terminal spaces (sections 6.7.2 - 6.7.4). On average, neutral temperature for passengers was lower by 1.0 °C in summer and by 2.2 °C in winter than for employees, who were more sensitive to temperature changes (figure 6-35). For both groups, thermal neutrality was found at temperatures cooler than the mean indoor temperature (with the exception of staff in MAN T2 in winter). For employees, however, neutrality was constantly closer to the mean temperature as a result of their long-term acclimatisation to the indoor environment. Aligned with the neutrality discrepancies, passengers' preferred temperature was found lower than staff's in all cases; on average lower by 0.8 °C in summer and by 1.5 °C in winter.

The 80% and 90% acceptability temperature ranges were significantly wider for passengers (e.g. the 80% acceptability range was on average 4.0 °C wide for staff and 6.0 °C wide for passengers; table 6-23), demonstrating their higher level of tolerance of the thermal environment and consequently their wider adaptive capacity. The latter was also evident from the more stable profile of thermal sensation and preference for passengers opposed to the highly fluctuating profile for staff across the terminal spaces (figures 6-54, 6-62 and 6-68).

Regarding the lighting environment, the results show that bright rather than dim conditions were preferred in all terminals (figures 6-23b and 6-24). People demonstrated their consistent preference for natural light (figure 6-25b), even in cases where this was deemed to be sufficient (as in the case of MAN T2). Interestingly, a common trend was revealed in all cases, suggesting that preference for natural light follows the endogenous clock associated to the light-dark cycle. Preference for more daylight was peaking during the morning hours, declining thereafter in the day and turning into a preference for "no change" towards the sunset (figure 6-26).

The comfort gap between passengers and staff was further highlighted in the field of lighting, with the two groups often assessing differently the lighting environment (figure 6-39). For the majority of passengers lighting levels were just right and preference for brighter conditions was dominant among those requiring a change. On the contrary, nearly half the employees preferred different lighting conditions, and unlike passengers, a considerable fraction (about 20%) preferred a dimmer environment (figure 6-38). The experience of glare discomfort and the assessment of light distribution by the two groups (figure 6-40) are also representative of the different perspectives towards the lighting environment.

The divergent assessment of the lighting environment and the different thermal requirements between passengers and staff express in fact a gap between the needs for indoor and transitional comfort, arising from the different perception of the terminal as workspace vs. transition space. This was also highlighted in the indirect assessment of perceived importance of the indoor environment for the two groups. The findings indicate that thermal conditions were the top issue raised negatively among employees, whereas passengers were more concerned with matters such as seating, amount of space and time (figure 6-44). The different perception of the terminals as transition vs. workspace is further reflected in the overall comfort of the two groups; discomfort was expressed by only 8-21% of passengers and by 23-49% of employees (figure 6-72).

Overall, the results can be utilised towards the improvement of indoor comfort and the reduction of the large amounts of energy consumed in airport terminals. In addition, the broader outcomes can be useful in the refurbishment of existing terminals and the design of new terminal facilities.


*Figure 6-72: Percentage of (un)comfortable passengers and staff.*

# CHAPTER 7: CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

## 7.1 Introduction

Airport terminals are a particularly complex building type where the needs of very different population groups are accommodated. With air travel on the rise and forecasted to post strong growth numbers in the decades ahead, new terminals are built while existing facilities are growing larger. In this framework, the terminal's interior environment is becoming increasingly vital to its commercial success and holds a key role in the airport's operational cost.

With the thermal environment being the focal point, the study investigated the nature of comfort conditions in three airport terminals. During the seasonal field surveys in LCY, MAN T1 and MAN T2, the indoor environment was extensively monitored across the different terminal areas where 3,087 people were interviewed for the evaluation of comfort conditions. Overall function and mechanical ventilation were the only common features between the otherwise very different terminal buildings. Dissimilarity in building size and capacity, in passenger traffic as well as in terminal design and spatial characteristics allowed for a representative range of indoor conditions commonly encountered in airport terminals.

## 7.2 The thermal environment

The investigation of the distinct thermal profile of each building highlighted the importance of terminal design and the effect of certain particularities on the indoor environment. As a result of its small size and spatial homogeneity, LCY presented a very narrow temperature range (4.4 °C in summer and 3.6 °C in winter; table 6-5) and a uniform thermal environment across its spaces (table 6-26). Although beneficial in terms of fast passenger processing, the terminal's compactness presented a major thermal drawback during busy times. The HVAC system could not cope efficiently (figure 6-51) with the large volume of passengers handled at peak times and the thermal environment was largely occupancy-driven, as demonstrated by the similar mean hourly profiles of temperature and $CO_2$ (figure 6-5). With the exception of gate lounges where the mean temperature is representative of the nearly free-running conditions (table 6-26), outdoor temperature had no essential impact on the indoor environment (figure 6-4).

On the contrary, as a result of air quality controls and the extensive use of glazing, 50% of the temperature variance in MAN T2 was associated to outdoor temperature (figure 6-4). External heat gains were a major contributing factor for the higher temperatures in summer (table 6-26) and for the particularly high mean temperature (24.6 °C) in the check-in hall. Similarly to LCY, the thermal environment of certain spaces was influenced by occupancy levels, (figure 6-59a) with the overall effect, however, being smaller due to the larger volume of spaces and the use of air quality sensors. A high mean temperature (23.7 °C) was also encountered in the search area in summer, with this case, however, representing an example of space - function mismatch to avoid. Prior to its current use, the area consisted of different office rooms which were overhauled into a single open-plan area. The unevenly distributed vents along with the particularly low floor-to-ceiling height resulted in the insufficient conditioning of the space. This was more profound in the busy summer period due to the increased internal heat gains from people and screening systems. On the other hand, the uniform thermal profile in winter reflects the terminal's operational particularity at this time of the year. With the external heat gains having a minor effect and with prolonged periods of time with very low occupancy, the mean temperature was very close to 21.0 °C (temperature set-point) throughout the terminal spaces.

MAN T1 reflects the evolution of an old terminal over the years. Built years apart and refurbished a number of times, its areas comprise an assortment of different design trends ranging from the old "boxed up" style to modern spaces. Consequently, the terminal houses a variety of thermal environments with successive temperature changes across its spaces (figure 6-67 and table 6-26) and a wide temperature range (6.3 °C in summer and 9.4 °C in winter; table 6-5). Representative of the temperature contrasts entailed by design dissimilarities is the mean temperature difference between the neighboring departures lounge 1 and 2 in summer (2.5 °C), as well as that between the check-in halls 1 and 2 in winter (1.1 °C; section 6.7.4). A distinct thermal environment, however, exists in the arrivals halls where the low mean temperatures (19.8 °C in summer and 17.4 °C winter; table 6-26) testify the impact of outdoor weather on the indoor conditions.

### 7.3 Comfort requirements

The set of variables identified to explain better TS consists of temperature, clothing insulation and 15′ met in the case of LCY, supplemented with the square root of air movement for MAN T1 and MAN T2 (table 6-10). Clothing diversity is among the key factors responsible for the complex nature of thermal comfort in airport terminals. Characteristic is the range of insulation levels encountered; 0.20 clo to 1.29 clo in summer and 0.43 clo to 1.89 clo in winter. In all cases, people's outfits were more influenced by outdoor rather than by indoor temperature (figure 6-8). Despite that lower outdoor temperatures prevailed during the winter surveys in MAN T2 (figure 6-3), passengers' mean clothing insulation was lower than in MAN T1 and LCY (table 6-6). Given that MAN T2 serves predominantly holiday destinations in warmer climates, this suggests that destination was also among the parameters affecting passenger outfits.

Activity levels were found to differentiate TS in spaces of different function, as well as within a space where people performed different tasks. Occupancy levels were also shown to impact TS, with the relationship between the two (table 6-9) demonstrating an increasing trend of TS in overcrowded conditions (figures 6-11, 6-52 and 6-59b). A common feature between the search areas in all terminals was the high mean TS scores. In particular, it was the highest among all spaces in MAN T2 (1.2 in summer and 0.8 in winter; figure 6-61), the highest in LCY during summer (1.7; figure 6-53) and the second highest in MAN T1 (0.8 in summer and 1.1 in winter; figure 6-67). The consistency of these figures - irrespective of thermal conditions - highlights the key role of activity, congestion and stress in the thermal experience in such spaces. Reflecting the diversity of parameters affecting thermal perception, a juxtaposition of TS and TP votes revealed that neutral was not the desired thermal state for more than half the interviewees (figure 6-13). The same finding applies to both passengers and staff (figure 6-34).

Before addressing the comfort requirements, it is important that the broader subject of indoor comfort in terminals is placed in the right framework in terms of people’s perspective. The relationship established between the subjective assessments of indoor environment and overall comfort showed that the environmental conditions have an impact on overall comfort (section 6.5.6.1) and consequently on occupant terminal experience. Nevertheless, people were not concerned with the indoor environment unless conditions were viewed negatively (figure 6-29). This implies that in such facilities a comfortable indoor environment is expected; therefore occupants were not concerned with it unless expectations were belied and conditions were deemed to be unsatisfactory.

In this context, the indoor environment and thermal conditions in particular were becoming equally weighty to common concerns such as amount of space/crowding and seating. In accordance with the view of temperature as the most important environmental factor (air freshness comes 2$^{nd}$; figure 6-28), more people were concerned with the thermal conditions than with any other dimension of the indoor environment (figure 6-30). This is merely because temperature was more frequently the issue in the specific buildings. Therefore, it does not necessarily indicate that thermal conditions get in general the highest perceived importance among the indoor environmental aspects in airport terminals.

The baggage reclaim area of LCY in winter is a representative case of a space where both thermal and air quality issues were encountered, but it was the latter that received a higher ranking. The space is adjacent to the apron where aircrafts are parked angled nose-out. When parking stands in close proximity were in use, there was an inflow of aircraft fumes through the baggage conveyors. The space was also among the most frequently overheated terminal areas (temperature exceeded the 80% acceptability range for 35% of the monitoring time). Nonetheless, no thermal issues were raised while air quality was highlighted as the major concern by nearly 40% of interviewees.

The thermal profile of all three terminals was closer to the upper limit of the 80% acceptability temperature range which was often surpassed (figure 6-19). Accordingly, the mean TS lay on the warm side of the ASHRAE scale in both seasons (table 6-7) and over half the population at each terminal required variation in the thermal environment (figure 6-12). Air movement was particularly low in all cases and reflected in the respective assessment (figure 6-14a). Preference for higher air movement (36-46% in summer and 31-47% in winter; figure 6-14b) and cooler conditions (40-44% in summer and 26-53% in winter; figure 6-20) was expressed by a high percentage of respondents and was dominant among those requiring a change.

The thermal distance between occupant requirements and conditions experienced was quantified through neutral and preferred temperatures. Thermal neutrality was found 1.6 - 2.8 °C lower than the mean indoor temperature (1.6 - 1.9 °C in summer and 1.9 - 2.8 °C in winter; table 6-18) and cooler temperatures by 0.7 - 2.1 °C were preferred (1.4 - 2.0 °C in summer and 0.7 - 2.1 °C in winter; table 6-19). The winter figures for MAN T1 and MAN T2, where the lowest temperatures occurred, demonstrate people's tolerance of cooler conditions. Similarly to summer, the bulk of unacceptable sensations were on the warm side of the scale (figure 6-10). Preferred temperature was 20.6 °C in MAN T1 and 20.2 °C in MAN T2, however, occupants were still comfortable at 19.4 °C and 18.3 °C respectively. These results suggest that warm rather than cool conditions can be an issue for the general population.

"Bright and airy" was a common phrase among interviewees in the "like/dislike the most" questions and largely reflects the preferred conditions. "Airy" can be multi-interpretable. Subsequent clarifications included references to the size and/or openness of the space, the fine illumination with an emphasis placed on natural light and to the pleasant temperature or air movement. The latter is in agreement with the results above and also with the considerable percentage of people (31-43%) preferring no change while having assessed the air movement as high (figure 6-15). Spaciousness and openness were among the most frequent aspects viewed positively (incorporated in "amount of space" and "space design/aesthetics"; figure 6-30).

As far as lighting is concerned, it was shown that bright rather than dim conditions were preferred in all terminals (figures 6-23b and 6-24). As a matter of fact, lighting was the environmental aspect to receive the highest positive response in MAN T2 (15%; figure 6-30) where natural light abounds. In general, where lighting-related issues were raised, the (in)sufficiency of daylight was most commonly the reason. References to artificial lighting were few (e.g. about the "river of light" in the seating area of MAN T1). In all terminals, people demonstrated their desire for natural light (figure 6-25b) which can have significant implications for the design of terminal buildings. The extent of this desire was further highlighted in MAN T2 where the majority acknowledged the sufficiency of natural light, yet nearly half the interviewees preferred even more. Moreover, a relationship between time and preference over daylight was revealed in all cases (table 6-20). The results indicate a stronger preference in the morning hours which decays later in the day and turns into a preference for "no change" towards the sunset (figure 6-26), suggesting that preference for natural light follows the endogenous clock associated to the light-dark cycle.

### 7.4 Indoor vs. transition space

Providing a comfortable indoor environment becomes more intricate when accounting for the comfort requirements of passengers and staff, shown to vary considerably. Passengers' neutrality and preferred temperatures lay below the mean operative temperature in all cases. On average, they preferred cooler temperatures by 1.6 °C in summer and 1.3 °C in winter and felt neutral at temperatures lower than the mean temperature by 1.9 °C in summer and by 2.4 °C in winter.

Except from the winter cases of staff in MAN T1 and MAN T2, employees also preferred cooler temperatures and achieved neutrality at lower levels than the mean temperature. For staff in MAN T2, neutral and preferred temperatures were higher than the mean temperature reflecting the terminal's operational particularity. More specifically, this was the combined result of staff's reduced activity levels and the cool conditions prevailing during the prolonged periods of very low occupancy. With the mean temperature at 21.3 °C in MAN T1, employees preferred a slightly higher temperature (21.7 °C) but were still comfortable at 20.6 °C, demonstrating some tolerance of cooler conditions. However, significantly higher tolerance levels were demonstrated by passengers who preferred 20.6 °C and they were also comfortable at 19.2 °C. Similarly, in MAN T2, passengers experienced a mean temperature of 21.1 °C, preferred the temperature to drop to 19.9 °C but they were still comfortable at 18.4 °C.

The juxtaposition of the thermal requirements for the two groups quantifies the thermal conflict (table 6-25). Passengers achieved neutrality at lower temperatures than staff by 0.6 - 3.9 °C. On average, this was lower by 1.0 °C in summer and by 2.2 °C in winter. In accordance with the neutrality discrepancies, passengers' preferred temperature was 0.4 - 2.0 °C lower than employees'; on average lower by 0.8 °C in summer and by 1.5 °C in winter. All differences were greater in winter when clothing insulation was higher for passengers (table 6-6), as a result of the higher impact of outdoor temperature on their outfits (figure 6-9). In all cases, it is evident that staff's neutrality and preferred temperature were constantly closer to the mean temperature. This underscores their long-term acclimatisation to the terminals' thermal environment, resulting from the long dwell times and the continuous experience with it.

In spite of staff's familiarity with the indoor thermal environment, the results show that passengers have a wider adaptive capacity. Solid evidence comes also from other findings. Employees were 1.6 times on average more sensitive to temperature changes than passengers (figure 6-35). In all terminals, staff's TS and TP profile fluctuated significantly across the spaces while passengers' was more stable (figures 6-54, 6-62 and 6-68). More importantly, the 80% and 90% acceptability temperature ranges were significantly wider for passengers, indicating their higher tolerance of warmer conditions as well. The 80% range was on average 6.4 °C wide in summer and 5.8 °C wide in winter for passengers, restricted to 4.0 °C for staff in both seasons (table 6-23).

Lighting was another field of diverging assessments between the two groups across the terminal spaces (figure 6-39). The majority of passengers (70%) found lighting just right and preference for brighter conditions was widespread among those requiring a change. On the other hand, about half the employees preferred a different lighting environment in their workspace, and unlike passengers, a considerable percentage (about 20%) preferred dimmer conditions (figure 6-38). The experience of glare discomfort (as reported by 40% of staff and by only 10% of passengers; figure 6-40b) and the assessment of light distribution (deemed to be well distributed by 57-75% of staff and by 75-89% of passengers; figure 6-40a) are also representative of the different perspective towards the lighting environment.

Overall, the results indicate that passengers view the terminal as a transition space, with the consistency of the findings among the case studies highlighting such facilities as places of conflict between indoor and transitional comfort. Indicative are also the "dislike the most" responses received from the two groups. The thermal environment was ranked 6$^{th}$ among passengers' worst aspects of MAN T1 and 5$^{th}$ for LCY and MAN T2, with only 4-6% of the passenger population raising a thermal issue. On the contrary, thermal conditions were ranked first among staff in all terminals, concerning the most 34-40% of employees (figure 6-44).

Illustrative of the higher impact of thermal conditions on staff's overall comfort is figure 7-1[15]. The highest discomfort levels among employees emerged in the terminal spaces identified as the most thermally-problematic; arrivals halls in MAN T1 and search area in MAN T2. On the

[15] All spaces comprising the broader departures lounge area are unified and labelled "departures lounge".

other hand, the highest discomfort levels among passengers are 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 (figure 7-1b). To the extent that discomfort and stress are interdependent, the figures are comparable with the travel stress curve (figure 2-4) which implies that higher levels of stress are expected in the check-in, security points and boarding. The existence of these trends could not be investigated for LCY due to the insignificant number of interviews in the search area and gate lounges. However, the perceived difference of the terminal as indoor workspace vs. transition and its impact on comfort was strongly expressed for all cases in the overall comfort levels (figure 6-72).

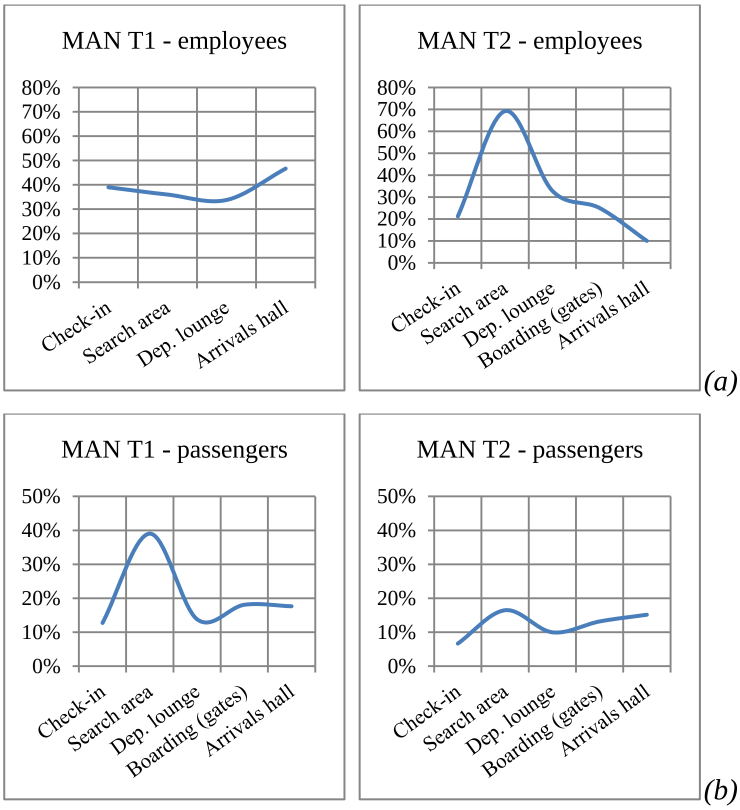



*Figure 7-1: Percentage of uncomfortable (a) employees and (b) passengers in the terminals spaces.*

The overall results for passengers are consistent with the broader context of adaptation to the thermal environment. 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 efficiently with uncomfortable conditions. Additionally, an important element of their wider adaptive capacity is the short dwell time. On the other hand, the rigid working conditions for staff originate from the terminal function and form a very limited adaptive capacity. Characteristic is the high percentage of staff rating the clothing policy as “inflexible” for maintaining its thermal comfort (30-40%) and the lack of controls over the indoor environment, as reported by the vast majority of employees (86-94%).

Individual and perceived control has been shown to be equally weighty to thermal variables in thermal comfort assessments and to have a significant impact on occupant comfort and satisfaction (Paciuk, 1990; Fountain et al., 1996; Mahdavi and Kumar, 1996). Therefore, providing terminal staff with means of controlling its immediate thermal environment can be a key action towards the elimination of the comfort gap between passengers and employees. For instance, the – approved by the health and safety regulations – use of small radiators would allow check-in staff to cope with local discomfort caused by air draughts from baggage conveyors and opening doors.

## 7.5 Energy implications

Ultimately, understanding the thermal environment in airport terminals and the comfort requirements of people using these facilities can improve significantly thermal comfort conditions. Also, the outcomes of this project can be utilised towards the reduction of energy consumption in these energy-intensive buildings. With the target set at 80% general acceptability, the results showed that people can accept on average a temperature range of 6.1 °C in summer and 6.7 °C in winter (table 6-18). This is considerably wider than the range recommended by CIBSE for the majority of terminal spaces (tables 7-1 and 7-2).

*Table 7-1: Winter comfort requirements juxtaposed with CIBSE comfort criteria.*

| Results from the three terminals | | | |
|---|---|---|---|
| | $T_{mean}$ (°C) | $T_{pref.}$ (°C) | 80% accept. (°C) |
| LCY | 23.4 | 21.3 | 19.7 – 23.4 |
| MAN T1 | 21.3 | 20.6 | 16.4 – 22.3 |
| MAN T2 | 21.1 | 20.2 | 13.1 – 23.6 |

| CIBSE comfort criteria | |
|---|---|
| Terminal area | Temperature range (°C) |
| Check-in areas | 18.0 – 20.0 |
| Customs area | 18.0 – 20.0 |
| Departures lounge | 19.0 – 21.0 |
| Baggage reclaim | 12.0 – 19.0 |
| Concourse (no seats) | 19.0 – 24.0 |

Alongside the 80% acceptability ranges, preferred temperatures indicate a great potential for energy savings in winter by lowering the heating set-points without compromising thermal comfort conditions (table 7-1). The potential is larger for LCY, where overheating was more profound in winter and the distance between mean and preferred temperature is 2.1 °C wide. The respective difference is nearly 1.0 °C for MAN T1 and MAN T2.

On the contrary, the results suggest that an increase of the cooling set-points in summer would not be consistent with people's thermal requirements. As shown in figure 6-19, the thermal profile of all terminals was close to the upper limit of the 80% acceptability range and preferred temperatures imply that more cooling was required (table 7-2). In such cases, alternative means can be employed for the elimination of peak temperatures, e.g. use of phase change materials (PCM). Modelled in an airport terminal, the application of PCM was shown to prevent overheating in the summer months while reducing peak temperatures up to 3.0 °C (Gowreesunker and Tassou, 2013; Gowreesunker et al., 2013). Moreover, demand control ventilation strategies are nowadays gaining ground in airport terminals (ACRP, 2010a) and they can be particularly energy-efficient in terminals with irregular occupancy profiles (e.g. MAN T2).

