UNIVERSITÀ DEGLI STUDI DI PADOVA

Facoltà di Ingegneria
Dipartimento di Ingegneria Industriale

DOTTORATO DI RICERCA IN
INGEGNERIA INDUSTRIALE
XXX ciclo
Anno 2018

in cooperation with

eurac research

MIXED-MODE VENTILATION DESIGN AND THERMAL COMFORT IN TRANSITIONAL SPACES

PhD candidate:

Marta Avantaggiato

Supervisors:

Prof. Michele De Carli

PhD Annamaria Belleri

PhD Wilmer Pasut

Table of Contents

Abstract I

Acknowledgments III

Introduction.. 1

1 Transitional Spaces 5

1.1 Definition and main features... 5

1.2 Typological classification and functional value 6

1.3 The role of transitional spaces in mixed-mode ventilation design.............. 8

1.3.1 Mixed-mode schemes 8

1.3.2 Database of mixed-mode operated transitional spaces 11

1.3.3 Mixed-mode operation in shopping centre transitional spaces................. 17

Bibliography 20

2 Retrofitting shopping centres transitional spaces into mixed-mode operation 23

2.1 Design procedure... 24

2.1.1 Step 1 – Ventilative cooling potential analysis.. 25

2.1.2 Step 2 – Definition of the ventilation strategy... 27

2.1.3 Step 3&4 – Mixed-mode control strategy and performance analysis....... 28

2.1.4 Step 5&6 –Optimization and approval 31

2.1.5 Step 7 – Implementation and commissioning.. 32

2.2 Acknowledgements 32

Bibliography 33

3 Thermal comfort in transitional spaces.. 35

3.1 Definition of Thermal comfort.. 35

3.2 Other important definitions 36

3.3.1 Thermal sensation and Comfort temperature 36

3.3.2 Thermal neutrality 36

3.3 Thermal comfort approach... 37

3.3.3 The rational or heat-balance approach.. 37

3.3.4 Adaptive approach 39

3.4 Previous findings on transitional spaces 40

Bibliography 44

4 Thermal comfort in shopping centres transitional spaces 47

4.1 Introduction.. 47

4.2 Methods ... 49
4.2.1 Environmental monitoring ... 49
4.2.1.1 Indoor environmental monitoring ... 49
4.2.1.2 Outdoor environmental monitoring ... 51
4.2.2 Questionnaires with customers ... 51
4.2.2.1 Background ... 51
4.2.2.2 Thermal comfort field survey ... 51
4.2.2.3 Clothing ... 52
4.3 Case studies ... 52
4.4 Research Process ... 55
4.5 Analysis and Results ... 56
4.5.1 Statistics of the sample ... 56
4.5.2 Validation of operative temperature measurements ... 57
4.5.3 Environmental characterization ... 58
4.5.4 Thermal comfort model applied to transitional spaces ... 60
4.5.4.1 PMV-PPD model ... 60
4.5.4.2 EN 15251 Adaptive comfort model ... 62
4.5.5 Investigation of customers' perception of the thermal environment ... 64
4.5.5.1 Customers thermal acceptability ... 65
4.5.5.2 Customers thermal sensation ... 65
4.5.5.3 Customers thermal preference ... 67
4.5.5.4 Customers thermal comfort ... 69
4.5.6 Investigation of temperature-initiated thermal overshoot ... 70
4.5.6.1 Effect of the permanence period on customers sensation ... 70
4.5.6.2 Down-step outdoor–indoor temperature difference effect on thermal sensation ... 74
4.5.6.3 Down-step outdoor–indoor temperature difference effect on thermal preference ... 76
4.5.6.4 Effect of outdoor-indoor temperature step under different seasons ... 77
4.6 Conclusion ... 80
4.7 Study limitation ... 81
4.8 Acknowledgements ... 81
Bibliography ... 82
5 Thermal comfort and airflow performance of a mixed-mode atrium in a warm temperate climate ... 83
5.1 Introduction ... 83

5.2 Case study 84
5.3 Methodology 86
5.3.1 Correlation coefficient and bulk airflow measurement 87
5.3.1.1 Experimental set-up 88
5.3.2 Long term measurement campaign 90
5.4 Results and discussion 90
5.4.1 Determination of the correlation constant k 91
5.4.2 Analysis of the atrium energy and thermal performances 94
5.4.2.1 Comparison between NV & RFC and RFC 97
5.4.2.2 Comparison between NV and NV & RFC 99
5.4.3 Thermal comfort assessment 102
5.5 Conclusion 107
5.6 Acknowledgements 107
Bibliography 108
6 Conclusion 109
Publication List 111
Annex A 113
Annex B 115
Annex C 117
Annex D 119
Annex E 125

List of Figures

Figure 1 Types of transitional spaces: Type (a)-central, Type (b)-perimetral, Type (c)-lobby space, Type (d)-not attached, Type (e)-passing 6

Figure 2 Example of "mashrabyia" (left) and "engawa" (right) [Source: Google] 7

Figure 3 Flow chart for the classification of the mixed-mode scheme (Source of information then re-elaborated is [1.14]) 10

Figure 4 Location of the 17 mixed-mode non-residential building considered for the analysis 13

Figure 5 Statistics of the transitional space typology and mixed mode schemes adopted in the 17 cases studies (Table 1) 14

Figure 6 Examples of transitional space *type a* and *e* included into mixed-mode solution. From left to right: PowerGen Headquarter central atrium (source: here), Ecoport (source: IEA EBC Annex 62 Ventilative Cooling International Ventilative Cooling Application Database [1.15]) and Seixal City Hall (source: Natural Works) 14

Figure 7 Examples of transitional spaces *type b* adopted into the mixed-mode solution. From left to right: Forum Kloster and Oststeiermarkhau (source: IEA EBC Annex 62 Ventilative Cooling International Ventilative Cooling Application Database [1.15]), Windkraft Simonsfeld AG (source: IEA EBC Annex 62 Ventilative Cooling International Ventilative Cooling Application Database [1.15]) 16

Figure 8 Ventilation concept (left) and a detail of the gallery roof openings (right) for the Ernst-August-Gallerie Source: Window Master 17

Figure 9 Picture of Field´s common area (left) and ventilation strategy (right) 18

Figure 10 Ventilation strategy for Mercado dal Val (left) and details of the modular multifunctional façade used. 19

Figure 11 Wind scoops application on Blue Water shopping centre, Kent Source: http://www.battlemccarthy.com/bluewater-shopping-centre-kent 20

Figure 12 Distribution of the European building stock according