*Table 7-2: Summer comfort requirements juxtaposed with CIBSE comfort criteria.*

| Results from the three terminals | | | |
|---|---|---|---|
| | $T_{mean}$ (°C) | $T_{pref.}$ (°C) | 80% accept. (°C) |
| LCY | 23.3 | 21.3 | 18.1 – 24.8 |
| MAN T1 | 22.0 | 20.6 | 17.6 – 23.3 |
| MAN T2 | 23.0 | 21.0 | 18.2 – 24.1 |

| CIBSE comfort criteria | |
|---|---|
| Terminal area | Temperature range (°C) |
| Check-in areas | 21.0 – 23.0 |
| Customs area | 21.0 – 23.0 |
| Departures lounge | 22.0 – 24.0 |
| Baggage reclaim | 21.0 – 25.0 |
| Concourse (no seats) | 21.0 – 25.0 |

The PMV index is used as an input parameter for the design and assessment of energy performance of buildings. The study included it in the data analysis and tested its accuracy in the mechanically ventilated terminals. The index led to considerably narrower ranges and predicted significantly cooler sensations for both seasons (figure 6-10). The mean absolute TS-PMV discrepancy ranged between 1.04 and 1.67 units and was higher for summer (table 6-8). In addition, PPD implied a higher percentage of dissatisfied in summer, whilst more "unacceptable" sensations were reported during winter in all terminals. Consequently, the PMV-based neutral temperatures for the general population as well as for passengers and staff were higher than the actual ones.

More specifically, predicted neutrality was found higher by 1.0 - 7.6 °C (table 6-18) with the smallest discrepancy corresponding to LCY in winter, where the narrowest temperature range occurred. For passengers and staff neutrality was predicted at temperatures higher on average by 3.5 °C and 5.3 °C, with the respective acceptability temperature ranges being essentially inapplicable to mechanical ventilated buildings in a mild climatic zone (tables 6-23 and 6-24). It is evident that PMV is not a reliable tool for the highly dynamic conditions in airport terminals.

### 7.6 Recommendations for future work

This work shed light on the thermal environment and the diverging comfort requirements accommodated in airport terminal buildings. It is the first study to conduct extensive field surveys in different terminals and use a large sample population representative of the different groups occupying these facilities. As such, it provides a solid platform for investigating thermal comfort conditions in airport terminals.

A key topic associated with the findings of this research warrants further investigation. Staff's TS did not always fluctuate in accordance with the temperature profile across the terminal spaces (figures 6-54, 6-62 and 6-68), implying diverging thermal requirements among employees engaged in activities of different intensity. A series of statistical tests was first conducted to investigate potential differences in TS, TP and overall comfort between the different types of staff, with the results being often inconsistent between the case studies. This is likely because of the impact of each terminal's particularities on staff's variable in question. An attempt to evaluate neutral temperatures for the different staff types provided evidence of differentiation (table G-1, appendix G). For instance, neutrality for retail employees was found higher than for airport and airline staff in MAN T1 and significantly higher than security staff in MAN T2. However, the temperature range was not sufficiently wide in all cases. Consequently, some models did not reach statistical significance thus preventing the conduction of further analysis. Given that the evidence exists, it is important that the different thermal requirements of staff types are further explored and quantified.

The study assessed indirectly the perceived importance of environmental conditions and of the thermal environment in particular. The assessment was based on the assumption that a person who reports to like or dislike a certain condition the most, views that condition as important (not necessarily the most important). Certainly, a direct assessment of satisfaction (e.g. by means of a three-point scale) would eliminate the vagueness of (dis)satisfaction underlying the preference votes for "a bit" different environment.

Moreover, it is important that the dataset is enriched by further research on airport terminals located in different climatic zones. This will allow the extraction of useful conclusions about the extent of the comfort gap between passengers and staff and the impact of outdoor weather on it. Future work could also explore the relevance – in terms of comfort requirements – between airport terminals and other building types with similar attributes. Shopping centres, for example, are comparable to terminals in that they accommodate large and diverse populations in a variety of indoor environments. The evaluation of comfort conditions in such facilities can provide a comparative assessment of the diverging comfort requirements of passenger and staff vs. visitors and staff, and resulting in conclusions that explain the impact of the building's operational nature on the comfort gap.

The findings of this study can be a useful input for the rising demand control ventilation strategies that take into account flight schedule and outdoor weather data. It is important that research on the evaluation of indoor comfort conditions in airport terminals will be conducted along with energy performance assessments. This will allow the quantification of energy savings achieved through different energy efficiency measures while accounting for occupant needs that are evaluated through subjective assessments of the indoor conditions, and not via PMV which was shown to be an unreliable tool for such environments.

Unlike other building types, airport terminals lack of a systematic and efficient way to benchmark their energy use. To a great extent, this is because of the wide variations among terminal buildings. Therefore, it is necessary that future work tracks and analyses energy data with the view of developing benchmarks that will assist airports' decision-making on retrofit interventions. Last but not least, the outcomes of this project can influence the design of new terminal buildings as well as the refurbishment schemes of existing facilities, which are subject to much internal change and external growth in response to the increasing passenger volumes and the evolving nature of aircraft design.

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## APPENDIX A: Questionnaire

Date: …………Location in terminal:……..……...Start Time: ……………Gender: □ Female □ Male

Current Activity: □ Seated □ Standing □ Standing, light activity

**SECTION A**

**Q1. What is the main purpose of your visit to the airport today?**

□ Working here as…………………….□ Travelling to…………………...for □leisure or □business

□ Meeter / Greeter □ Other……………………...................

**Q2. How long have you been in this terminal building?**

□ <15 mins □ 15-30 mins □ 30-60 mins □ >60mins

**Q3. What was your activity in the last 15 minutes?**

□ Seated, relaxed □ Sedentary activity □ Standing, light activity

□ Standing, medium activity □ Walking □ Other………………...

**Q4. Have you modified your clothing during the past 15 minutes?**

□ Yes, clothes on □ Yes, clothes off □ No

**Q5. Have you consumed any drink in the last 15 minutes?**

□ Yes ( □ Hot drink □ Cold drink ) □ No

**SECTION B**

**Q6. How do you feel at the moment?**

□ Cold □ Cool □ Slightly Cool □ Neither cold nor hot □ Slightly warm □ Warm □ Hot

**Q7. How would you prefer to be at the moment?**

□ Much warmer □ A bit warmer □ No change □ A bit cooler □ Much cooler

**Q8. How would you describe the air movement at the moment?**

□ Very low □ Low □ Neither low nor high □ High □ Very high

**Q9. Would you prefer the air movement to be:**

□ Much more □ A bit more □ No change □ A bit less □ Much less

**Q10. What do you think of the air at the moment?**

□ Stuffy □ A bit stuffy □ Neither stuffy nor fresh □ A bit fresh □ Fresh

**Q11. How do you find the humidity conditions inside this terminal?**

□ Damp □ Neither damp nor dry □ Dry

**SECTION C**

**Q12. How would you describe the overall lighting environment at the moment?**

□ Very bright □ Bright □ Slightly bright □ Neither bright nor dim □ Slightly dim □ Dim □ Very dim

**Q13. Would you prefer it to be:**

□ Much dimmer □ A bit dimmer □ No change □ A bit brighter □ Much brighter

**Q14. What do you think about the daylight at the moment?**

□ Very little □ Little □ Sufficient □ Much □ Very much

**Q15. Would you prefer the daylight to be:**

□ Less □ No change □ More

**Q16. Have you experienced discomfort due to glare during your stay in this terminal?**

□ Yes □ No

**Q17. Overall, do you find the light well distributed?**

□ Yes □ No

**Q18. How would you rate your overall comfort in this terminal at the moment?**
□ Very comfortable □ Comfortable □ Slightly comfortable
□ Slightly uncomfortable □ Very uncomfortable

**Q19. Which one do you consider the most important factor in this building?**
□ Air temperature □ Humidity □ Air movement □ Air freshness □ Daylight

**Q20. What do you like the most in this space?**
…………………………………………………………………………………………………….........

**Q21. What you do not like the most in this space?**
…………………………………………………………………………………………………….........

**SECTION D (only for airport employees)**
**Q22. Are you working full or part-time?**
□ Full-time □ Part-time

**Q23. How long have you been working at this terminal?** …....years .……months

**Q24. Have you noticed any environmental condition problems in this terminal?**
□ Thermally related…………………..……..□ Visually related…………………………
□ Other…………………………………...□ Nothing

**Q25. Do you have any control over your thermal and visual environment?**
□ No □ Yes (What kind of control?.........................................................................)

**Q26. How would you describe this control?**
□ Satisfactory □ Neither satisfactory nor unsatisfactory □ Unsatisfactory

**Q27. How would you rate the clothing policy in maintaining your thermal comfort?**
□ Flexible □ Neither flexible nor inflexible □ Inflexible

**Q28. How would you describe the effect of the environmental conditions on your productivity?**
□ Negative (why?.................................) □ Neither negative nor positive □ Positive

**SECTION E**
**Q29. What is your age group?** □ <18 □18-24 □25-34 □35-44 □45-54 □55-64 □ >65

**Q30. Do you live in the Greater London area?**
□ Yes □ No (Where do you live?.........................................................)

**Q31. Have you always lived in this area?**
□ Yes □ No (Where are you from?...........................................................)

**Q32. What is your educational level?** □ Primary □ Secondary □ College □ University

**Q33. Are you a:** □ In employment □ Pensioner □ Housekeeper □ Student □ Other……

CLOTHING
Trousers / Skirt / Dress: □ short(s) □ long / □ light □ normal □ thick
Shirts/blouses: □ T-shirt □ Short sleeves □ Long sleeves – light, Long sleeves – thick
Sweater / Jacket / Coat : □ short □ long / □ thin □ normal □ thick
Footwear: □ Closed □ Open □ Boots

End Time:……………

# APPENDIX B: CR800 data logger programming

```
'CR800 Series

'Created by Short Cut (2.9)

'Declare Variables and Units

Dim WSStr As String * 21

Dim ByteRet

Dim ChkSumF As Boolean

Public BattV

Public PTemp_C

Public WSData(3)

Public N(9)

Public TRHData(2)

Public Temp_C

Public Light

Public CO2

Public WBT

Public BGT

Public WBGT

Alias WSData(1)=WindDir

Alias WSData(2)=WS_ms

Alias WSData(3)=WSDiag

Alias N(1)=SmplsF

Alias N(2)=Diag1F

Alias N(3)=Diag2F

Alias N(4)=Diag4F

Alias N(5)=Diag8F

Alias N(6)=Diag9F

Alias N(7)=Diag10F

Alias N(8)=NNDF

Alias N(9)=CSEF

Alias TRHData(1)=AirTC

Alias TRHData(2)=RH

Units BattV=Volts

Units PTemp_C=Deg C

Units Temp_C=Deg C

Units Light=Lux

Units CO2=ppm

Units WindDir=degrees

Units WS_ms=meters/second

Units WSDiag=unitless

Units AirTC=Deg C

Units RH=%

'Define Data Tables

DataTable(Table1,True,-1)

DataInterval(0,1,Min,10)

WindVector (1,WS_ms,WindDir,FP2,False,0,0,1)

FieldNames("WS_ms_S_WVT,WindDir_D1_WVT")

EndTable

DataTable(Table2,True,-1)

DataInterval(0,1,Min,10)

Minimum(1,BattV,FP2,False,False)

Average(1,AirTC,FP2,False)

Sample(1,RH,FP2)

Average(1,Temp_C,FP2,False)

Average(1,Light,IEEE4,False)

Average(1,CO2,FP2,False)

Average (1,WBT,FP2,False)

Average (1,WBGT,FP2,False)

Average (1,BGT, FP2, False)

EndTable

'Main Program

BeginProg

SerialOpen(Com1,38400,3,0,505)

'Main Scan

Scan(5,Sec,1,0)

'Default Datalogger Battery Voltage measurement 'BattV'

Battery(BattV)

'Default Wiring Panel Temperature measurement 'PTemp_C'

PanelTemp(PTemp_C,250)

'WindSonic1 Two Dimensional Sonic Wind Speed & Direction Sensor measurements 'WindDir', 'WS_ms', and 'WSDiag'

'Get data from WindSonic1

SerialInRecord(Com1,WSStr,&h02,0,&h0D0A,ByteRet,00)

WindDir=Mid(WSStr,3,3)

WS_ms=Mid(WSStr,7,6)

WSDiag=Mid(WSStr,16,2)

ChkSumF=HextoDec(Mid(WSStr,20,2)) Eqv CheckSum(WSStr,9,18)

'Set diagnostic variables as needed

If ByteRet=0 Then WSDiag=NAN

Move(SmplsF,9,0,1)

Select Case WSDiag

Case=0

SmplsF=1

Case=1

Diag1F=1

Case=2

Diag2F=1

Case=4

Diag4F=1

Case=8

Diag8F=1

Case=9

Diag9F=1

Case=10

Diag10F=1

Else

NNDF=1

EndSelect

If Not (ByteRet<>0 Imp ChkSumF) Then CSEF=1

'CS215 Temperature & Relative Humidity Sensor measurements 'AirTC' and 'RH'

SDI12Recorder(TRHData(),3,"0","R!",1,0)

'PT100 PRT Temperature Probe (3WHB10K) (CSL) measurement 'Temp_C'

BrHalf3W (Temp_C,1,mV25,1,Vx1,1,2100,True,0,_50Hz,100,0)

PRT (Temp_C,1,Temp_C,1.0,0)

'Generic Differential Voltage measurements 'Light' HOPL SKL 2633

VoltDiff(Light,1,mV5000,3,True,0,_50Hz,30,0)

'Generic Single-Ended Voltage measurements 'CO2'

VoltSe(CO2,1,mV5000,3,False,0,_50Hz,0.4,0)

'Black Globe measurement and calculation of wet bulb globe temperature index (Humidex)

BrHalf (BGT,1,mV25,4,Vx2,1,1000,True,0,250,200,0)

BGT=(-26.97+69.635*BGT)+(-40.66*BGT^2+16.573*BGT^3)+(-3.455*BGT^4+0.301*BGT^5)

'Calcualte wet bulb temperature

WBT=(-5.806+0.672*AirTC-0.006*AirTC^2+(0.061+0.004*AirTC+0.000099*AirTC^2)*RH+(-0.000033-0.000005*AirTC-0.0000001*AirTC^2)*RH^2)

'Calculate wet bulb globe temperature index

WBGT=(0.1*AirTC)+(0.2*BGT)+(0.7*WBT)

'Call Data Tables and Store Data

CallTable(Table1)

CallTable(Table2)

NextScan

EndProg
```

## APPENDIX C: Thermal insulation values for separate garment pieces used for the estimation of clothing insulation

*Table C-1: Thermal insulation for garments (source: ISO 7730, 2005).*

| Garment | $I_{clu}$ clo | $I_{clu}$ $m^2 \cdot K/W$ | Change of optimum operative temperature, °C |
|---|---|---|---|
| **Underwear** | | | |
| Panties | 0,03 | 0,005 | 0,2 |
| Underpants with long legs | 0,10 | 0,016 | 0,6 |
| Singlet | 0,04 | 0,006 | 0,3 |
| T-shirt | 0,09 | 0,014 | 0,6 |
| Shirt with long sleeves | 0,12 | 0,019 | 0,8 |
| Panties and bra | 0,03 | 0,005 | 0,2 |
| **Shirts/Blouses** | | | |
| Short sleeves | 0,15 | 0,023 | 0,9 |
| Light-weight, long sleeves | 0,20 | 0,031 | 1,3 |
| Normal, long sleeves | 0,25 | 0,039 | 1,6 |
| Flannel shirt, long sleeves | 0,30 | 0,047 | 1,9 |
| Light-weight blouse, long sleeves | 0,15 | 0,023 | 0,9 |
| **Trousers** | | | |
| Shorts | 0,06 | 0,009 | 0,4 |
| Light-weight | 0,20 | 0,031 | 1,3 |
| Normal | 0,25 | 0,039 | 1,6 |
| Flannel | 0,28 | 0,043 | 1,7 |
| **Dresses/Skirts** | | | |
| Light skirts (summer) | 0,15 | 0,023 | 0,9 |
| Heavy skirt (winter) | 0,25 | 0,039 | 1,6 |
| Light dress, short sleeves | 0,20 | 0,031 | 1,3 |
| Winter dress, long sleeves | 0,40 | 0,062 | 2,5 |
| Boiler suit | 0,55 | 0,085 | 3,4 |
| **Sweaters** | | | |
| Sleeveless vest | 0,12 | 0,019 | 0,8 |
| Thin sweater | 0,20 | 0,031 | 1,3 |
| Sweater | 0,28 | 0,043 | 1,7 |
| Thick sweater | 0,35 | 0,054 | 2,2 |
| **Jackets** | | | |
| Light, summer jacket | 0,25 | 0,039 | 1,6 |
| Jacket | 0,35 | 0,054 | 2,2 |
| Smock | 0,30 | 0,047 | 1,9 |
| **High-insulative, fibre-pelt** | | | |
| Boiler suit | 0,90 | 0,140 | 5,6 |
| Trousers | 0,35 | 0,054 | 2,2 |
| Jacket | 0,40 | 0,062 | 2,5 |
| Vest | 0,20 | 0,031 | 1,3 |
| **Outdoor clothing** | | | |
| Coat | 0,60 | 0,093 | 3,7 |
| Down jacket | 0,55 | 0,085 | 3,4 |
| Parka | 0,70 | 0,109 | 4,3 |
| Fibre-pelt overalls | 0,55 | 0,085 | 3,4 |
| **Sundries** | | | |
| Socks | 0,02 | 0,003 | 0,1 |
| Thick, ankle socks | 0,05 | 0,008 | 0,3 |
| Thick, long socks | 0,10 | 0,016 | 0,6 |
| Nylon stockings | 0,03 | 0,005 | 0,2 |
| Shoes (thin soled) | 0,02 | 0,003 | 0,1 |
| Shoes (thick soled) | 0,04 | 0,006 | 0,3 |
| Boots | 0,10 | 0,016 | 0,6 |
| Gloves | 0,05 | 0,008 | 0,3 |

## APPENDIX D: Environmental conditions and mean clothing insulation values for passengers and staff in the different terminal spaces

*Table D-1: Air movement, RH (%), $CO_2$ and illuminance in summer, LCY.*

| | Air velocity | | | RH (%) | | | $CO_2$ (ppm) | | | Illuminance (lux) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Mean | Range | SD | Mean | Range | SD | Mean | Range | SD | Mean | Range | SD |
| Check-in | 0.17 | 0.23 | .06 | 51.3 | 9.1 | 2.2 | 396 | 140 | 35 | 298 | 351 | 44 |
| Search area | 0.13 | 0.01 | .01 | 49.8 | 1.3 | .7 | 483 | 13 | 7 | 338 | 13 | 8 |
| Seating area | 0.09 | 0.10 | .02 | 50.0 | 7.0 | 1.4 | 448 | 223 | 76 | 506 | 548 | 156 |
| Dep. lounge 2 | 0.08 | .11 | .03 | 53.2 | 15.6 | 3.5 | 496 | 203 | 65 | 258 | 165 | 36 |
| Retail | 0.09 | .13 | .04 | 48.1 | 6.0 | 2.2 | 386 | 16 | 6 | 3422 | 7618 | 3818 |
| Dep. lounge 1 | 0.10 | .13 | .02 | 49.5 | 11.2 | 2.7 | 598 | 770 | 168 | 169 | 354 | 72 |
| Gates | 0.22 | .32 | .08 | 43.3 | 2.4 | .7 | 489 | 186 | 62 | 286 | 205 | 49 |
| Baggage recl. | 0.15 | .53 | .16 | 45.3 | 1.6 | .6 | 394 | 128 | 47 | 383 | 256 | 60 |

*Table D-2: Air movement, RH (%), $CO_2$ and illuminance in winter, LCY.*

| | Air velocity | | | RH (%) | | | $CO_2$ (ppm) | | | Illuminance (lux) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Mean | Range | SD | Mean | Range | SD | Mean | Range | SD | Mean | Range | SD |
| Check-in | .17 | .16 | .03 | 29.8 | 16.8 | 5.9 | 705 | 122 | 26 | 259 | 60 | 17 |
| Search area | .09 | .08 | .02 | 36.8 | 27.3 | 12.5 | 763 | 162 | 58 | 210 | 67 | 19 |
| Seating area | .15 | .16 | .04 | 40.4 | 19.8 | 7.6 | 850 | 258 | 89 | 438 | 490 | 97 |
| Dep. lounge 2 | .10 | .14 | .04 | 34.3 | 28.9 | 10.6 | 760 | 112 | 33 | 303 | 664 | 143 |
| Retail | .10 | .11 | .04 | 34.7 | 16.8 | 7.8 | 715 | 58 | 23 | 2024 | 2593 | 1267 |
| Dep. lounge 1 | .13 | .14 | .02 | 31.2 | 13.2 | 2.1 | 924 | 543 | 155 | 85 | 47 | 8 |
| Gates | .14 | .36 | .09 | 29.9 | 19.1 | 4.4 | 857 | 623 | 162 | 574 | 1101 | 434 |
| Baggage recl. | .09 | .09 | .03 | 30.7 | 6.0 | 1.6 | 927 | 658 | 223 | 451 | 709 | 129 |

*Table D-3: Air movement, RH (%), $CO_2$ and illuminance in summer, MAN T1.*

| | Air velocity | | | RH (%) | | | $CO_2$ (ppm) | | | Illuminance (lux) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Mean | Range | SD | Mean | Range | SD | Mean | Range | SD | Mean | Range | SD |
| Check-in 1 | .11 | .16 | .02 | 61.4 | 18.0 | 4.9 | 528 | 398 | 95 | 403 | 293 | 83 |
| Check-in 2 | .15 | .08 | .02 | 58.7 | 23.8 | 7.8 | 623 | 460 | 160 | 109 | 238 | 41 |
| Search area | .13 | .08 | .03 | 56.4 | 3.1 | 1.1 | 683 | 103 | 33 | 433 | 189 | 70 |
| Circulation | .19 | .21 | .06 | 53.7 | 3.9 | 1.1 | 721 | 198 | 53 | 57 | 40 | 20 |
| Seating area | .19 | .10 | .02 | 58.7 | 11.9 | 3.6 | 567 | 227 | 78 | 206 | 289 | 95 |
| Dep. lounge 2 | .17 | .13 | .03 | 56.8 | 10.2 | 3.4 | 820 | 384 | 122 | 77 | 21 | 5 |
| Retail | .15 | .16 | .07 | 55.9 | 4.5 | 2.2 | 737 | 65 | 27 | 315 | 504 | 235 |
| Dep. lounge 1 | .14 | .15 | .03 | 49.0 | 15.3 | 3.0 | 827 | 441 | 125 | 502 | 1774 | 414 |
| Pier C (beg.) | .07 | .07 | .02 | 56.8 | 3.4 | 1.2 | 770 | 297 | 108 | 55 | 94 | 35 |
| Pier C (gates) | .16 | .19 | .06 | 63.8 | 9.6 | 3.7 | 611 | 116 | 38 | 123 | 263 | 78 |
| Pier B (gates) | .16 | .18 | .08 | 65.0 | 1.1 | .5 | 641 | 129 | 58 | 215 | 168 | 77 |
| Arrivals hall | .15 | .22 | .03 | 58.1 | 12.0 | 3.9 | 606 | 680 | 227 | 216 | 24 | 7 |

*Table D-4: Air movement, RH (%), $CO_2$ and illuminance in winter, MAN T1.*

| | Air velocity | | | RH (%) | | | $CO_2$ (ppm) | | | Illuminance (lux) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Mean | Range | SD | Mean | Range | SD | Mean | Range | SD | Mean | Range | SD |
| Check-in 1 | .13 | .17 | .04 | 27.3 | 4.6 | 1.2 | 708 | 217 | 65 | 222 | 253 | 68 |
| Check-in 2 | .20 | .16 | .04 | 33.8 | 6.8 | 2.3 | 701 | 79 | 23 | 230 | 149 | 62 |
| Search area | .10 | .08 | .02 | 29.9 | 8.1 | 2.0 | 840 | 465 | 162 | 275 | 219 | 59 |
| Circulation | .66 | .94 | .37 | 28.8 | 7.3 | 2.8 | 727 | 257 | 69 | 184 | 85 | 33 |
| Seating area | .21 | .45 | .15 | 24.7 | 3.3 | 1.1 | 746 | 151 | 37 | 180 | 222 | 97 |
| Dep. lounge 2 | .11 | .29 | .09 | 33.9 | 12.8 | 3.3 | 783 | 202 | 53 | 94 | 58 | 18 |
| Retail | .19 | .30 | .11 | 25.8 | 3.8 | 1.6 | 696 | 102 | 48 | 935 | 2139 | 870 |
| Dep. lounge 1 | .12 | .35 | .06 | 29.9 | 12.0 | 3.3 | 789 | 295 | 81 | 1978 | 8092 | 2223 |
| Pier C (beg.) | .10 | .20 | .05 | 34.4 | 4.8 | 1.5 | 879 | 251 | 75 | 216 | 49 | 12 |
| Pier C (gates) | .14 | .36 | .07 | 36.5 | 12.9 | 3.6 | 841 | 350 | 96 | 398 | 957 | 316 |
| Pier B (gates) | .13 | .17 | .05 | 33.8 | 8.0 | 2.9 | 999 | 616 | 235 | 131 | 221 | 86 |
| Arrivals hall | .10 | .18 | .03 | 44.8 | 14.1 | 4.1 | 729 | 125 | 33 | 237 | 69 | 13 |

*Table D-5: Air movement, RH (%), $CO_2$ and illuminance in summer, MAN T2.*

| | Air velocity | | | RH (%) | | | $CO_2$ (ppm) | | | Illuminance (lux) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Mean | Range | SD | Mean | Range | SD | Mean | Range | SD | Mean | Range | SD |
| Check-in | .34 | .17 | .04 | 47.2 | 10.4 | 2.7 | 584 | 107 | 35 | 1477 | 6218 | 1645 |
| Search area | .20 | .39 | .11 | 50.7 | 26.9 | 8.4 | 1107 | 590 | 171 | 182 | 536 | 90 |
| Seating area | .23 | .42 | .09 | 58.0 | 20.4 | 5.1 | 591 | 129 | 40 | 2260 | 2693 | 546 |
| Dep. lounge | .14 | .23 | .04 | 47.4 | 23.0 | 5.9 | 649 | 658 | 133 | 727 | 1031 | 191 |
| Retail | .15 | .19 | .06 | 57.3 | 19.3 | 6.5 | 630 | 162 | 59 | 345 | 1138 | 415 |
| Gates | .12 | .44 | .09 | 52.4 | 19.4 | 5.3 | 831 | 563 | 167 | 289 | 825 | 190 |
| Arrivals hall | .12 | .23 | .04 | 56.3 | 12.3 | 3.0 | 680 | 264 | 64 | 461 | 567 | 204 |

*Table D-6: Air movement, RH (%), $CO_2$ and illuminance in winter, MAN T2.*

| | Air velocity | | | RH (%) | | | $CO_2$ (ppm) | | | Illuminance (lux) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Mean | Range | SD | Mean | Range | SD | Mean | Range | SD | Mean | Range | SD |
| Check-in | .14 | .19 | .06 | 26.6 | 16.7 | 6.3 | 746 | 185 | 51 | 387 | 300 | 106 |
| Search area | .21 | .20 | .05 | 30.0 | 6.8 | 1.9 | 936 | 275 | 73 | 152 | 228 | 85 |
| Seating area | .29 | .27 | .06 | 34.1 | 15.0 | 5.8 | 661 | 480 | 121 | 266 | 1841 | 412 |
| Dep. lounge | .12 | .26 | .05 | 31.6 | 15.1 | 4.8 | 699 | 615 | 167 | 853 | 3116 | 716 |
| Retail | .14 | .13 | .04 | 31.6 | 19.7 | 7.0 | 742 | 144 | 49 | 818 | 1905 | 590 |
| Gates | .20 | .44 | .11 | 37.3 | 11.6 | 3.8 | 927 | 620 | 186 | 170 | 364 | 109 |
| Arrivals hall | .09 | .13 | .03 | 38.2 | 3.6 | 1.1 | 712 | 174 | 53 | 298 | 43 | 10 |

*Table D-7: Mean clothing insulation for passengers and staff in the different terminal spaces.*

| | | Summer | | Winter | |
|---|---|---|---|---|---|
| | | Employees | Passengers | Employees | Passengers |
| LCY | Check-in | .64 | .72 | .87 | 1.24 |
| | Search area | .74 | n/a | .98 | 1.03 |
| | Seating area | .70 | .69 | .91 | 1.14 |
| | Dep. Lounge 2 | .63 | .58 | .73 | .92 |
| | Retail | .64 | n/a | .76 | n/a |
| | Dep. Lounge 1 | .61 | .59 | .86 | 1.14 |
| | Gates | n/a | n/a | n/a | n/a |
| | Baggage reclaim | n/a | .63 | 1.03 | 1.18 |
| MAN T1 | Check-in 1 | .53 | .56 | .83 | 1.03 |
| | Check-in 2 | .74 | .52 | .85 | 1.30 |
| | Search area | .66 | .48 | .69 | .96 |
| | Circulation | .49 | .51 | 1.10 | .93 |
| | Seating area | .55 | .49 | .72 | 1.02 |
| | Dep. Lounge 2 | .61 | .50 | .94 | .83 |
| | Retail | .49 | n/a | .71 | n/a |
| | Dep. Lounge 1 | .46 | .51 | .91 | .96 |
| | Pier C(beg.) | .74 | .53 | .93 | 1.07 |
| | Pier C (gates) | n/a | .59 | .71 | 1.11 |
| | Pier B (gates) | n/a | .64 | n/a | .98 |
| | Arrivals hall | .75 | .59 | .94 | 1.05 |
| MAN T2 | Check-in | .65 | .53 | .84 | 1.02 |
| | Search area | .48 | .49 | .92 | .88 |
| | Seating area | .53 | .53 | .73 | .92 |
| | Retail | .55 | .44 | .74 | n/a |
| | Dep. Lounge | .58 | .50 | .64 | .82 |
| | Gates | .56 | .51 | .95 | .84 |
| | Arrivals hall | .54 | .41 | .89 | 1.01 |

## APPENDIX E: TS-based & PMV-based evaluation of neutral temperature for passengers & staff

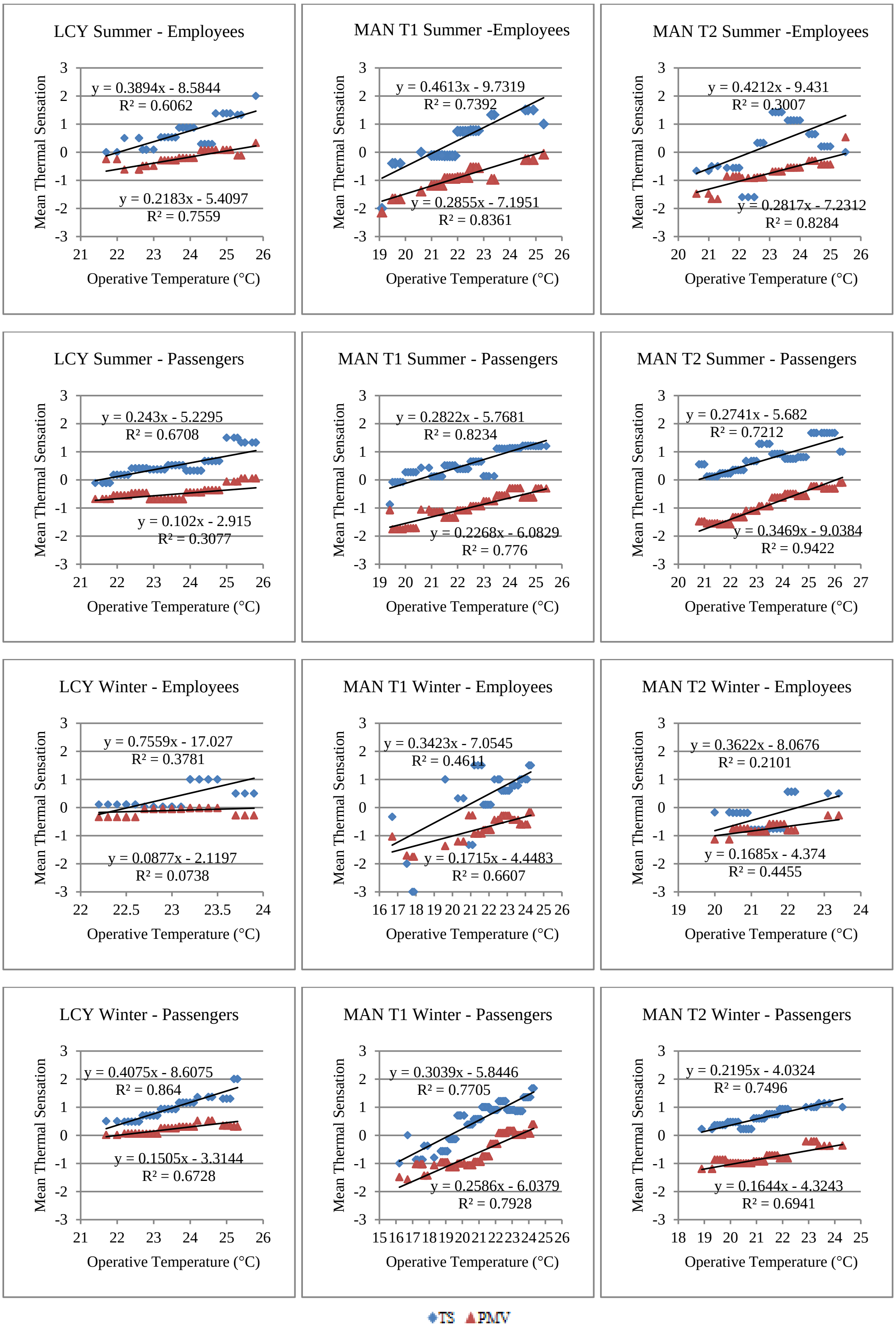


*Figure E-1: Relationship between actual and predicted thermal sensation with operative temperature for passengers and staff.*

# APPENDIX F: Number of cases (N) where binned method was used

*Table F-1: Number of cases (N) and mean scores of RH sensation in each RH bin.*

| RH (%) bins | LCY | | MAN T1 | | MAN T2 | |
|---|---|---|---|---|---|---|
| | N | Mean RH sensation | N | Mean RH sensation | N | Mean RH sensation |
| 20.0 - 24.9 | 48 | -0.17 | 37 | -0.41 | 87 | -0.33 |
| 25.0 - 29.9 | 104 | -0.32 | 150 | -0.35 | 104 | -0.25 |
| 30.0 - 34.9 | 161 | -0.19 | 192 | -0.30 | 112 | -0.26 |
| 35.0 - 39.9 | 54 | -0.26 | 92 | -0.25 | 225 | -0.30 |
| 40.0 - 44.9 | 32 | -0.22 | 42 | -0.24 | 112 | -0.34 |
| 45.0 - 49.9 | 168 | -0.08 | 91 | -0.08 | 131 | -0.33 |
| 50.0 - 54.9 | 222 | -0.02 | 157 | -0.16 | 105 | -0.25 |
| 55.0 - 59.9 | 27 | 0.15 | 203 | -0.10 | 151 | -0.30 |
| 60.0 - 64.9 | 2 | 0.00 | 167 | -0.06 | 35 | -0.23 |
| 65.0 - 69.9 | n/a | n/a | 56 | -0.13 | 9 | -0.11 |
| 70.0 - 74.9 | n/a | n/a | 11 | -.09 | n/a | n/a |

*Table F-2: Number of cases (N) and mean scores of TS and PMV in each operative temperature bin for MAN T1.*

| | Top bins | N | Mean TS | Mean PMV |
|---|---|---|---|---|
| Summer | 19.0 - 19.4 | 29 | -0.62 | -1.68 |
| | 19.5 - 19.9 | 64 | -0.16 | -1.68 |
| | 20.0 - 20.4 | 14 | 0.21 | -1.63 |
| | 20.5 - 20.9 | 19 | 0.16 | -1.24 |
| | 21.0 - 21.4 | 107 | 0.11 | -1.14 |
| | 21.5 - 21.9 | 109 | 0.44 | -1.29 |
| | 22.0 - 22.4 | 117 | 0.50 | -1.04 |
| | 22.5 - 22.9 | 74 | 0.68 | -.82 |
| | 23.0 - 23.4 | 11 | 0.45 | -.81 |
| | 23.5 - 23.9 | 31 | 1.23 | -.53 |
| | 24.0 - 24.4 | 24 | 1.13 | -.30 |
| | 24.5 - 24.9 | 48 | 1.25 | -.59 |
| | 25.0 - 25.4 | 16 | 1.19 | -.29 |
| Winter | 16.2 - 16.6 | 3 | -1.67 | -1.36 |
| | 16.7 - 17.1 | 5 | -0.40 | -1.24 |
| | 17.2 - 17.6 | 40 | -0.65 | -0.99 |
| | 17.7 - 18.1 | 12 | -0.92 | -1.42 |
| | 18.2 - 18.6 | 5 | -0.80 | -1.07 |
| | 18.7 - 19.1 | 23 | -0.57 | -0.96 |
| | 19.2 - 19.6 | 25 | 0.00 | -1.17 |
| | 19.7 - 20.1 | 23 | 0.70 | -1.01 |
| | 20.2 - 20.6 | 16 | 0.38 | -1.10 |
| | 20.7 - 21.1 | 52 | 0.52 | -0.90 |
| | 21.2 - 21.6 | 69 | 1.03 | -0.73 |
| | 21.7 - 22.1 | 66 | 0.71 | -0.37 |
| | 22.2 - 22.6 | 46 | 1.17 | 0.00 |
| | 22.7 - 23.1 | 50 | 0.84 | 0.07 |
| | 23.2 - 23.6 | 51 | 0.84 | -0.07 |
| | 23.7 - 24.1 | 34 | 1.26 | -0.10 |
| | 24.2 - 24.6 | 10 | 1.60 | 0.17 |
| | 24.7 - 25.1 | 3 | -1.00 | 0.26 |
| | 25.2 - 25.6 | 2 | 3.00 | 0.08 |

*Table F-3: Number of cases (N) and mean scores of TS and PMV in each operative temperature bin for LCY.*

| | Top bins | N | Mean TS | Mean PMV |
|---|---|---|---|---|
| Summer | 21.4 - 21.8 | 21 | -0.19 | -0.64 |
| | 21.9 - 22.3 | 42 | 0.21 | -0.55 |
| | 22.4 - 22.8 | 86 | 0.43 | -0.48 |
| | 22.9 - 23.3 | 64 | 0.45 | -0.68 |
| | 23.4 - 23.8 | 87 | 0.57 | -0.60 |
| | 23.9 - 24.3 | 48 | 0.42 | -0.36 |
| | 24.4 - 24.8 | 29 | 0.72 | -0.27 |
| | 24.9 - 25.3 | 11 | 1.27 | 0.05 |
| | 25.4 - 25.8 | 15 | 1.27 | 0.05 |
| Winter | 21.7 - 22.1 | 6 | 0.50 | 0.01 |
| | 22.2 - 22.6 | 30 | 0.37 | -0.06 |
| | 22.7 - 23.1 | 95 | 0.48 | 0.02 |
| | 23.2 - 23.6 | 141 | 0.94 | 0.22 |
| | 23.7 - 24.1 | 112 | 1.13 | 0.27 |
| | 24.2 - 24.6 | 13 | 1.00 | 0.49 |
| | 24.7 - 25.1 | 10 | 1.30 | 0.34 |
| | 25.2 - 25.6 | 8 | 2.00 | 0.31 |

*Table F-4: Number of cases (N) and mean scores of TS and PMV in each operative temperature bin for MAN T2.*

| | Top bins | N | Mean TS | Mean PMV |
|---|---|---|---|---|
| Summer | 20.6 - 21.0 | 14 | 0.29 | -1.48 |
| | 21.1 - 21.5 | 28 | 0.07 | -1.58 |
| | 21.6 - 22.0 | 119 | 0.13 | -1.47 |
| | 22.1 - 22.5 | 107 | 0.25 | -1.21 |
| | 22.6 - 23.0 | 45 | 0.60 | -1.06 |
| | 23.1 - 23.5 | 30 | 1.33 | -0.84 |
| | 23.6 - 24.0 | 46 | 0.96 | -0.62 |
| | 24.1 - 24.5 | 70 | 0.70 | -0.48 |
| | 24.6 - 25.0 | 42 | 0.79 | -0.54 |
| | 25.1 - 25.5 | 19 | 1.58 | -0.19 |
| | 25.6 - 26.0 | 15 | 1.67 | -0.31 |
| | 26.1 - 26.5 | 3 | 1.00 | -0.10 |
| Winter | 18.9 - 19.3 | 23 | 0.22 | -1.20 |
| | 19.4 - 19.8 | 22 | 0.36 | -0.87 |
| | 19.9 - 20.3 | 45 | 0.38 | -0.99 |
| | 20.4 - 20.8 | 69 | 0.13 | -0.94 |
| | 20.9 - 21.3 | 170 | 0.49 | -0.82 |
| | 21.4 - 21.8 | 119 | 0.48 | -0.70 |
| | 21.9 - 22.3 | 48 | 0.75 | -0.80 |
| | 22.4 - 22.8 | 11 | 0.45 | -0.80 |
| | 22.9 - 23.3 | 13 | 0.69 | -0.27 |
| | 23.4 - 23.8 | 9 | 1.33 | -0.29 |
| | 23.9 - 24.3 | 2 | 1.00 | -0.37 |
| | 24.4 - 24.8 | 2 | 0.50 | 0.42 |

*Table F-5: Number of cases (N) and mean scores of lighting sensation and preference in each illuminance bin.*

| | LCY | | | MAN T1 | | | MAN T2 | | |
|---|---|---|---|---|---|---|---|---|---|
| Illuminance bins (lux) | N | Mean LS | Mean LP | N | Mean LS | Mean LP | N | Mean LS | Mean LP |
| 0 - 199 | 236 | -0.26 | 0.24 | 458 | -0.38 | 0.40 | 198 | -0.28 | 0.40 |
| 200 - 399 | 446 | 0.28 | 0.13 | 515 | 0.13 | 0.28 | 338 | 0.77 | 0.02 |
| 400 - 599 | 106 | 0.51 | -0.01 | 125 | 0.24 | 0.28 | 174 | 0.81 | 0.07 |
| 600 - 799 | 10 | 1.10 | -0.10 | 19 | 0.74 | 0.16 | 141 | 0.91 | 0.06 |
| 800 - 999 | 4 | 0.50 | 0.00 | 23 | 0.70 | 0.30 | 70 | 1.07 | 0.07 |
| 1000 - 1199 | 8 | 1.75 | -0.25 | 3 | 0.33 | 0.33 | 21 | 1.00 | -0.10 |
| 1200 - 1399 | 0 | n/a | n/a | 13 | 1.08 | -0.08 | 18 | 1.11 | 0.06 |
| 1400 - 1599 | 0 | n/a | n/a | 4 | 1.75 | -0.25 | 11 | 0.55 | -0.09 |
| 1600 - 1799 | 1 | 0.00 | 1.00 | 12 | 0.92 | -0.17 | 5 | 1.00 | 0.00 |
| 1800 - 1999 | 0 | n/a | n/a | 2 | 2.00 | -0.50 | 10 | 1.00 | 0.10 |
| 2000 - 2199 | 0 | n/a | n/a | 0 | n/a | n/a | 10 | 1.10 | -0.10 |
| 2200 - 2399 | 0 | n/a | n/a | 5 | 2.40 | -0.80 | 16 | 1.63 | 0.00 |
| 2400 - 2599 | 0 | n/a | n/a | 1 | 2.00 | 0.00 | 9 | 1.89 | 0.00 |
| 2600 - 2799 | 0 | n/a | n/a | 3 | 2.00 | -0.33 | 20 | 1.65 | 0.00 |
| 2800 - 2999 | 0 | n/a | n/a | 0 | n/a | n/a | 9 | 1.67 | 0.00 |
| 3000 - 3199 | 0 | n/a | n/a | 2 | 0.50 | 0.00 | 4 | 0.75 | 0.00 |
| 3200 - 3399 | 0 | n/a | n/a | 0 | n/a | n/a | 2 | 1.00 | -0.50 |
| 3400 - 3599 | 0 | n/a | n/a | 0 | n/a | n/a | 6 | 2.00 | 0.00 |
| 3600 - 3799 | 4 | 3.00 | -2.00 | 0 | n/a | n/a | 0 | n/a | n/a |
| 3800 - 3999 | 0 | n/a | n/a | 0 | n/a | n/a | 0 | n/a | n/a |
| 4000 - 4199 | 0 | n/a | n/a | 0 | n/a | n/a | 1 | 1.00 | 1.00 |
| 4200 - 4399 | 0 | n/a | n/a | 0 | n/a | n/a | 0 | n/a | n/a |
| 4400 - 4599 | 0 | n/a | n/a | 0 | n/a | n/a | 2 | 2.00 | 0.00 |
| 4600 - 4799 | 0 | n/a | n/a | 2 | 2.00 | 0.00 | 0 | n/a | n/a |
| 4800 - 4999 | 0 | n/a | n/a | 0 | n/a | n/a | 0 | n/a | n/a |
| 5000 - 5199 | 0 | n/a | n/a | 0 | n/a | n/a | 1 | 1.00 | 0.00 |
| 5200 - 5399 | 0 | n/a | n/a | 2 | 3.00 | -1.00 | 0 | n/a | n/a |
| 5400 - 5599 | 0 | n/a | n/a | 1 | 3.00 | 0.00 | 0 | n/a | n/a |
| 5600 - 5799 | 0 | n/a | n/a | 0 | n/a | n/a | 0 | n/a | n/a |
| 5800 - 5999 | 0 | n/a | n/a | 2 | 1.00 | -1.00 | 0 | n/a | n/a |
| 6000 - 6199 | 0 | n/a | n/a | 0 | n/a | n/a | 4 | 0.00 | 0.50 |
| 6200 - 6399 | 0 | n/a | n/a | 0 | n/a | n/a | 0 | n/a | n/a |
| 6400 - 6599 | 0 | n/a | n/a | 0 | n/a | n/a | 1 | 3.00 | -1.00 |
| 6600 - 6799 | 0 | n/a | n/a | 0 | n/a | n/a | 0 | n/a | n/a |
| 6800 - 6999 | 0 | n/a | n/a | 3 | 2.00 | 0.00 | 0 | n/a | n/a |
| 7000 - 7199 | 0 | n/a | n/a | 0 | n/a | n/a | 0 | n/a | n/a |
| 7200 - 7399 | 0 | n/a | n/a | 0 | n/a | n/a | 0 | n/a | n/a |
| 7400 - 7599 | 0 | n/a | n/a | 0 | n/a | n/a | 0 | n/a | n/a |
| 7600 - 7799 | 0 | n/a | n/a | 0 | n/a | n/a | 0 | n/a | n/a |
| 7800 - 7999 | 3 | 0.67 | -0.33 | 0 | n/a | n/a | 0 | n/a | n/a |
| 8000 - 8199 | 0 | n/a | n/a | 3 | 2.00 | 0.00 | 0 | n/a | n/a |

*Table F-6: Number of cases (N) and mean scores of TS and PMV in each operative temperature bin for passengers and employees at LCY, summer.*

| Passengers | | | | Employees | | | |
|---|---|---|---|---|---|---|---|
| Top bins | N | Mean TS | Mean PMV | Top bins | N | Mean TS | Mean PMV |
| 21.4 - 21.8 | 19 | -0.11 | -0.68 | 21.7 - 22.1 | 2 | 0.00 | -0.25 |
| 21.9 - 22.3 | 39 | 0.18 | -0.55 | 22.2 - 22.6 | 6 | 0.50 | -0.62 |
| 22.4 - 22.8 | 64 | 0.41 | -0.47 | 22.7 - 23.1 | 11 | 0.09 | -0.49 |
| 22.9 - 23.3 | 59 | 0.37 | -0.69 | 23.2 - 23.6 | 15 | 0.53 | -0.29 |
| 23.4 - 23.8 | 63 | 0.52 | -0.69 | 23.7 - 24.1 | 15 | 0.87 | -0.21 |
| 23.9 - 24.3 | 39 | 0.33 | -0.45 | 24.2 - 24.6 | 7 | 0.29 | 0.07 |
| 24.4 - 24.8 | 21 | 0.67 | -0.37 | 24.7 - 25.1 | 8 | 1.38 | 0.08 |
| 24.9 - 25.3 | 4 | 1.50 | -0.06 | 25.2 - 25.6 | 3 | 1.33 | -0.12 |
| 25.4 - 25.8 | 12 | 1.33 | 0.05 | 25.7 - 26.1 | 1 | 2.00 | 0.33 |

*Table F-7: Number of cases (N) and mean scores of TS and PMV in each operative temperature bin for passengers and employees at LCY, winter.*

| Passengers | | | | Employees | | | |
|---|---|---|---|---|---|---|---|
| Top bins | N | Mean TS | Mean PMV | Top bins | N | Mean TS | Mean PMV |
| 21.7 - 22.1 | 6 | 0.50 | 0.01 | 21.7 - 22.1 | 0 | n/a | n/a |
| 22.2 - 22.6 | 21 | 0.48 | 0.06 | 22.2 - 22.6 | 9 | 0.11 | -0.34 |
| 22.7 - 23.1 | 63 | 0.70 | 0.05 | 22.7 - 23.1 | 31 | 0.03 | -0.05 |
| 23.2 - 23.6 | 108 | 0.93 | 0.25 | 23.2 - 23.6 | 24 | 1.00 | -0.02 |
| 23.7 - 24.1 | 105 | 1.16 | 0.30 | 23.7 - 24.1 | 6 | 0.50 | -0.28 |
| 24.2 - 24.6 | 11 | 1.36 | 0.52 | 24.2 - 24.6 | 2 | -1.00 | 0.30 |
| 24.7 - 25.1 | 10 | 1.30 | 0.34 | 24.7 - 25.1 | 0 | n/a | n/a |
| 25.2 - 25.6 | 8 | 2.00 | 0.31 | 25.2 - 25.6 | 0 | n/a | n/a |

*Table F-8: Number of cases (N) and mean scores of TS and PMV in each operative temperature bin for passengers and employees at MAN T1, summer.*

| Passengers | | | | Employees | | | |
|---|---|---|---|---|---|---|---|
| Top bins | N | Mean TS | Mean PMV | Top bins | N | Mean TS | Mean PMV |
| 19.0 - 19.4 | 8 | -0.88 | -1.08 | 19.0 - 19.4 | 1 | -2.00 | -2.14 |
| 19.5 - 19.9 | 13 | -0.08 | -1.76 | 19.5 - 19.9 | 5 | -0.40 | -1.67 |
| 20.0 - 20.4 | 11 | 0.27 | -1.72 | 20.0 - 20.4 | 0 | n/a | n/a |
| 20.5 - 20.9 | 7 | 0.43 | -1.06 | 20.5 - 20.9 | 1 | 0.00 | -1.39 |
| 21.0 - 21.4 | 82 | 0.12 | -1.14 | 21.0 - 21.4 | 17 | -0.12 | -1.18 |
| 21.5 - 21.9 | 87 | 0.51 | -1.35 | 21.5 - 21.9 | 15 | -0.13 | -0.94 |
| 22.0 - 22.4 | 85 | 0.39 | -1.09 | 22.0 - 22.4 | 31 | 0.74 | -0.91 |
| 22.5 - 22.9 | 52 | 0.65 | -0.94 | 22.5 - 22.9 | 21 | 0.76 | -0.56 |
| 23.0 - 23.4 | 8 | 0.13 | -0.76 | 23.0 - 23.4 | 3 | 1.33 | -0.97 |
| 23.5 - 23.9 | 28 | 1.11 | -0.55 | 23.5 - 23.9 | 0 | n/a | n/a |
| 24.0 - 24.4 | 24 | 1.13 | -0.30 | 24.0 - 24.4 | 0 | n/a | n/a |
| 24.5 - 24.9 | 42 | 1.21 | -0.63 | 24.5 - 24.9 | 6 | 1.50 | -0.27 |
| 25.0 - 25.4 | 15 | 1.20 | -0.31 | 25.0 - 25.4 | 1 | 1.00 | -0.08 |

*Table F-9: Number of cases (N) and mean scores of TS and PMV in each operative temperature bin for passengers and employees at MAN T1, winter.*

| Passengers | | | | Employees | | | |
|---|---|---|---|---|---|---|---|
| Top bins | N | Mean TS | Mean PMV | Top bins | N | Mean TS | Mean PMV |
| 16.2 - 16.6 | 2 | -1.00 | -1.49 | 16.2 - 16.6 | 0 | n/a | n/a |
| 16.7 - 17.1 | 1 | 0.00 | -1.57 | 16.7 - 17.1 | 3 | -0.33 | -1.03 |
| 17.2 - 17.6 | 15 | -0.87 | -1.03 | 17.2 - 17.6 | 3 | -2.00 | -1.71 |
| 17.7 - 18.1 | 8 | -0.38 | -1.44 | 17.7 - 18.1 | 2 | -3.00 | -1.75 |
| 18.2 - 18.6 | 5 | -0.80 | -1.07 | 18.2 - 18.6 | 0 | n/a | n/a |
| 18.7 - 19.1 | 23 | -0.57 | -0.96 | 18.7 - 19.1 | 0 | n/a | n/a |
| 19.2 - 19.6 | 22 | -0.14 | -1.14 | 19.2 - 19.6 | 3 | 1.00 | -1.37 |
| 19.7 - 20.1 | 23 | 0.70 | -1.01 | 19.7 - 20.1 | 0 | n/a | n/a |
| 20.2 - 20.6 | 13 | 0.38 | -1.07 | 20.2 - 20.6 | 3 | 0.33 | -1.21 |
| 20.7 - 21.1 | 46 | 0.57 | -0.95 | 20.7 - 21.1 | 3 | -1.33 | -0.28 |
| 21.2 - 21.6 | 58 | 1.00 | -0.75 | 21.2 - 21.6 | 6 | 1.50 | -0.93 |
| 21.7 - 22.1 | 52 | 0.90 | -0.31 | 21.7 - 22.1 | 10 | 0.10 | -0.80 |
| 22.2 - 22.6 | 38 | 1.21 | 0.08 | 22.2 - 22.6 | 7 | 1.00 | -0.44 |
| 22.7 - 23.1 | 40 | 0.90 | 0.16 | 22.7 - 23.1 | 10 | 0.60 | -0.29 |
| 23.2 - 23.6 | 42 | 0.86 | 0.01 | 23.2 - 23.6 | 9 | 0.78 | -0.44 |
| 23.7 - 24.1 | 26 | 1.35 | 0.05 | 23.7 - 24.1 | 8 | 1.00 | -0.60 |
| 24.2 - 24.6 | 6 | 1.67 | 0.39 | 24.2 - 24.6 | 4 | 1.50 | -0.17 |
| 24.7 - 25.1 | 3 | -1.00 | 0.26 | 24.7 - 25.1 | 0 | n/a | n/a |
| 25.2 - 25.6 | 2 | 3.00 | 0.08 | 25.2 - 25.6 | 0 | n/a | n/a |

*Table F-10: Number of cases (N) and mean scores of TS and PMV in each operative temperature bin for passengers and employees at MAN T2, summer.*

| Passengers | | | | Employees | | | |
|---|---|---|---|---|---|---|---|
| Top bins | N | Mean TS | Mean PMV | Top bins | N | Mean TS | Mean PMV |
| 20.6 - 21.0 | 11 | 0.55 | -1.48 | 20.6 - 21.0 | 3 | -0.67 | -1.48 |
| 21.1 - 21.5 | 25 | 0.12 | -1.55 | 21.1 - 21.5 | 2 | -0.50 | -1.67 |
| 21.6 - 22.0 | 94 | 0.23 | -1.58 | 21.6 - 22.0 | 9 | -0.56 | -0.86 |
| 22.1 - 22.5 | 66 | 0.35 | -1.33 | 22.1 - 22.5 | 5 | -1.60 | -0.92 |
| 22.6 - 23.0 | 36 | 0.67 | -1.10 | 22.6 - 23.0 | 9 | 0.33 | -0.90 |
| 23.1 - 23.5 | 18 | 1.28 | -0.94 | 23.1 - 23.5 | 12 | 1.42 | -0.69 |
| 23.6 - 24.0 | 38 | 0.92 | -0.64 | 23.6 - 24.0 | 8 | 1.13 | -0.55 |
| 24.1 - 24.5 | 55 | 0.75 | -0.50 | 24.1 - 24.5 | 11 | 0.64 | -0.31 |
| 24.6 - 25.0 | 27 | 0.81 | -0.58 | 24.6 - 25.0 | 5 | 0.20 | -0.44 |
| 25.1 - 25.5 | 18 | 1.67 | -0.23 | 25.1 - 25.5 | 1 | 0.00 | 0.53 |
| 25.6 - 26.0 | 15 | 1.67 | -0.31 | 25.6 - 26.0 | 0 | n/a | n/a |
| 26.1 - 26.5 | 3 | 1.00 | -0.10 | 26.1 - 26.5 | 0 | n/a | n/a |

*Table F-11: Number of cases (N) and mean scores of TS and PMV in each operative temperature bin for passengers and employees at MAN T2, winter.*

| Passengers | | | | Employees | | | |
|---|---|---|---|---|---|---|---|
| Top bins | N | Mean TS | Mean PMV | Top bins | N | Mean TS | Mean PMV |
| 18.9 - 19.3 | 23 | 0.22 | -1.20 | 20.0 - 20.4 | 6 | -0.17 | -1.14 |
| 19.4 - 19.8 | 22 | 0.36 | -0.87 | 20.5 - 20.9 | 16 | -0.19 | -0.75 |
| 19.9 - 20.3 | 43 | 0.47 | -0.99 | 21.0 - 21.4 | 28 | -0.79 | -0.85 |
| 20.4 - 20.8 | 50 | 0.22 | -1.00 | 21.5 - 21.9 | 16 | -0.75 | -0.59 |
| 20.9 - 21.3 | 99 | 0.60 | -0.93 | 22.0 - 22.4 | 16 | 0.56 | -0.81 |
| 21.4 - 21.8 | 88 | 0.75 | -0.72 | 22.5 - 22.9 | 0 | n/a | n/a |
| 21.9 - 22.3 | 30 | 0.93 | -0.82 | 23.0 - 23.4 | 4 | 0.50 | -0.28 |
| 22.4 - 22.8 | 11 | 0.45 | -0.80 | | | | |
| 22.9 - 23.3 | 11 | 1.00 | -0.22 | | | | |
| 23.4 - 23.8 | 7 | 1.14 | -0.38 | | | | |
| 23.9 - 24.3 | 2 | 1.00 | -0.37 | | | | |
| 24.4 - 24.8 | 2 | 0.50 | 0.42 | | | | |

## APPENDIX G: Neutral temperature for the different types of terminal staff

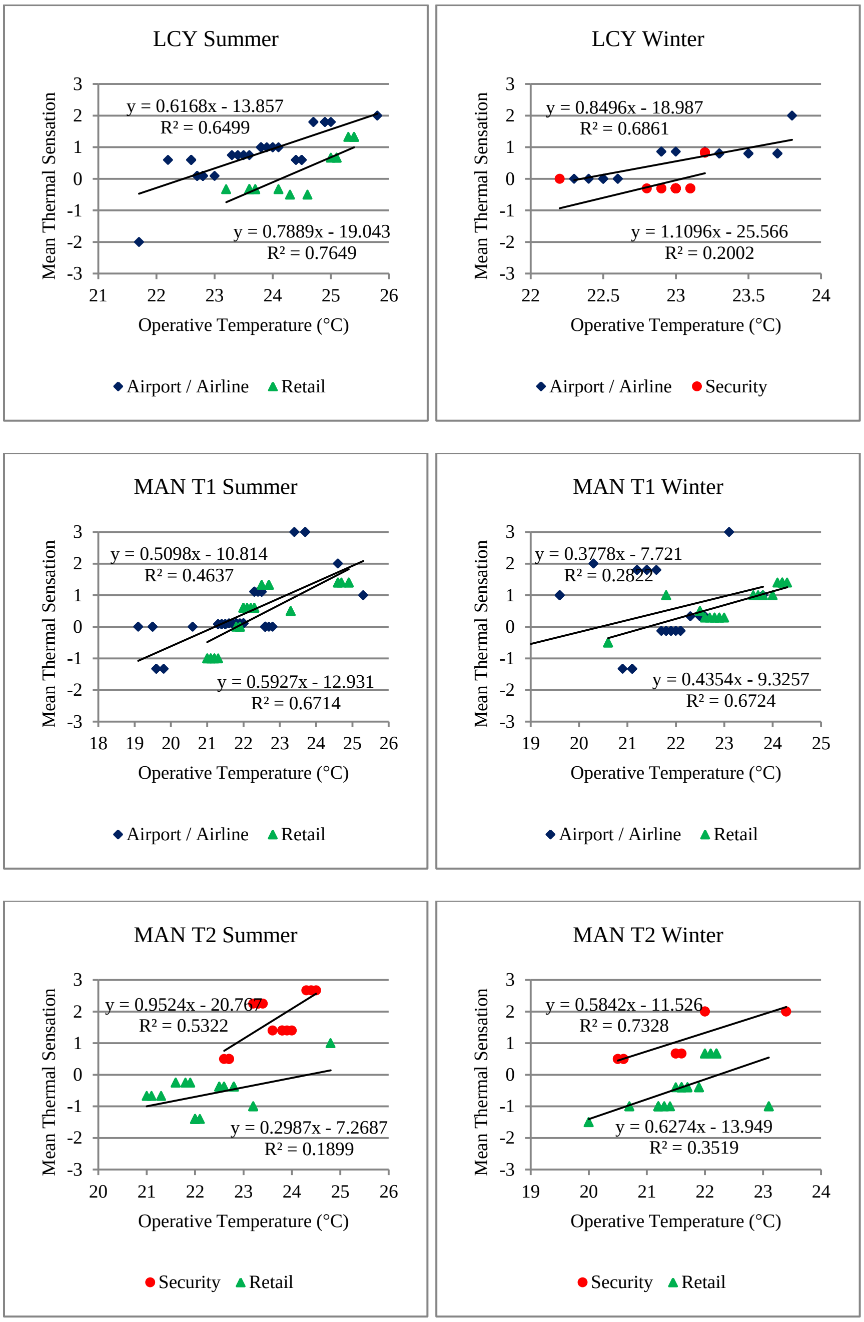


*Figure G-1: Relationship between thermal sensation and operative temperature for the different types of terminal staff.*

*Table G-1: Neutral temperature for the different types of terminal staff.*

| | LCY | | MAN T1 | | MAN T2 | |
|---|---|---|---|---|---|---|
| | Summer | Winter | Summer | Winter | Summer | Winter |
| Security | n/a | 23.0 | n/a | n/a | 21.8 | 19.7 |
| Airport / Airline | 22.2 | 22.3 | 21.3 | 20.4 | n/a | n/a |
| Retail | 24.1 | n/a | 21.8 | 21.4 | 24.3 | 22.3 |

**APPENDIX H: Paper presented at CIBSE ASHRAE Technical Symposium 2014**

## Airport terminal buildings: Indoor or transitional spaces?

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### Abstract
This paper reports on the investigation of the indoor thermal environment in three airport terminal buildings in the UK, through extensive seasonal field surveys. The study involved environmental monitoring with questionnaire-guided interviews with 3,087 terminal users. The paper focuses on the thermal perception, preference and comfort conditions of passengers and terminal employees. The results revealed significant differences between the thermal requirements of these groups, both preferring a thermal environment different to the one experienced. Passengers consistently demonstrated a wider range of comfort temperatures, while staff had limited adaptive capacity, leading to a narrower comfort zone. Furthermore, passengers' neutral and preferred temperatures were lower than staff's and significantly lower than the mean indoor temperature, which has significant implications for the design and refurbishment strategies for airport terminals.

Keywords: airport terminal, passengers and staff, indoor thermal comfort, neutral temperature, thermal preference.

### 1. Introduction
Airport terminals are characteristic of the diversity of spaces and the very different groups of population using these buildings. They are designed predominantly as indoor spaces, while the vast majority is people under transient conditions. Various factors differentiate the thermal requirements of terminal users, mostly dressed in outdoor clothing appropriate for the different seasons. Activity levels vary between passengers and employees as well as between the various types of terminal staff. Furthermore, for employees, the working conditions are very rigid with no control over the thermal environment. All these provide for very narrow adaptive capacity [i]. Such differentiation between different terminal users results not only in thermal discomfort but also energy wastage.

Both CIBSE [ii] and ASHRAE [iii] provide recommended design conditions for airport terminals. ASHRAE's recommendations are 23-26°C temperature and 30-40% RH in winter and 40-55% RH in summer. CIBSE provides seasonal comfort criteria for specific terminal areas based on standard activity levels and clothing insulation values, allowing a wider variation in the internal conditions (table 1).

| | Summer* | Winter* | |
|---|---|---|---|
| | Operative temperature (°C) | | Activity (met) |
| **Baggage Reclaim** | 21-25** | 12-19** | 1.8 |
| **Check-in areas*** ** | 21-23 | 18-20 | 1.4 |
| **Concourse (no seats)** | 21-25** | 19-24** | 1.8 |
| **Customs area** | 21-23 | 18-20 | 1.4 |
| **Departure lounge** | 22-24 | 19-21 | 1.3 |

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

**Table 1: Recommended comfort criteria for airport terminal areas by CIBSE.**

However, there has been very limited work on the evaluation of these spaces, to investigate whether the recommendations are met, or more importantly, the thermal acceptability of these spaces by different user groups. A study in Terminal 1 at Chengdu Shuangliu International Airport, China, surveying 569 passengers found very high thermal acceptability levels, 95.8% [iv]. Another study with 285 questionnaires with passengers and staff in three Greek airports highlighted the different satisfaction levels of the two groups [v].

The current study is the most extensive work available to date, investigating the breadth of thermal comfort conditions in three airport terminal buildings in the UK and quantifying the thermal requirements of passengers and staff.

## 2. Airport terminal surveys

Extensive field surveys, involving monitoring of the indoor environmental conditions and questionnaire-guided interviews, were employed in London City Airport (LCY), Manchester Terminal 1 (MAN T1) and Manchester Terminal 2 (MAN T2). A weekly survey was carried out in each terminal during summer and winter in 2012 and 2013, to allow for the seasonal variations.

### 2.1 Description of the terminal buildings

The cases of study were selected to represent terminals of different size and typology. Built in 1987, the small-scale terminal at LCY is a two-storey building with a total floor area of 8000 $m^2$. Adjoining the west side of the terminal, a two-storey pier is housing ten gate lounges while four more gates were constructed in the recently developed (2008) east apron (figure 1). The spaces within the LCY terminal display the highest degree of uniformity compared to the terminals in Manchester airport. The major refurbishments to date aimed to improve space utilization. Currently, LCY handles about 3 million passengers a year representing the 15th busiest airport in the UK [vi].

The facilities in the significantly bigger MAN T1 and MAN T2 are spread over a total floor area of 43,499 $m^2$ and 26,063 $m^2$ respectively with a current capacity of 11 and 8 million passengers per year [vii].

**Figure 1: LCY terminal (a) as opened in 1987, (b) today after the recent refurbishment and (c) sky view (from Google earth).**

**Figure 2: MAN T1 (a) and (b) areas of the departure lounge as expanded at different times and (c) sky view (from Google earth).**

**Figure 3: MAN T2 (a) check-in area, (b) departure lounge and (c) sky view (from Google earth).**

MAN T1 is a large complex building housing a variety of spaces with heterogeneous architectural features (figures 2a & 2b). This is a result of consecutive overhauls and various expansions over the years since the terminal's opening in 1962.The terminal was the first in Europe to incorporate the pier system and today has 28 gate lounges in total, spread on its finger and satellite piers. MAN T2, on the other hand, is the newest of the three terminals in Manchester (1993), with very high floor-to-ceiling heights and extensive use of daylight, which will allow expanding the terminal without altering its character (figure 3). The terminal uses 16 gate lounges in total and two piers spanning from the central building.

Passenger dwell time is also a principal differentiating factor. Due to its small size and the focus on business passengers, LCY is characteristic of the rapid passenger processing and consequently for the significantly shorter dwell time, which can be down to 20 minutes from check-in to boarding.

The indoor environment in LCY is controlled through the use of 13 air handling units, with a temperature set-point of 20°C for winter and 23°C for summer. Spaces in MAN T1 and MAN T2 are conditioned by variable refrigerant volume (VRV) and fan coil unit systems, while in smaller areas direct expansion (DX) systems are employed. The temperature set-point is fixed at 21°C throughout the year.

### 2.2 Field surveys

The environmental conditions were monitored continuously from 5:00 am until 9:00 pm, during the week-long surveys to get the peak and off-peak profiles of use in the terminals.

The study required investigation of the immediate microclimate people experience. Thus, a portable weather station was designed to be easily transportable, and dismountable for passing through security screening while moving from landside to airside. The equipment consists of a data logging system, a shielded temperature and humidity probe, an ultrasonic anemometer, a black globe thermometer, a $CO_2$ sensor and a lux sensor, all conforming to ISO 7726 [viii]. The monitored physical quantities are dry bulb temperature, air movement, relative humidity, black globe temperature as well as carbon dioxide and horizontal illuminance levels. All parameters were measured at the 1.7 m level (average height of a standing person) and recorded at one-minute intervals. The spaces monitored included check-in areas, security search areas, circulation spaces, retail facilities, departure lounges, gates, baggage reclaim areas and arrivals halls.

The questionnaire developed intended to collect subjective data for the evaluation of comfort conditions. Interviewees were selected randomly to represent the typical range of terminal users. The questionnaire used the 7-point ASHRAE scale for the assessment of thermal sensation and a 5-point scale for thermal preference. Similar form of questions was used to assess other environmental parameters including air movement, humidity and lighting levels. Interviewees were also asked for their overall comfort state. In addition, data about time spent in the terminal, clothing insulation and activity levels during and 15 minutes prior to the questionnaire were also collected along with demographic data.

## 3. Data analysis

All data were analysed by means of the statistical software package SPSS 19. The total sample population from the three terminal buildings is 3,087 people (table 2) with a 50:50 male-female ratio.

| | LCY | MAN T1 | MAN T2 |
|---|---|---|---|
| **Summer** | 403 | 663 | 538 |
| **Winter** | 415 | 535 | 533 |
| **Total** | 818 | 1198 | 1071 |

**Table 1: Number of terminal users interviewed at the surveyed terminals.**

The outdoor mean daily temperature (24h average) ranged between 11-20°C, 15-16°C and 10-16°C during the summer surveys in LCY, MAN T1and MAN T2 and between 3.9-12.0°C, 0.9-6.6°C and -1.6-6.3°C during the respective winter surveys. The indoor environmental conditions for the three terminal buildings are presented in table 3.

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

**Table 3: Indoor environmental conditions in the surveyed terminals.**

The operative temperature range in LCY was 21.4 - 25.8°C in summer and 21.7 - 25.3°C in winter. The narrow range is a result of the terminal's small size and the uniformity of its spaces, where the highest temperatures occurred during the main occupancy peaks. The thermal environment in the larger spaces of MAN T2 is characterized by wider temperature ranges; 20.6 – 26.3°C in summer and 18.9 - 24.5°C in winter. As a result of the great diversity of spaces in MAN T1, thermal conditions varied significantly between the different zones, where the temperature range was 19.1 - 25.4°C in summer and 16.2 - 25.6°C in winter. The average air movement did not exceed 0.2 m/s in all three terminals, where the infrequent high air speeds occurred in spaces exposed to the outdoor conditions through the openings. The mean RH (%) was found within the ASHRAE recommended range despite that none of the surveyed terminals include (de)humidification in the control strategy.

The terminal users were classified into employees, passengers, meeters-greeters and other. Airport, airline and retail employees, 465 in total, were studied in their work areas representing 12-17% of each terminal's sample population. Overall, 2333 transit, arriving and mostly departing passengers were interviewed across the different terminal areas, accounting for 70-80% of participants in each terminal. This paper focuses on passengers and staff who represent the vast majority of the subjects participating in the surveys.

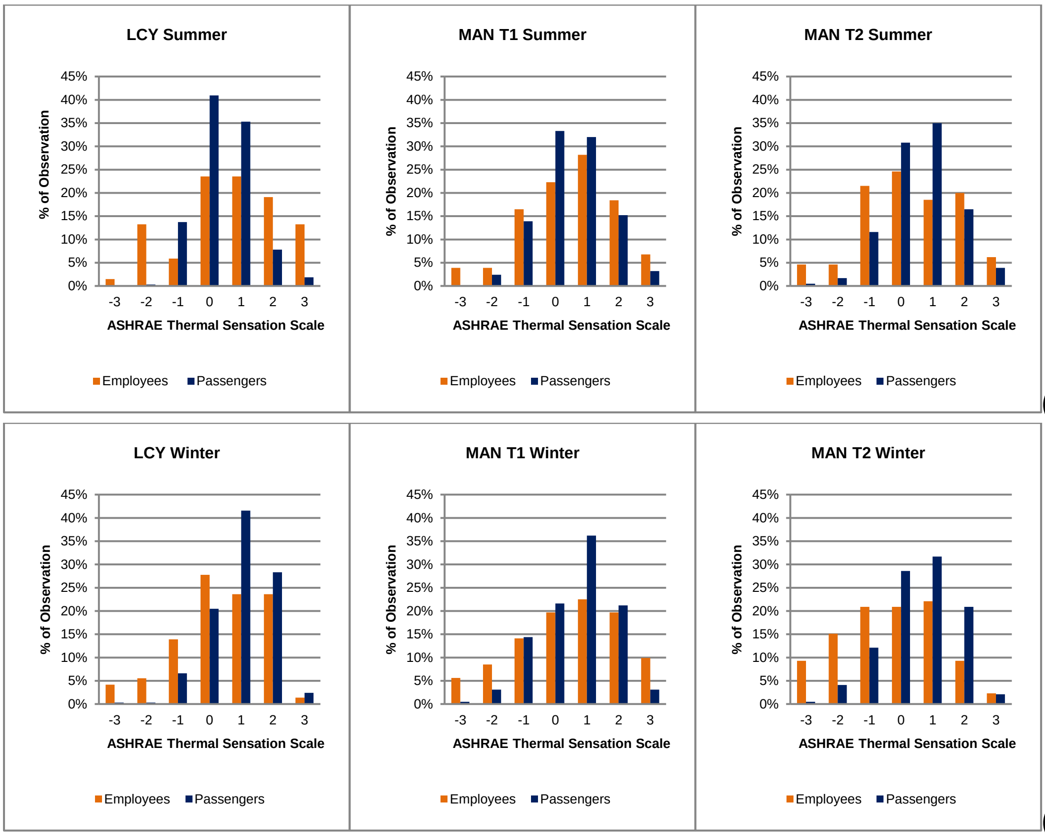
In summer, the mean clothing insulation for passengers and staff was very similar at 0.56 and 0.60 clo (table 4). This increased to 0.88-1.15 clo for passengers and 0.80-0.90 clo for staff, in winter, reflecting the greater impact of outdoor weather on passengers' outfits. The passengers' destination, also appeared to influence clothing insulation, as in MAN T2, which serves mostly holiday destinations in warmer climates, clothing insulation was lower than the other two terminals in winter.

| | LCY | | MAN T1 | | MAN T2 | |
|---|---|---|---|---|---|---|
| | Summer | Winter | Summer | Winter | Summer | Winter |
| **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 |

**Table 4: Mean clothing insulation (clo) for employees and passengers.**

## 3.1 Thermal Sensation

The shared variance between thermal sensation (TS) and physical variables was investigated with Pearson (2-tailed) correlations, where the correlation coefficients refer to $p<0.01$, unless otherwise mentioned. The results showed that TS correlates better with operative temperature: 0.25 in LCY, 0.40 in MAN T1 and 0.20 in MAN T2. A positive correlation was also found with $CO_2$ levels (0.23 in LCY, 0.24 in MAN T2, and 0.06 in MAN T1, $p<0.05$). Higher $CO_2$ concentrations were normally the result of overcrowded spaces where TS had an increasing trend. Moreover, the analysis also revealed weak correlation between TS and the subjects' activity level 15 min prior to the questionnaire (0.18, 0.09 and 0.14 in LCY, MAN T1 and MAN T2).



(a)
(b)

**Figure 4: Percentage distribution of thermal sensation for passengers and staff during (a) the summer surveys and (b) the winter surveys.**

Figures 4(a) and 4(b) illustrate the percentage distribution of TS for passengers and staff. The vast majority (90%) of passengers' TS in LCY during summer is within the three central categories of the ASHRAE scale ($-1 \le TS \le +1$). In winter, the same percentage shifts towards warmer votes, lying between "neutral", "slightly warm" and "warm". These categories represent also the majority of passengers in MAN T1 and MAN T2 (nearly 80%) during summer and winter.

On the other hand, employees' TS distribution is wider in all cases, demonstrating that more unacceptable thermal sensations (±3, ±2) were experienced among staff. Statistically, this is confirmed from the constantly higher standard deviation of employees' mean TS (table 6).

More specifically, at least one third of employees reported unacceptable TS, which increases to almost half (47%) of the terminal staff in LCY during summer (table 5). On the contrary, unacceptable thermal sensations are experienced from 10-31% of passengers with the highest percentages found in winter, predominantly from "warm" votes.

| **% of unacceptable TS** | **LCY** | | **MAN T1** | | **MAN T2** | |
|---|---|---|---|---|---|---|
| | Summer | Winter | Summer | Winter | Summer | Winter |
| **Employees** | 47% | 35% | 33% | 44% | 35% | 36% |
| **Passengers** | 10% | 31% | 21% | 28% | 23% | 28% |

**Table 5: Percentage of unacceptable thermal sensation votes for passengers and staff.**

In seasonal terms, the mean TS (table 6) 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. On the contrary, for passengers the mean TS increases in winter (with the exception of T2), despite the lower temperatures (table 3). This is due to the higher clothing insulation worn, particularly at LCY and MAN T1 (table 4).

| | | **Employees** | | **Passengers** | |
|---|---|---|---|---|---|
| | | Mean TS | St.Dev. | Mean TS | St.Dev. |
| **Summer** | LCY | 0.65 | 1.59 | 0.42 | 0.90 |
| | MAN T1 | 0.50 | 1.44 | 0.53 | 1.08 |
| | MAN T2 | 0.32 | 1.51 | 0.63 | 1.09 |
| **Winter** | LCY | 0.38 | 1.39 | 0.97 | 0.96 |
| | MAN T1 | 0.44 | 1.65 | 0.66 | 1.17 |
| | MAN T2 | -0.31 | 1.54 | 0.58 | 1.16 |

**Table 6: Mean score and standard deviation of thermal sensation for staff and passengers.**

The neutral temperatures for passengers and staff were calculated using weighted linear regressions. Based on the acceptance of the statistical assumptions underlying PMV/PPD heat-balance model (ISO 7730), the regression models were used for the calculation of the operative temperature ranges in which 80% and 90% of terminal users find the thermal environment acceptable. Thus, it was assumed that a mean TS of ±0.85 corresponds to 80% general acceptability (20% dissatisfaction) and a mean TS of ±0.50 to 90% general acceptability (10% dissatisfaction). Table 7 presents the results for summer and winter neutral temperatures.

| | | | Gradient | $R^2$ | Tneutral (°C) | 80% Accept.(°C) | 90% Accept.(°C) |
|---|---|---|---|---|---|---|---|
| **Summer** | **Employees** | **LCY** | 0.389 | 0.61 | 22.1 | 19.9 - 24.3 | 20.8 - 23.4 |
| | | **MAN T1** | 0.461 | 0.74 | 21.1 | 19.3 - 23.0 | 20.0 - 22.2 |
| | | **MAN T2** | 0.421 | 0.30 | 22.4 | 20.4 - 24.4 | 21.2 - 23.6 |
| | **Passengers** | **LCY** | 0.243 | 0.67 | 21.5 | 18.0 - 25.0 | 19.5 - 23.6 |
| | | **MAN T1** | 0.282 | 0.82 | 20.5 | 17.4 - 23.5 | 18.7 - 22.2 |
| | | **MAN T2** | 0.274 | 0.72 | 20.7 | 17.6 - 23.8 | 18.9 - 22.6 |
| **Winter** | **Employees** | **LCY** | 0.756 | 0.38 | 22.5 | 21.4 - 23.6 | 21.9 - 23.2 |
| | | **MAN T1** | 0.342 | 0.46 | 20.6 | 18.1 - 23.1 | 19.2 - 22.1 |
| | | **MAN T2** | 0.362 | 0.21 | 22.3 | 19.9 - 24.6 | 20.9 - 23.7 |
| | **Passengers** | **LCY** | 0.407 | 0.86 | 21.1 | 19.1 - 23.2 | 19.9 - 22.4 |
| | | **MAN T1** | 0.304 | 0.77 | 19.2 | 16.4 - 22.0 | 17.6 - 20.9 |
| | | **MAN T2** | 0.219 | 0.75 | 18.4 | 14.5 - 22.3 | 16.1 - 20.7 |

**Table 7: Regression models, acceptability temperature ranges (°C) and neutral temperatures (°C) in summer and winter.**

As the slope of the regression models represents the thermal sensitivity (figure 5), the results reveal that in all cases employees are on average 1.6 times more sensitive to temperature changes than passengers in both seasons. Consequently, the temperature change required to shift the TS of the two groups differs significantly. For instance, in LCY during summer, a unit increase in staff's TS would require 2.5°C temperature rise whereas for passengers that is 4.1°C.

The neutral temperatures demonstrate the discrete thermal requirements of the two groups, who achieve neutrality at different temperatures in all cases. The results show that employees have a narrower acceptability range, while their neutral temperature is always higher than passengers'. This difference is found to vary from as little as 0.6°C (in LCY and MAN T1 in summer) to 3.9°C (in MAN T2 in winter). Additionally, employees' neutral temperature (table 7) in all terminals differs from the mean indoor temperature they experience (table 3) only by 0.6-1.6°C, whilst for passengers thermal neutrality is achieved at lower temperatures, by 1.8-2.7°C, than the mean temperature they experience.

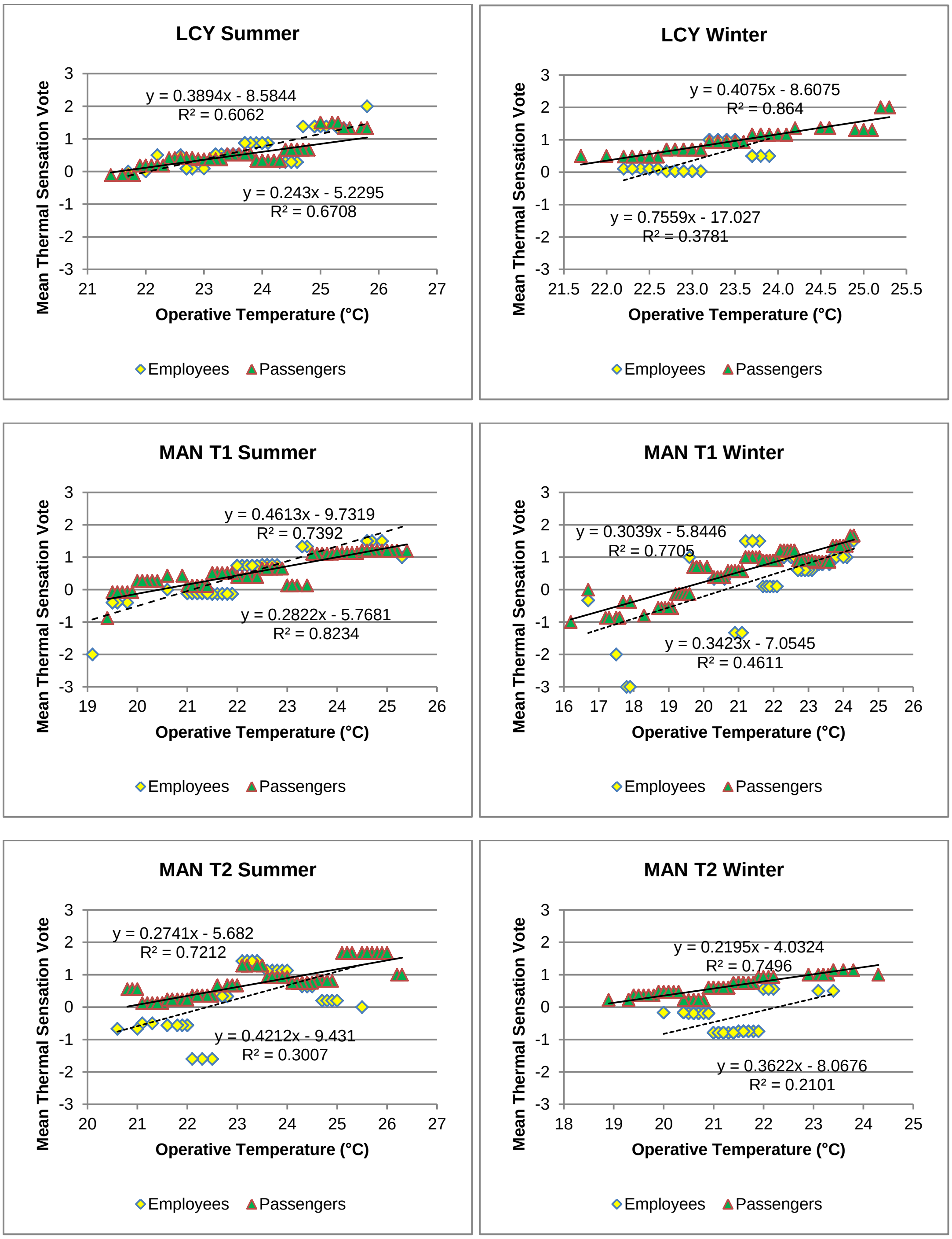



**Figure 5: Relationship between thermal sensation and operative temperature for passengers and staff.**

### 3.2 Thermal preference

Similarly to TS, thermal preference correlates better with operative temperature; 0.27, 0.41 and 0.40 in LCY, MAN T1 and MAN T2 respectively. For the analysis, thermal preference has been transformed to a 3-point variable where the “prefer cooler” represents the votes for a “much cooler” and “a bit cooler” environment, and “prefer warmer” the votes for a “much warmer” and “a bit warmer” environment.

In both seasons nearly 70% of employees in all terminals favour a change, with the majority preferring a cooler environment (figure 6). Approximately 50% of passengers in summer prefer no change, while the vast majority of those requiring a different thermal environment prefer to be cooler. In winter, passengers’ preference profile varies between the terminals. In LCY 57% of passengers prefer to be cooler, suggesting a problem with overheating. This is due to the small size of the terminal building, which frequently becomes overcrowded, resulting in the highest temperatures recorded, even in winter (table 3). Overheating was more pronounced in winter when LCY was busiest (business trips, ski holidays, and more cancellations due to bad weather), and passengers’ clothing insulation was considerably higher (table 4).

MAN T2 has the highest thermal satisfaction rate from all terminals, where up to 62% of passengers find the thermal environment ‘just right’.

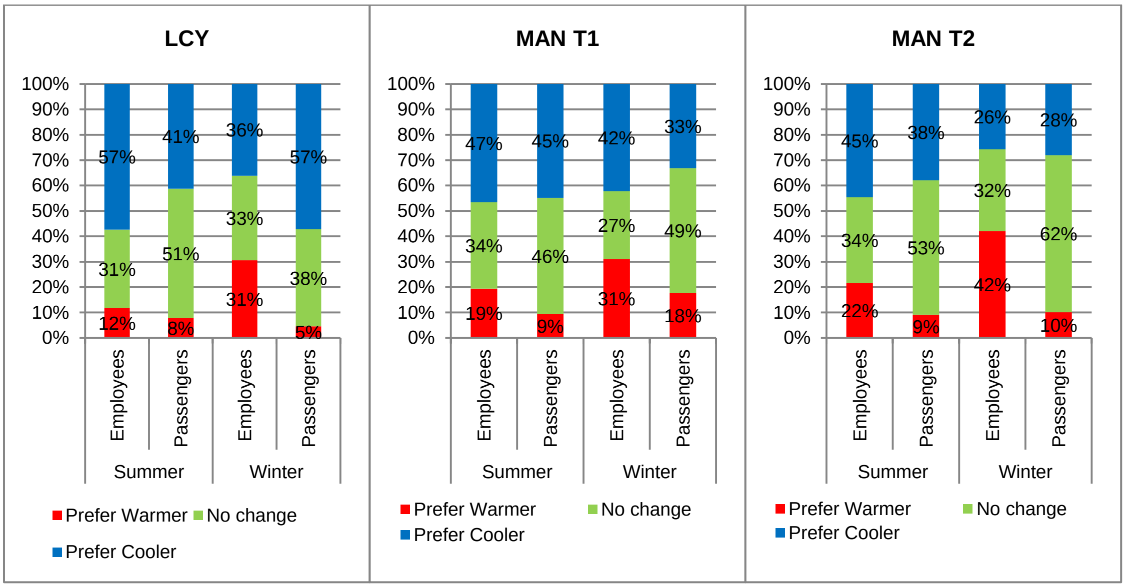



**Figure 6: Percentage of binned thermal preference votes for staff and passengers.**

Linear regression models were generated to associate the thermal preference with temperature. The percentages of “prefer warmer” and “prefer cooler” votes was calculated for each half-degree (°C) increment while using the sample size of each bin as weighting factor. Separate linear regression models were fitted between the “prefer warmer” and “prefer cooler” percentages and the operative temperature. The intersection of the two regression lines (figure 7) marks the preferred operative temperatures (table 8).

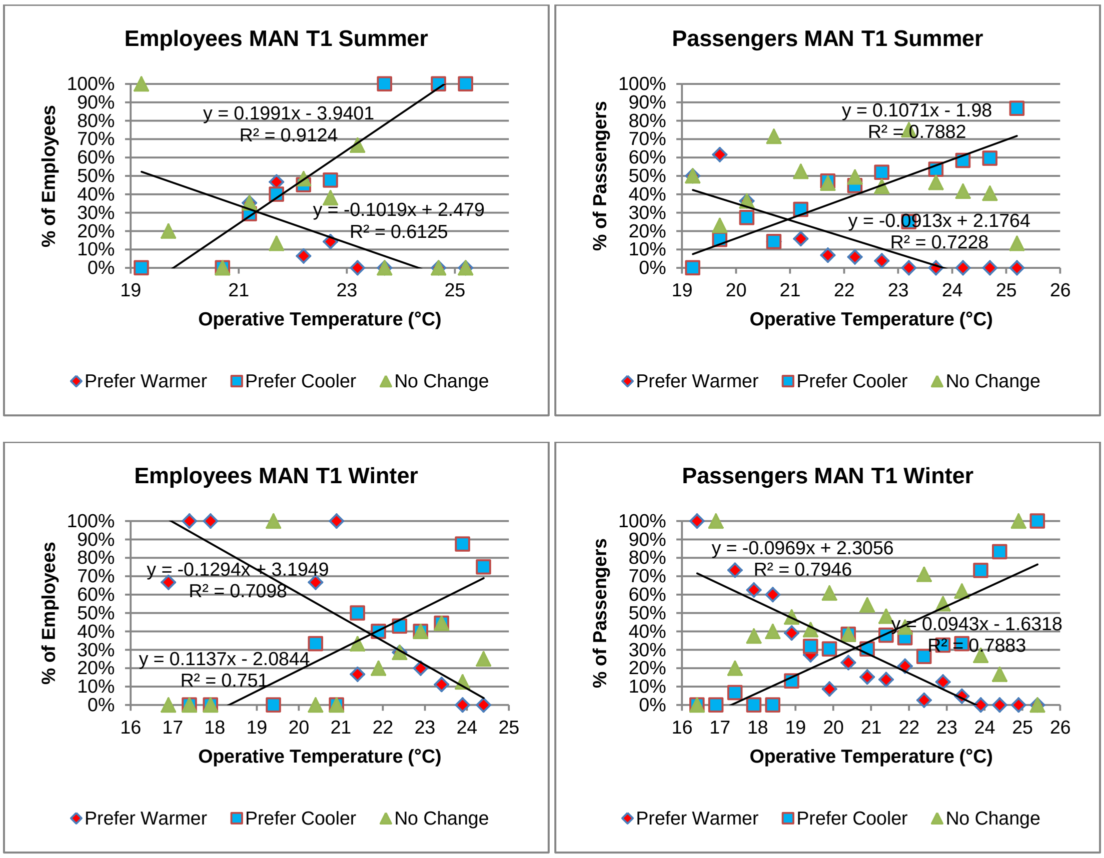



**Figure 7: Calculation of preferred temperatures for passengers and staff in MAN T1.**

The profile of the preferred temperatures follows that of the neutral temperatures with the two being very close in most cases. Both groups prefer a cooler environment, with passengers constantly preferring lower temperatures than staff.

In MAN T1 and MAN T2 where the lowest operative temperatures were observed during winter, passengers' neutral temperature is at 19.2 °C and 18.4 °C but they prefer this to rise to 20.6 °C and 19.9 °C respectively. This demonstrates that passengers are more tolerant of the cooler conditions.

| | | LCY | | | MAN T1 | | | MAN T2 | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Mean $T_{op.}$ (°C) | $T_{neutral}$ (°C) | $T_{pref.}$ (°C) | Mean $T_{op.}$ (°C) | $T_{neutral}$ (°C) | $T_{pref.}$ (°C) | Mean $T_{op.}$ (°C) | $T_{neutral}$ (°C) | $T_{pref.}$ (°C) |
| **Summer** | **Employees** | 23.7 | 22.1 | 22.1 | 22.1 | 21.1 | 21.3 | 23.2 | 22.4 | 22.5 |
| | **Passengers** | 23.3 | 21.5 | 21.4 | 22.3 | 20.5 | 20.9 | 23.0 | 20.7 | 21.1 |
| **Winter** | **Employees** | 23.1 | 22.5 | 22.8 | 21.9 | 20.6 | 21.7 | 21.4 | 22.3 | 21.9 |
| | **Passengers** | 23.5 | 21.1 | 21.5 | 21.4 | 19.2 | 20.6 | 21.1 | 18.4 | 19.9 |

**Table 8: Summary of preferred, neutral and mean temperatures (°C) for staff and passengers.**

## 4. Discussion

The data analysis showed that thermal discomfort is regular, as the high percentage of unacceptable thermal sensations demonstrates (passengers 10-31%, staff 33-47%; table 5), and the high percentage requiring variation in their thermal environment (50% of passengers in summer and 38-62% in winter, 70% of staff in both seasons; figure 6).

In most cases passengers and staff prefer cooler temperatures and achieve neutrality at lower levels than the mean temperature they experience. An exception is the staff in MAN T2 during winter, where employees' neutral and preferred temperature was slightly higher than the mean indoor temperature. This reflects a specific characteristic of this terminal during winter, with two flight peaks daily and very low passenger occupancy during the rest of the day. Therefore, there were prolonged periods of time when the building had low temperature – MAN T2 being the terminal with the lowest mean temperature (table 3). Combined with the reduced activity levels of staff during these periods, it resulted in preferences for a slightly warmer environment.
The findings also indicate that the thermal requirements between passengers and staff vary considerably (table 8). The difference in neutral temperature shows that passengers feel comfortable at lower temperatures than staff by 0.6-3.9 °C. This difference becomes greater in winter when passengers' clothing insulation is higher. On average, passengers feel comfortable at temperatures lower than the mean operative temperature by 2 °C in summer and 2.4 °C in winter. For staff, neutrality is achieved closer to the mean indoor temperatures. This reflects their adaptation to the indoor environment, related to their long dwell times and continuous experience with it.

The differences in preferred temperatures further highlight the thermal conflict between the two groups, with passengers constantly preferring lower temperatures than staff. Interestingly, the analysis also suggests that passengers are more tolerant of the cooler environment, supporting the hypothesis that they view the terminal as transition space, where the comfort zone can be wider.

This perceived difference in the terminal as transition vs. normal workspace is also reflected in the overall comfort of the two groups. As figure 8 demonstrates, discomfort was considerably higher among staff, expressed by 23-49% of employees in the three terminals. Employees' discomfort was higher in summer indicating the difficulty in coping with the higher temperatures. Regarding the passengers, only 8-21% expressed discomfort, which meets the requirement for 80% occupant acceptability in typical applications [ix].

In all terminals, the passengers' wider acceptable temperature range demonstrates their higher levels of tolerance of the thermal environment and consequently their wider adaptive capacity. This is consistent with the wider framework of adaptation in the thermal environment, where short time of exposure, expectations and perceived control (e.g. changing clothing, moving to another space, etc.) increase passengers' tolerance, enabling them to cope effectively with thermal discomfort [x].

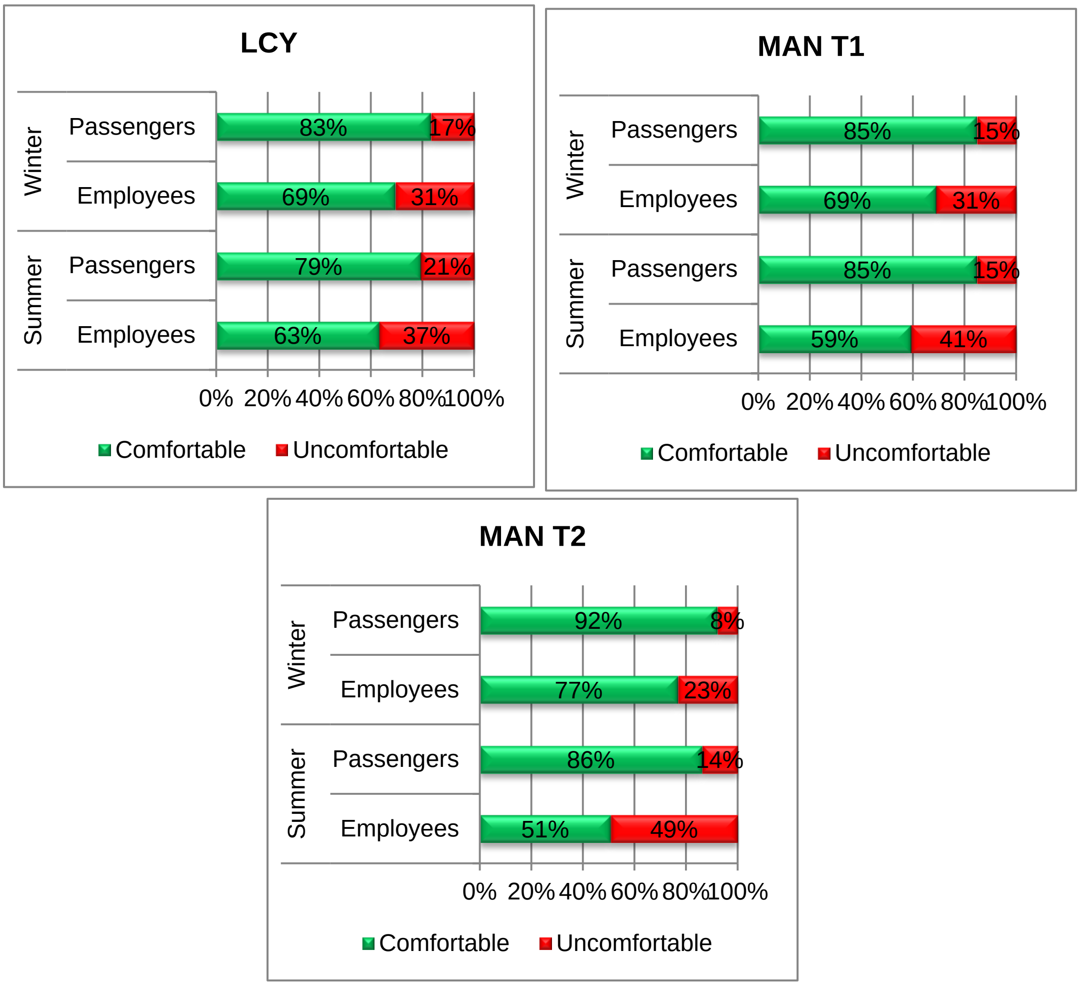



**Figure 8: Percentage of (un)comfortable passengers and staff.**

## Conclusions

This study investigated the range of thermal comfort conditions in three airport terminal buildings of different size and typology, through extensive seasonal field surveys. The results of the analysis from the environmental monitoring and interviews with 3,087 people were presented. Focusing on passengers and staff as the main user groups of the terminal buildings, the findings demonstrated significant differences in their neutral and preferred temperature, as well as their overall comfort.

Both groups regularly prefer a different thermal environment to the one experienced, while the staff is more sensitive to temperature changes. 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 savings.

Differences in clothing levels, time spent in the terminals, as well as expectations are some of the factors differentiating the thermal requirements of these groups, resulting in thermal comfort conflicts. Passengers demonstrated a wider range of neutral temperatures, approaching the terminal as a transition space, where the thermal comfort zone can be extended. On the other hand, staff has limited adaptive capacity, consistently leading to a narrower comfort zone.

The analysis also demonstrated that discomfort from higher temperatures was predominant in all cases, although affected by the particularities of each terminal. Where such problems are apparent in winter, lower temperature set-point of the heating system can improve thermal comfort while leading to energy savings. In the summer, there is little scope for increasing the cooling systems set-points; instead different design solutions would need to be explored to reduce the peak temperatures particularly during high occupancy periods. For example phase change materials modeled in airport terminals were recently shown to reduce peak temperatures by 3 °C, preventing overheating in the summer months [xi, xii].

Ultimately, understanding the thermal environment in airport terminals and the diverging needs of the different user groups can significantly improve thermal comfort conditions. Such knowledge can also influence the design and refurbishment strategies of these very energy-intensive buildings in order to reduce energy consumption.

**Acknowledgements**
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**APPENDIX I: Paper presented at Windsor Conference 2014**

Proceedings of 8th Windsor Conference: ***Counting the Cost of Comfort in a changing world*** Cumberland Lodge, Windsor, UK, 10-13 April 2014. London: Network for Comfort and Energy Use in Buildings, http://nceub.org.uk

# Understanding thermal comfort conditions in airport terminal buildings

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## Abstract

This paper presents the results from the thermal comfort studies at three airport terminal buildings in the UK where seasonal on-site surveys were conducted. The investigation involved extensive monitoring of the indoor environmental conditions along with 3,087 questionnaire-guided interviews with terminal users. The paper quantifies the thermal requirements of the terminal population and focuses on the thermal perception of passengers and staff in different terminal spaces. The findings demonstrate the preference for a different thermal environment than the one experienced and that thermal neutrality is found to lie at lower temperatures than those experienced, suggesting an overheating issue, predominantly in winter. Passengers and staff present different satisfaction levels with the indoor environment while their thermal sensation is greatly affected from the characteristics and function of the terminal spaces.

Keywords: airport terminal, passengers and staff, indoor thermal comfort, thermal sensation, thermal preference.

## 1. Introduction

Airport terminals are a particularly complex building type where the needs of very different population groups are accommodated. The indoor microclimatic conditions are expected to provide a comfortable working environment to the small number of terminal staff and at the same time a comfortable transient environment to passengers. Variations in clothing levels and activity, along with time spent in the area and overall expectations are differentiating factors for variations in thermal requirements between the two groups. The diversity of spaces and the heterogeneous functions across the different terminal zones further contribute to thermal comfort conflicts. Understanding such conflicts can improve thermal comfort conditions, while reducing the large amounts of energy consumed for the conditioning of terminal buildings.

ASHRAE design recommendations for airport terminals are 23-26°C temperature and 30-40% RH in winter and 40-55% RH in summer (ASHRAE, 2003). Allowing for wider temperature ranges, CIBSE provides seasonal comfort criteria for specific terminal areas, based on standard activity and clothing insulation levels as shown in table 1 (CIBSE, 2006).

**Table 1: Recommended comfort criteria for airport terminal spaces (CIBSE).**

| | Summer* | Winter* | |
|---|---|---|---|
| | Operative temperature (°C) | | Activity (met) |
| **Baggage Reclaim** | 21-25** | 12-19** | 1.8 |
| **Check-in areas*** ** | 21-23 | 18-20 | 1.4 |
| **Concourse (no seats)** | 21-25** | 19-24** | 1.8 |
| **Customs area** | 21-23 | 18-20 | 1.4 |
| **Departure lounge** | 22-24 | 19-21 | 1.3 |

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

However, there are very few published studies on the evaluation of the thermal environment in airport terminal spaces. A study in three Greek airports with 285 questionnaires highlighted the different satisfaction levels between staff and passengers (Balaras et al, 2003). Another study, surveying 128 staff and passengers in the terminal of Ahmedabad airport, India, found a very high comfortable temperature range in the air-conditioned part of the building, 24-32 °C (Babu, 2008). A study with 569 questionnaires from passengers in Terminal 1 at Chengdu Shuangliu International Airport in China reported 95.8% thermal acceptability (Liu et al, 2009).

The current study is the most extensive work available to date. Through field surveys in different terminal areas it investigates and quantifies the thermal comfort requirements using a large population sample from three airport terminal buildings in the UK.

## 2. Field surveys in airport terminals

On-site surveys were carried out in London City Airport (LCY), Manchester Terminal 1 (MAN T1) and Manchester Terminal 2 (MAN T2). The work involved extensive monitoring of the indoor environmental conditions across the different terminal areas along with questionnaire-based interviews with terminal users. Each terminal was surveyed for a week in summer and winter (2012-2013) to get the seasonal variations.

### 2.1 Description of terminals surveyed

The selection of the terminals aimed for buildings of different characteristics and capacities. LCY terminal is a compact building with a total floor area of 8,000 $m^2$. In 2012, LCY was the 15th busiest airport in the UK serving over 3 million passengers (CAA, 2013). In the same year, Manchester represented the 3rd busiest airport with 20 million passengers (CAA, 2013). The current capacity of MAN T1 and MAN T2 is 11 and 8 million passengers a year (Manchester Airport, 2007). The passenger-related facilities are spread over an area of 43,499 $m^2$ in MAN T1 and 26,063 $m^2$ in MAN T2, excluding the car parks, mechanical people movers and air bridges.

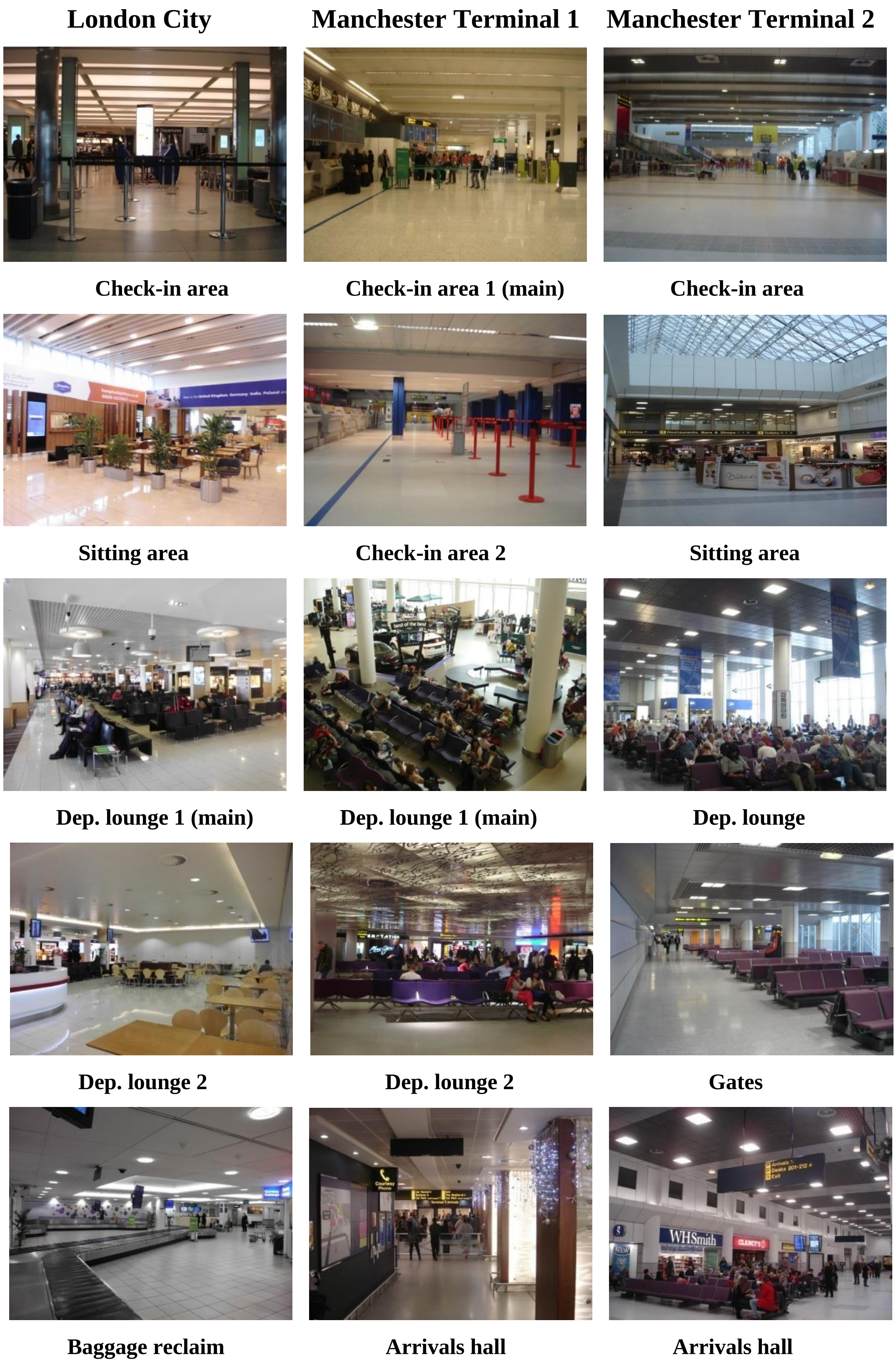



**Figure 1: Representative images of spaces in the three terminals surveyed.**

MAN T2 features the most contemporary terminal design between the three terminals in Manchester. The vast majority of its passenger-related facilities have high floor-to-ceiling heights with extensive use of natural light through window walls and rooflights. The gate lounges are the continuation of the departure lounge as they are located at the two diametrically opposed piers spanning from the central building. The largest among the case-studies, MAN T1, has undergone various expansions over the years. As a result, it houses a mixture of heterogeneous spaces (figure 1).

The thermal environment in MAN T1 and MAN T2 is controlled by variable refrigerant volume (VRV) and fan coil unit systems, whereas in smaller areas direct expansion (DX) systems are used. The temperature set-point is kept at 21°C throughout the year. The spaces in LCY are conditioned by 13 air handling units aiming for a temperature set-point of 20°C for winter and 23°C for summer.

Another differentiating factor between the terminals is the dwell time. As a result of its small size and the focus on business passengers, LCY provides short walking distances and significantly shorter dwell times, which can be limited to 20 minutes from check-in to emplaning.

The spaces monitored in each terminal include check-in areas, security search areas, circulation spaces, retail facilities, departure lounges, gates, baggage reclaim and arrivals halls.

### 2.2 Environmental and human monitoring

The terminals were monitored from 5am - 9pm to get the peak and off-peak times. The monitored physical parameters included dry bulb and black globe temperature, relative humidity, air movement, carbon dioxide and horizontal illuminance levels. All quantities were measured at the average height of a standing person (1.7 m) and recorded at one-minute intervals. The equipment employed conforms to ISO 7726 (ISO, 1998) and consists of a data logging system, a shielded temperature and humidity probe, black globe thermometer, ultrasonic anemometer, a $CO_2$ sensor and a light sensor. The weather station was designed to be mobile across the terminal spaces and dismountable when passing through the x-ray machines, allowing for the investigation of the immediate microclimate people experience.

The selection of interviewees was random in order to get a representative population sample of passengers, staff, meeters and greeters. The questionnaire aimed for the collection of subjective data for the evaluation of comfort conditions. Thermal sensation was assessed on the 7-point ASHRAE scale while a 5-point scale was used for thermal preference. Similar pattern of questions were used for the perception and the preference over other environmental parameters such as air movement, humidity and lighting levels, while people was also asked to assess their overall comfort state. Additional data collected include the activity levels during and 15 minutes prior to the questionnaire, clothing insulation, time spent in the terminal and demographic data.

## 3. Data analysis

The data were analysed with the statistical software package SPSS 19. The total sample population (table 2) consists of 3,087 people with a 50:50 male-female ratio. In each terminal the majority of interviewees (70-80%) are transit, arriving and mostly departing passengers. In LCY 52% of departing passengers were travelling on business, whereas this percentage was significantly lower in MAN T1 (14%) and MAN T2 (3%). The average passenger in all terminals is 35-44 years old, similarly to the average employee in MAN T2. Staff in LCY and MAN T1 displays a median age of 25-34. Reflecting the dwell time of terminal staff, 80% of interviewed employees are working full-time and 20% part-time. Airport, airline and retail staff was studied in their work spaces and account for 12-17% of the terminal population. Other interviewees include meeters and greeters studied in the landside areas of the terminals (check-in and arrivals halls).

**Table 2: Number of interviewees in the surveyed terminals.**

| | Summer | Winter | Total |
|---|---|---|---|
| **LCY** | 403 | 415 | 818 |
| **MAN T1** | 663 | 535 | 1198 |
| **MAN T2** | 538 | 533 | 1071 |

During the summer surveys the outdoor 24h-mean temperature ranged between 11-20°C in LCY, 15-16°C in MAN T1 and 10-16°C in MAN T2, while the respective winter temperature ranges were 3.9-12°C, 0.9-6.6°C and -1.6-6.3°C. In summer the terminal population had very similar clothing insulation values, while in winter, the effect of outdoor weather resulted in distinct variations in clothing levels between the groups (table 3).

**Table 3: Mean clothing insulation (clo) of terminal users.**

| | LCY | | MAN T1 | | MAN T2 | |
|---|---|---|---|---|---|---|
| | Summer | Winter | Summer | Winter | Summer | Winter |
| 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 |
| Meeters & Greeters | 0.67 | 1.28 | 0.57 | 1.04 | 0.54 | 1.05 |

An overview of the indoor environmental conditions for the three terminals is provided in table 4. In LCY the operative temperature presented a narrow range (4.4°C in summer and 3.6°C in winter) as a result of its small size and uniform environment. The lowest and highest temperatures were observed during the low occupancy and peaks respectively. In the bigger MAN T2 the temperature ranged between 20.6 - 26.3°C in summer and 18.9 - 24.5°C in winter. As a result of its diverse spaces, MAN T1 presented the widest temperature range in both seasons (19.1 - 25.4°C in summer and 16.2 - 25.6°C in winter). Despite the fact that all three terminals do not include (de)humidification, the mean RH (%) was found within the ASHRAE recommended range. The occasionally high air movement occurred in spaces exposed to the outdoor wind through the openings, but the mean air movement was very low (0.1- 0.2 m/s).

**Table 4: Descriptive values of physical quantities monitored in summer and winter.**

| | | Summer | | | | | Winter | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $T_{op.}$ (°C) | $V_{air}$ (m/s) | $CO_2$ (ppm) | RH (%) | Illum. (lux) | $T_{op.}$ (°C) | $V_{air}$ (m/s) | $CO_2$ (ppm) | RH (%) | Illum. (lux) |
| LCY | Mean | 23.3 | 0.12 | 483 | 50.4 | 339 | 23.4 | 0.13 | 817 | 32.3 | 300 |
| | SD | 0.9 | 0.06 | 138 | 3.0 | 680 | 0.6 | 0.04 | 152 | 7.0 | 390 |
| | Min | 21.4 | 0.04 | 324 | 44.7 | 80 | 21.7 | 0.04 | 660 | 21.7 | 70 |
| | Max | 25.8 | 0.58 | 1095 | 64.1 | 7999 | 25.3 | 0.26 | 1333 | 53.3 | 3746 |
| MAN T1 | Mean | 22.0 | 0.15 | 648 | 57.5 | 260 | 21.3 | 0.16 | 770 | 32.5 | 485 |
| | SD | 1.5 | 0.05 | 172 | 5.8 | 223 | 2.0 | 0.16 | 107 | 5.9 | 1044 |
| | Min | 19.1 | 0.04 | 298 | 46.6 | 40 | 16.2 | 0.03 | 587 | 23.2 | 20 |
| | Max | 25.4 | 0.32 | 1059 | 73.8 | 1854 | 25.6 | 1.04 | 1365 | 53.1 | 8173 |
| MAN T2 | Mean | 23.0 | 0.18 | 726 | 51.1 | 836 | 21.1 | 0.16 | 752 | 32.6 | 480 |
| | SD | 1.3 | 0.11 | 209 | 6.8 | 957 | 0.9 | 0.09 | 159 | 6.0 | 536 |
| | Min | 20.6 | 0.04 | 490 | 37.6 | 20 | 18.9 | 0.04 | 284 | 22.0 | 40 |
| | Max | 26.3 | 0.55 | 1380 | 66.6 | 6431 | 24.5 | 0.49 | 1273 | 44.5 | 3498 |

## 3.1 Thermal sensation of the total terminal population

The frequency distribution of actual thermal sensation (TS) and PMV for each terminal is presented in figure 2. The majority of people in LCY (83%) and MAN T1 (78%) reported acceptable TS (middle three categories on the ASHRAE scale) in summer, when "neutral" was the sensation with the highest percentage.

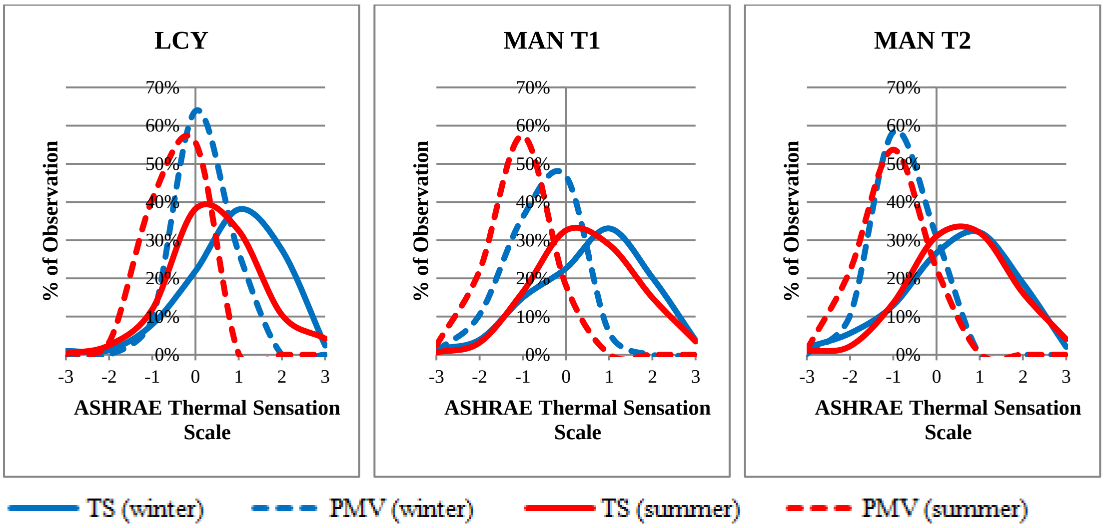



**Figure 2: Percentage distribution of actual and predicted thermal sensation.**

As a result of the increased clothing insulation in winter, the majority of TSs (87% in LCY and 76% in MAN T1) shifts towards warmer votes. This pattern is similar in MAN T2 in both seasons. Although PMV follows the seasonal shift of TS it predicts cooler TSs in summer and winter, as well as a significantly narrower range of TS in all three terminals. The mean absolute TS-PMV discrepancy ranges between 1.04 and 1.67 (ASHRAE scale units), and is higher in summer.

Correlation analysis showed that TS shares more variance with operative temperature than with any other of the physical variables, with the associated coefficients being 0.25 for LCY, 0.40 for MAN T1 and 0.20 for MAN T2 (all significant at $p<0.01$). Using half-degree (ºC) operative temperature bins, the actual and predicted neutral temperatures were calculated by means of weighted linear regressions (figure 3). The models were also used for the calculation of the temperature ranges in which 80% and 90% of terminal users find the thermal environment acceptable. Thus, in accordance to the statistical assumptions of the PMV/PPD heat-balance model (ISO 7730) it was assumed that a mean TS of ±0.85 and ±0.50 corresponds to 80% and 90% general acceptability respectively. All presented models (table 5) achieved a statistical significance level of 99% or better.

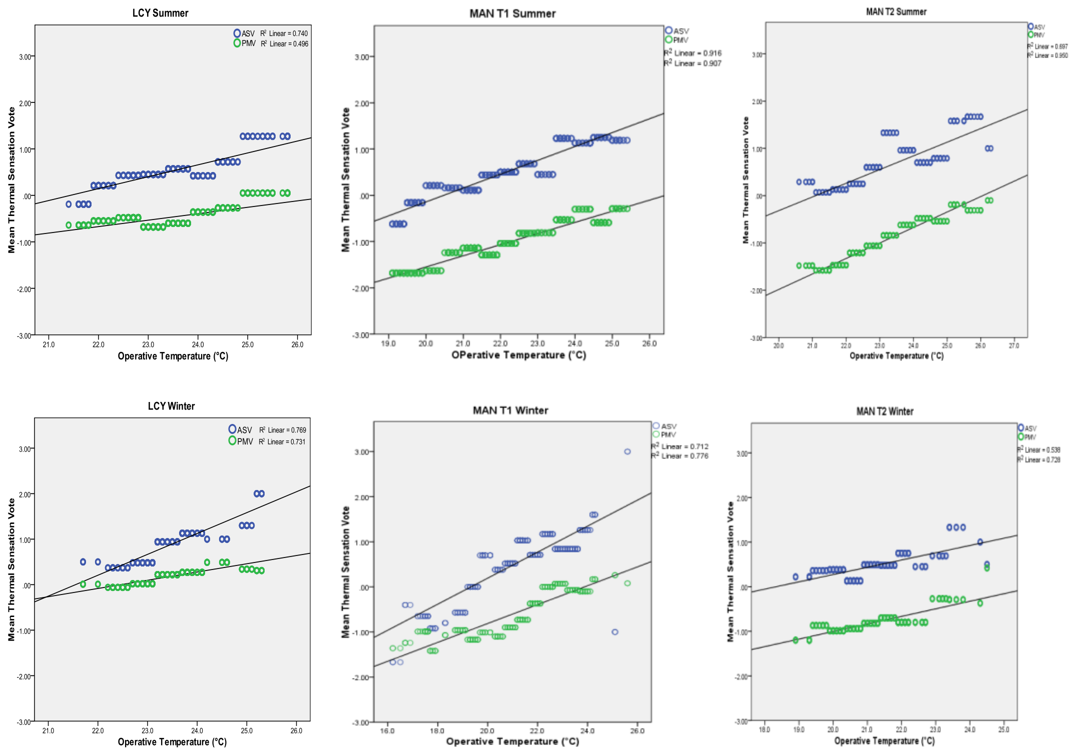



**Figure 3: Relationship between actual and predicted thermal sensation with operative temperature.**

The gradients of the regression models show that people presented similar thermal sensitivity in all terminals during summer. The temperature change necessary to shift the TS by one unit on the ASHRAE scale is 3.9 ºC in LCY, 3.4 ºC in MAN T1 and 3.5 ºC in MAN T2. In winter the slope varies widely between the terminals: in LCY respondents' thermal sensitivity is greatly increased and the TS change rate is one unit for every 2.2 ºC temperature change. In MAN T1, there is a similar thermal sensitivity and same rate of TS change with summer, whereas in MAN T2, the mean TS would not be altered with temperature changes below 6.2 ºC.

**Table 5: TS and PMV regression models, neutral temperatures (°C) and acceptability temperature ranges in summer and winter.**

| | | | Slope | $R^2$ | $T_{neutral}$ (°C) | 80% accept. (°C) | 90% accept. (°C) |
|---|---|---|---|---|---|---|---|
| Summer | Actual | **LCY** | 0.256 | 0.74 | 21.4 | 18.1 – 24.8 | 19.5 – 23.4 |
| | | **MAN T1** | 0.300 | 0.92 | 20.4 | 17.6 – 23.3 | 18.8 – 22.1 |
| | | **MAN T2** | 0.289 | 0.70 | 21.1 | 18.2 – 24.1 | 19.4 – 22.9 |
| | Predicted | **LCY** | 0.139 | 0.50 | 26.8 | 20.7 – 32.9 | 23.2 – 30.4 |
| | | **MAN T1** | 0.241 | 0.91 | 26.4 | 22.9 – 29.9 | 24.3 – 28.5 |
| | | **MAN T2** | 0.327 | 0.95 | 26.1 | 23.5 – 28.7 | 24.6 – 27.6 |
| Winter | Actual | **LCY** | 0.459 | 0.77 | 21.5 | 19.7 – 23.4 | 20.4 – 22.6 |
| | | **MAN T1** | 0.288 | 0.71 | 19.4 | 16.4 – 22.3 | 17.6 – 21.1 |
| | | **MAN T2** | 0.163 | 0.54 | 18.3 | 13.1 – 23.6 | 15.3 – 21.4 |
| | Predicted | **LCY** | 0.181 | 0.73 | 22.5 | 17.8 – 27.2 | 19.7 – 25.2 |
| | | **MAN T1** | 0.209 | 0.78 | 23.9 | 19.9 – 28.0 | 21.5 – 26.3 |
| | | **MAN T2** | 0.170 | 0.73 | 25.9 | 20.9– 30.9 | 22.9 – 28.8 |

In all cases the results reveal that neutral temperatures lie below the mean operative temperature people experience. In summer, neutrality temperature is lower by 1.6 ºC in MAN T1 and by 1.9 ºC in LCY and MAN T2. Despite the increased thermal sensitivity in LCY during winter, the neutral temperature is the same in both seasons and consistently lower than the mean operative temperature by 1.9 ºC. In MAN T1 and MAN T2, neutrality in winter is lower than the mean operative temperature by 1.9 ºC and 2.8 ºC. On the other hand, PMV regression models predict significantly higher neutral temperatures by 1.0-7.6 °C.

Figure 4 shows the operative temperature together with the 80% and 90% acceptability temperature ranges. During the summer surveys the temperature lies within the 80% acceptable range for 94%, 82% and 73% of the monitoring time in LCY, MAN T1 and MAN T2. This is also the case during winter in MAN T2 (99% of time), whereas in LCY and MAN T1 the temperature in winter remains within that range for only 48% and 66% of time, highlighting periods of overheating, as is also apparent from the thermal sensations in figure 2.

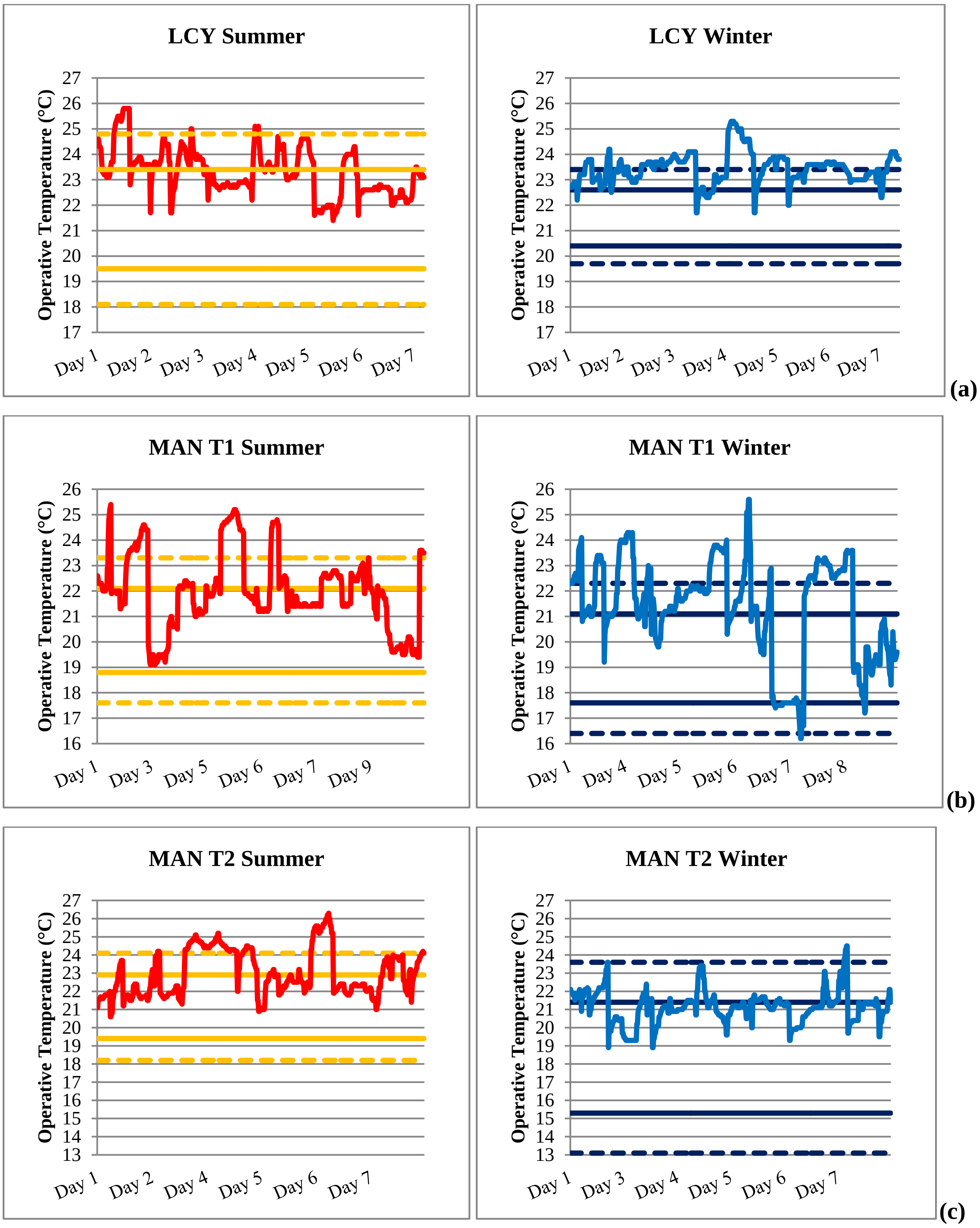



**Figure 4: Operative temperature, 80% (dotted lines) and 90% (continuous lines) acceptability temperature ranges in (a) LCY, (b) MAN T1 and (c) MAN T2.**

Interestingly, it was found that "neutral" is not the desired TS for the majority of passengers or staff. Assuming that those who voted "no change" in the thermal preference scale are satisfied with the thermal environment, the results show that 51%, 64% and 58% of passengers in LCY, MAN T1 and MAN T2 had reported a TS other than neutral. Similarly, 53%, 57% and 60% of the satisfied with the thermal environment staff in LCY, MAN T1 and MAN T2, had reported non-neutral TS.

### 3.2 Thermal preference

The correlation coefficients between thermal preference and operative temperature are 0.27, 0.41 and 0.40 for LCY, MAN T1 and MAN T2 respectively ($p<0.01$). For the analysis, thermal preference (TP) was transformed into a 3-point variable. Thus, the preferences for a "much cooler" and "a bit cooler" environment are represented by "prefer cooler" and those for a "much warmer" and "a bit warmer" environment by "prefer warmer".

In summer the thermal preference profile is very similar in all terminals, where approximately 50% of interviewees desire no change and nearly 40% prefer cooler conditions (figure 5). In winter the majority of people (53%) in LCY prefer to be cooler. In MAN T1 almost half find the thermal environment 'just right', however the percentage of those preferring to be warmer is almost twice of that in summer. People in MAN T2 display the highest thermal satisfaction from all terminals as nearly 60% requires no change.

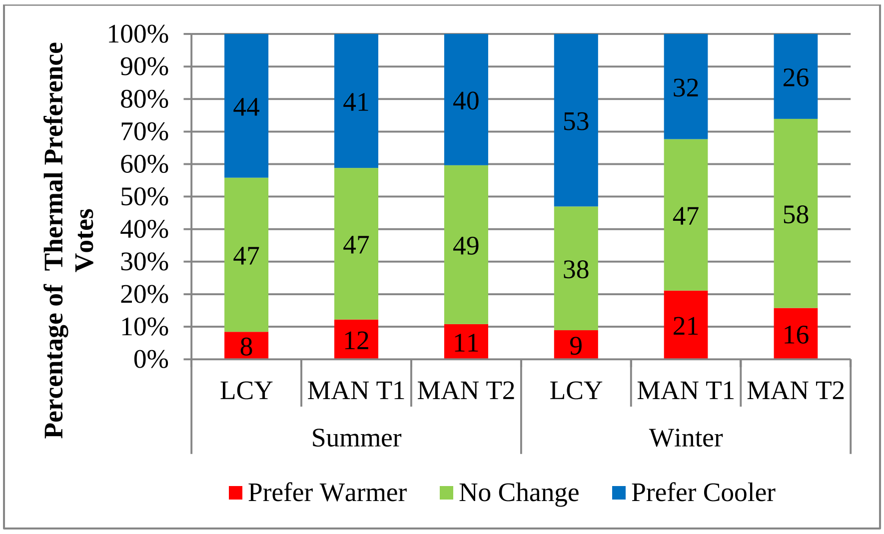



**Figure 5: Percentage of binned thermal preference votes.**

In order to quantify the preferred temperatures, weighted linear regressions were fitted separately between the "prefer warmer" and "prefer cooler" percentages and the operative temperature. Preferred temperature is obtained from the intersection of the two regression lines (figure 6).

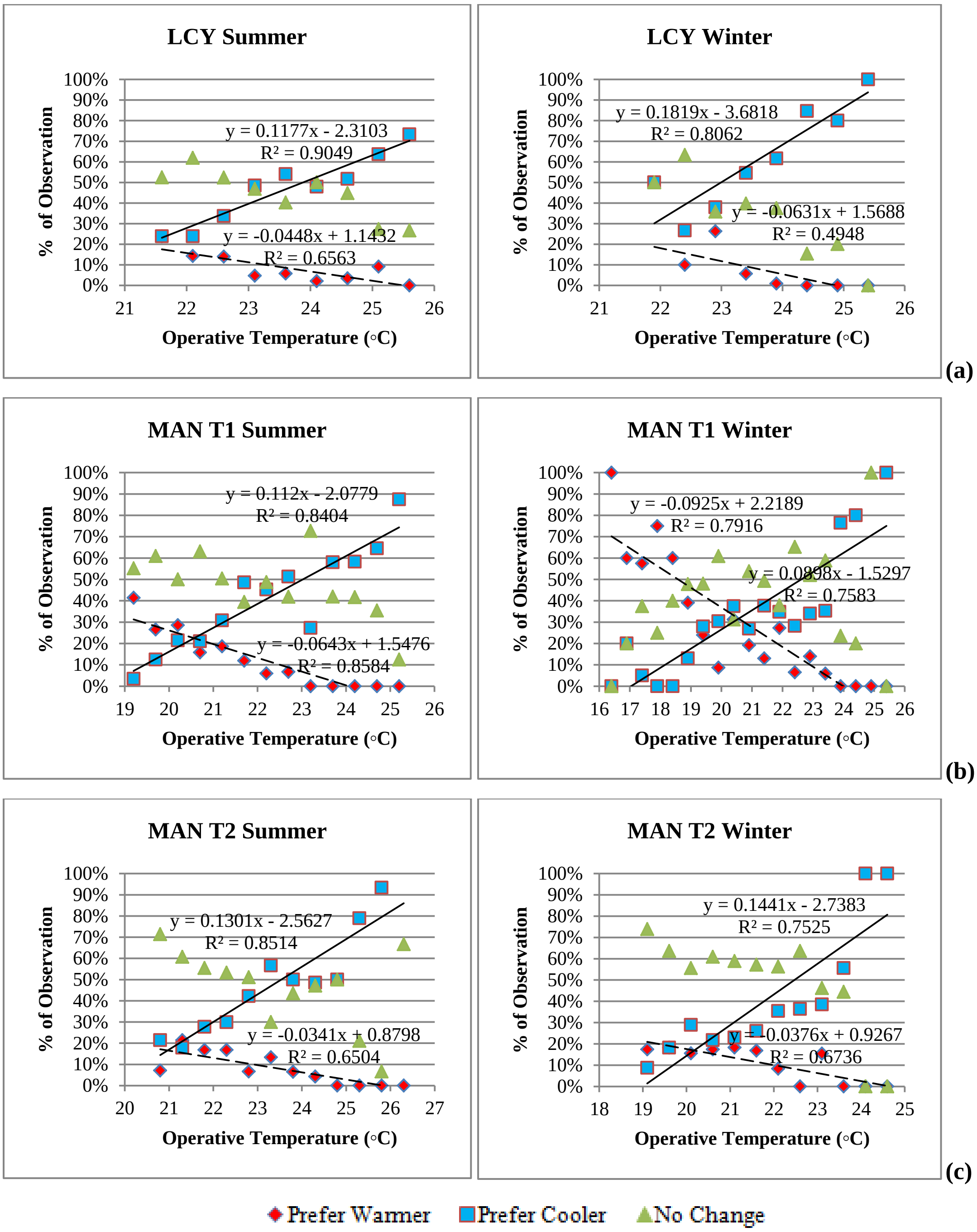



**Figure 6: Calculation of preferred temperatures in (a) LCY, (b) MAN T1 and (c) MAN T2 in summer and winter.**

The profile of preferred temperatures (table 6) follows that of the neutral temperatures and in most cases the two almost coincide. The results demonstrate the preference for cooler temperatures than those experienced in all terminals in both seasons. They also provide evidence of tolerance under cooler conditions; in MAN T1 and MAN T2 where the lowest indoor temperatures occurred during winter, the preferred temperature was 20.6 ºC and 20.2 ºC, while neutral temperature was 19.4 ºC and 18.3 ºC respectively. The preferred temperatures in LCY are found below the minimum temperature experienced (table 4), suggesting an overheating issue, more pronounced during winter.

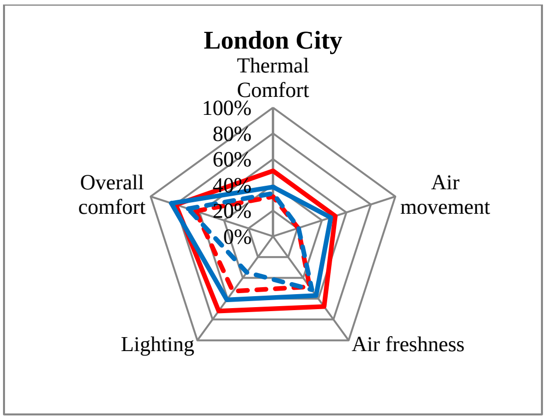
**Table 6: Summary of mean, neutral and preferred operative temperatures.**

| | Summer | | | Winter | | |
|---|---|---|---|---|---|---|
| **(°C)** | **LCY** | **MAN T1** | **MAN T2** | **LCY** | **MAN T1** | **MAN T2** |
| **Tmean** | 23.3 | 22.0 | 23.0 | 23.4 | 21.3 | 21.1 |
| **Tneutral** | 21.4 | 20.4 | 21.1 | 21.5 | 19.4 | 18.3 |
| **Tpreferred** | 21.3 | 20.6 | 21.0 | 21.3 | 20.6 | 20.2 |

### 3.3 Satisfaction of passengers and staff with the indoor environment

With a focus on the two major terminal population groups, the thermal comfort requirements were investigated separately for passengers and staff. The results demonstrate the different thermal requirements between the two groups, as discussed by Kotopouleas and Nikolopoulou (2014). Employees are on average 1.6 times more sensitive to temperature changes than passengers in both seasons, while both groups have neutral at temperatures lower than the mean temperature they experience. However, the acceptability range for staff is narrower, with neutral temperature higher than passengers' by 0.6-3.9 °C. The results also suggest that both groups prefer a cooler environment. Interestingly, passengers are more tolerant of cooler conditions, whereas employees prefer warmer temperatures than passengers by 0.4-1.4 °C in summer and 1.1-2 °C in winter. The diversity in comfort requirements is also reflected in the significantly higher percentages of uncomfortable employees (23-49%) as opposed to passengers (8-21%).

Examining the overall satisfaction, the staff has lower satisfaction levels with the indoor conditions (figure 7). For the assessment of the satisfaction with the air movement and thermal comfort it was assumed that people who voted "no change" in the corresponding preference questions are satisfied with the respective conditions. The results demonstrate that in all terminals 2/3 of employees are dissatisfied with the thermal environment, while 60-80% prefer either higher or lower air movement in their workspace. Widespread among the employees is also the assessment of the indoor air as "stuffy", as expressed from 40-60% of staff. Similar percentages of dissatisfaction are reported with the lighting environment.



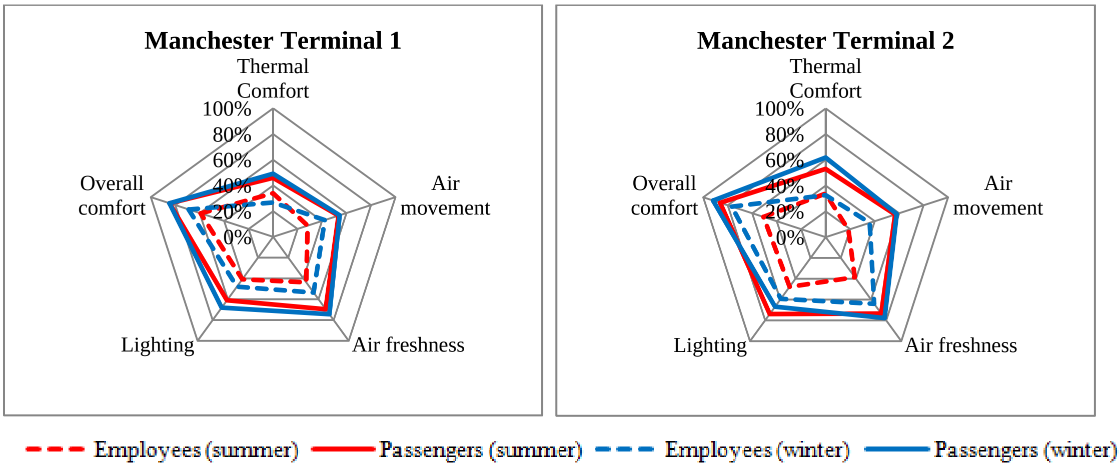



**Figure 7: Satisfaction levels of passengers and terminal staff with the indoor conditions in summer (S) and winter (W)**

### 3.4 Thermal conditions in different terminal spaces

An overview of the thermal conditions in the monitored terminal spaces is provided in table 7, where spaces are listed in the order met by a passenger. The mean temperatures in LCY are representative of the uniform thermal environment across the spaces. The exception is the retail area in the summer, which is warmer due to the extensive spot lighting from the very low ceiling resulting in higher temperatures. The gates also vary greatly, as they have free-running conditions.

Thermal uniformity is also found between the airside spaces (beyond the search area) of MAN T2 in summer, with the highest mean temperature difference (only 1.1 °C) found between the sitting area and the gates. 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. However, the highest mean temperature in summer (24.6 °C) occurred in the check-in area. Although it is the largest of all spaces and occupancy peaks should not have a substantial effect on its thermal environment, it has the highest mean temperature due to the extensive use of glazing. In winter, when the external heat gains have a minor effect, all spaces in MAN T2 presented similar mean temperatures (maximum difference is 1.6 °C between the sitting area and the departure lounge). This is also due to the operational profile of MAN T2 during winter, which serves mostly holiday destinations and was significantly busier during the summer monitoring period. Consequently, in winter there were prolonged periods of time with very low occupancy resulting in uniformly lower temperatures very close to the winter indoor temperature set-point (21.0 °C).

On the other hand, the variety of spaces in MAN T1 is reflected in the diverse thermal environments, presenting the highest temperature differences. The arrivals hall was on average 4.7 °C cooler than the departure lounge 1 in summer and 6.2 °C cooler than the sitting area in winter. The particularly lower mean temperatures in the arrivals (19.8 °C in summer and 17.4 °C in winter) are a result of its great exposure to the outdoor conditions. Additionally, departure lounge 1 is constantly warmer than the nearby departure lounge 2 located few meters away, with the highest mean temperature difference between them (2.5 °C) being met in summer, a result of the extensive glazing in the former.

**Table 7: Summary of minimum, maximum and mean operative temperature (°C) in each terminal space.**

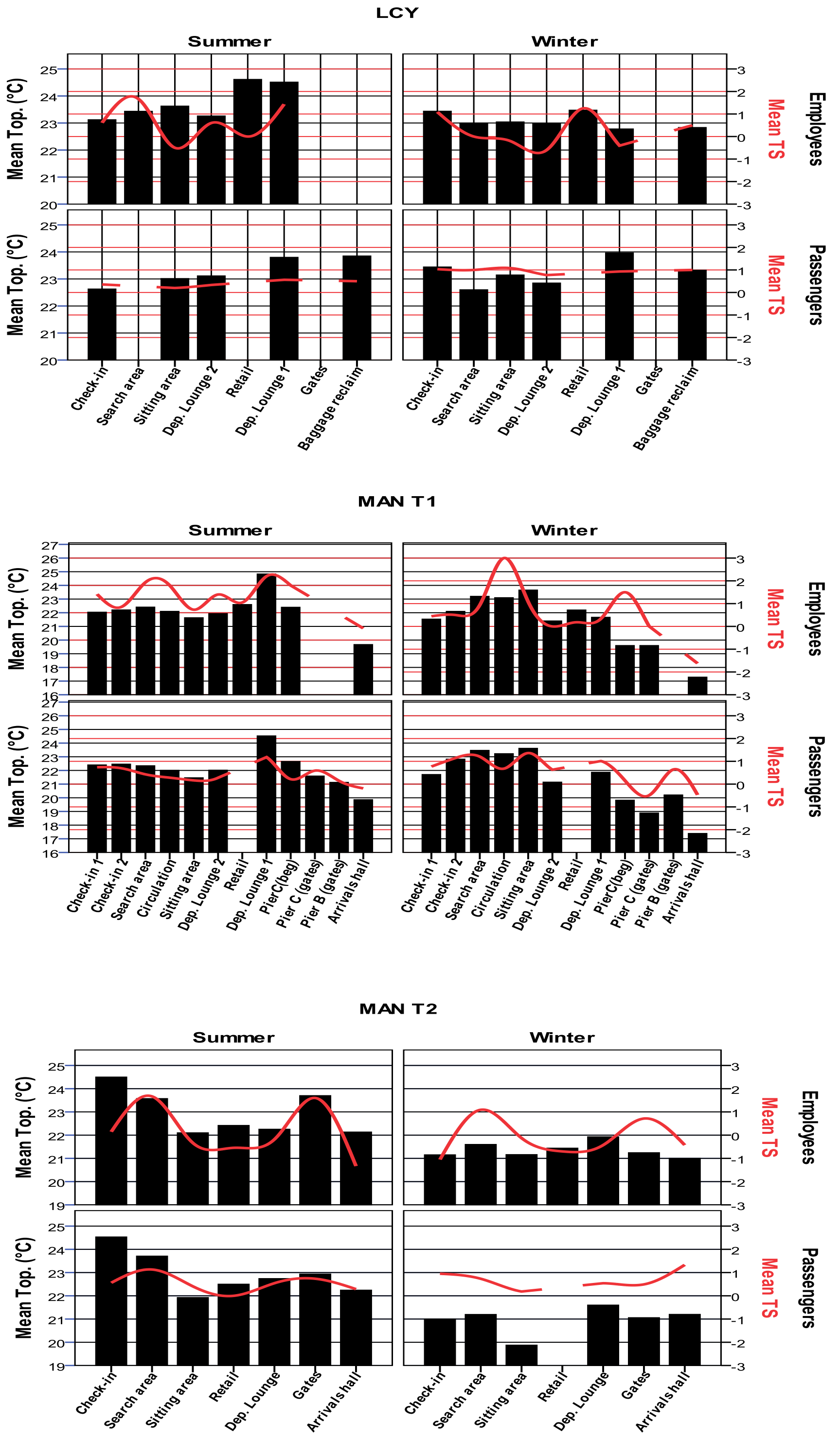
| | | Summer | | Winter | |
|---|---|---|---|---|---|
| | | **Min - Max** $T_{op}$ (°C) | **Mean** $T_{op}$ (°C) | **Min - Max** $T_{op}$ (°C) | **Mean** $T_{op}$ (°C) |
| **LCY** | **Check-in** | 21.4 - 25.0 | 22.7 | 21.7 - 23.9 | 23.4 |
| | **Search area*** | 23.2 - 23.7 | 23.4 | 22.2 - 23.2 | 23.0 |
| | **Sitting area** | 22.0 - 24.6 | 23.2 | 22.0 - 23.8 | 23.1 |
| | **Dep. Lounge 2** | 21.7 - 24.2 | 23.1 | 21.7 - 23.3 | 22.9 |
| | **Retail*** | 23.2 - 25.1 | 24.6 | 22.8 - 24.2 | 23.5 |
| | **Dep. Lounge 1** | 21.6 - 25.8 | 23.9 | 22.3 - 25.3 | 23.9 |
| | **Gates (west pier)**** | 24.4 - 25.6 | 25.1 | 12.7 - 21.1 | 18.1 |
| | **Baggage reclaim** | 23.2 - 24.3 | 23.9 | 22.3 - 24.1 | 23.2 |
| **MAN T1** | **Check-in 1** | 21.2 - 24.6 | 22.3 | 20.1 - 22.2 | 21.7 |
| | **Check-in 2** | 21.3 - 22.8 | 22.4 | 21.8 - 23.3 | 22.8 |
| | **Search area** | 22.1 - 22.6 | 22.4 | 21.4 - 24.0 | 23.4 |
| | **Circulation** | 21.5 - 22.4 | 22.0 | 22.3 - 23.9 | 23.2 |
| | **Sitting area** | 21.0 - 22.6 | 21.5 | 22.4 - 24.3 | 23.6 |
| | **Dep. Lounge 2** | 21.7 - 22.6 | 22.0 | 19.2 - 23.3 | 21.2 |
| | **Retail*** | 22.1 - 23.3 | 22.6 | 20.6 - 23.0 | 22.2 |
| | **Dep. Lounge 1** | 22.9 - 25.4 | 24.5 | 19.5 - 25.6 | 21.9 |
| | **Pier C (beg.)** | 22.4 - 23.1 | 22.6 | 19.2 - 21.1 | 19.8 |
| | **Pier C (gates)** | 20.3 - 22.6 | 21.6 | 17.2 - 20.4 | 18.9 |
| | **Pier B (gates)** | 20.9 - 21.3 | 21.1 | 19.4 - 20.9 | 20.2 |
| | **Arrivals hall** | 19.1 - 21.0 | 19.8 | 16.2 - 17.9 | 17.4 |
| **MAN T2** | **Check-in** | 23.4 - 25.2 | 24.6 | 18.9 - 21.8 | 21.0 |
| | **Search area** | 21.4 - 24.5 | 23.7 | 18.9 - 23.4 | 21.3 |
| | **Sitting area** | 20.9 - 22.9 | 21.9 | 19.3 - 22.1 | 20.0 |
| | **Retail*** | 21.3 - 23.2 | 22.4 | 20.0 - 23.1 | 21.4 |
| | **Dep. Lounge** | 20.6 - 26.3 | 22.7 | 19.6 - 24.5 | 21.6 |
| | **Gates** | 21.0 - 25.6 | 23.0 | 19.5 - 22.6 | 21.1 |
| | **Arrivals hall** | 21.8 - 22.5 | 22.2 | 20.6 - 21.6 | 21.1 |

* Based on staff responses predominantly
** Environmental monitoring without questionnaires

CIBSE's comfort criteria (table 1) allows for a comparison of the basic terminal spaces. In winter, all the departure lounges and check-in areas presented a higher mean temperature than the corresponding recommended ranges. More specifically, the mean temperature in the large check-in areas of MAN T1 (check-in 1) and MAN T2 are 1.7 °C and 1.0 °C higher, while significantly warmer are the smaller-sized check-in spaces in LCY and MAN T1 (check-in 2); 3.4°C and 2.8°C higher than the CIBSE range. In summer, the mean temperature in all departure lounges and the check-in areas is within or very close to the recommended range. Unique exception is the check-in area in MAN T2, which due to the high external heat gains during summer it presents a significantly warmer environment beyond the range. The search areas of all three terminals are regarded as concourse areas with no seating, and they meet the corresponding temperature range in both seasons. Similarly, the thermal conditions in the LCY baggage reclaim area are found within the seasonal range.

Figure 8 illustrates the mean temperature and TS separately for passengers and staff in the different terminal areas monitored. It is evident that in all three terminals employees' TS profile fluctuates significantly between the spaces, contrarily to passengers who present a more stable TS profile. This demonstrates passengers' wider adaptive capacity opposed to the rigid working conditions of staff, as the vast majority of staff (86-94%) at each terminal reported no control over the indoor environmental conditions.

Additionally, employees' TS profile does not always follow the temperature profile across the terminal spaces, i.e. staff in spaces with lower temperature may experience higher TS than in warmer spaces. This reflects the diverse activity levels between the different types of staff. For instance, security staff working in the search area of LCY in summer experienced a mean temperature of 23.4°C and reported a mean TS of 1.7. In the nearby sitting area with just 0.2°C higher temperature staff's mean TS is -0.5, while inside the warmer retail facilities (24.6°C) staff reported neutral TS. The results for MAN T1 and MAN T2 also show that security employees in search areas have higher mean TS than check-in and retail staff in both seasons (figure 8b & 8c).




(a)

(b)

(c)

**Figure 8: Mean operative temperature (bars) and thermal sensation (lines) for passengers and staff in the monitored spaces of (a) LCY, (b) MAN T1 and (c) MAN T2. Missing bars indicate insignificant number of questionnaires from the given population group in the corresponding space.**

The data analysis also showed that in spaces with highly variable occupancy (e.g. check-in areas and departure lounges) $CO_2$ levels followed the occupancy patterns. In these spaces higher temperatures occurred during the occupancy peaks, as suggested from the relevant Pearson correlation coefficients (0.62 in summer and 0.55 in winter for LCY, 0.29 for MAN T1 and 0.37 for MAN T2 in summer, $p<0.01$). Moreover, the correlation coefficients between $CO_2$ concentrations and TS (0.23 in LCY and 0.24 in MAN T2, $p<0.01$) indicate that in the overcrowded spaces TS had an increasing trend (figure 9) resulting in decreased levels of overall comfort.

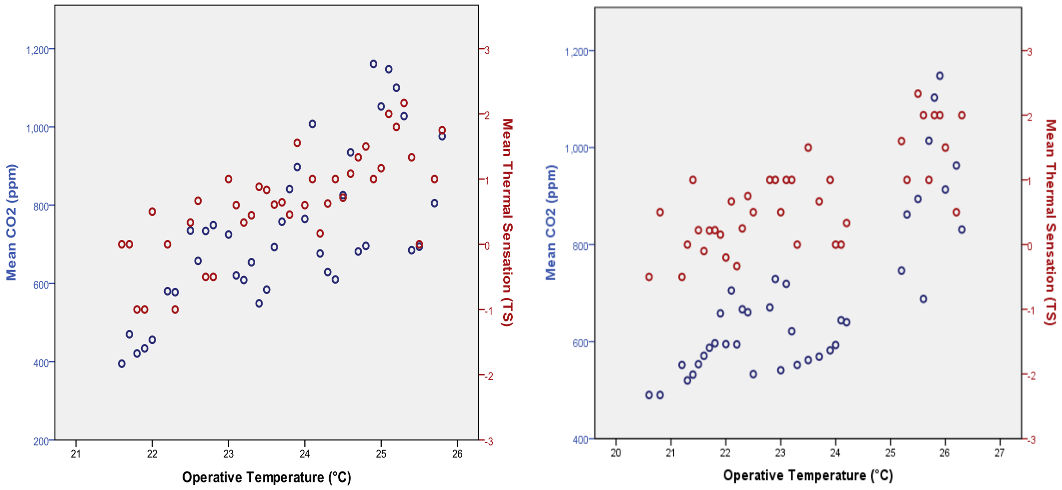



**Figure 9: Relationship of $CO_2$ levels (occupancy), operative temperature and thermal sensation in LCY departure lounge 1 (left) and in MAN T2 departure lounge (right), based on summer and winter data.**

## 4. Discussion

The data analysis showed that the thermal conditions in the three surveyed terminals regularly do not meet people's thermal requirements. In most cases more than half of the terminal population prefers a thermal environment other than the one experienced (figure 5). When compared to the criteria for 80% and 90% acceptability of temperature range (figure 4), the thermal profile of the terminals is predominantly closer to the upper limit and often surpasses it (figure 4), suggesting that the warm environment can be an issue for the terminal population in both summer and winter. The results reveal that cooler temperatures by 0.7-2.1 °C are preferred, while thermal neutrality is found 1.6-1.9 °C lower than the mean indoor temperature in summer and lower by 1.9-2.8 °C in winter (tables 5 & 6).

There are also consistent differences between the satisfaction levels of passengers and staff, with the latter group more sensitive to temperature changes. Differences in their adaptive capacity, restricted clothing levels with lack of control over their thermal environment result in employees' significantly lower satisfaction levels with the indoor environment (figure 7). In all terminals, staff's mean TS fluctuates more between the different spaces in summer and winter (figure 8). For passengers neutrality is achieved at cooler temperatures (by 0.6-3.9 °C) than for employees. For the latter, neutral temperature is also below the mean indoor temperature but closer to it as a result of the long-term acclimatisation to the indoor environment. Similarly, passengers' preferred temperatures are 0.4-2 °C lower than staff's with the highest differences found in winter.

The design of terminal spaces is a very important parameter influencing the thermal environment. Due to its compact nature, LCY presents a uniform thermal environment throughout. The indoor conditions are greatly influenced by the occupancy levels, as shown for the departure lounge in figure 9. The high percentage of people preferring a cooler environment (44% in summer and 53% in winter) suggests a problem with overheating, while, the neutral and preferred temperatures lie below the narrow temperature range of the terminal (table 4 & 6). Overheating was more pronounced in winter, when LCY was busier and passengers' clothing insulation was significantly higher (table 3). Occupancy levels were also a contributing factor to the higher temperatures in the majority of spaces in MAN T2 during summer, although the most important factor appears to be the extensive use of glazing. The high mean temperatures in the check-in area (24.6 °C) and gates (23°C) are representative of the effect of the external heat gains on the indoor environment in summer (figure 8c).

MAN T1 has the widest variety of spaces and respective temperature differences between the spaces in both seasons. Characteristic are the low mean temperatures in the arrivals halls which led to mean thermal sensations on the cool side of the ASHRAE scale in both seasons (figure 8). On the other hand, at the departure lounge 1 passengers experience on average 2.5 °C higher mean temperature than the nearby departure lounge 2 in summer, due to the sunlight entering from the extensive glazing.

## Conclusions

This work investigated the breadth of thermal comfort conditions in three airport terminals with different design characteristics and capacities. The indoor environment was extensively monitored in the different terminals' areas where in total 3,087 people were interviewed for the evaluation of the comfort conditions.

The results revealed the discrepancies between the preferred thermal conditions and those experienced. In both seasons, neutrality was found in lower temperatures than the indoor mean temperature for both passengers and staff, while the preference for a cooler thermal environment was demonstrated. The data analysis also showed the variety of the thermal environments experienced in the terminals, as a result of the different design characteristics and functions. Spaces where higher activity levels are performed resulted in higher mean TS. Additionally, higher temperatures and thermal sensations were also found in spaces with extensive sources of sunlight during the summer monitoring period.

The temperature ranges at which 80% and 90% of the terminal population would find the indoor thermal environment acceptable were presented and showed that they were not regularly met. Based on the 80% acceptability ranges, the results indicate that in winter, when overheating was more apparent, there may be a great potential for energy savings from lowering the heating systems set-points without compromising the thermal comfort conditions.

This study aimed to shed light on the thermal comfort conditions in airport terminal spaces and to quantify the thermal requirements of the terminal population. Such knowledge can be useful in improving thermal comfort while different energy conservation strategies are implemented, as well as in the regular refurbishments of existing terminal facilities and the design of new terminal buildings.

**Acknowledgments**

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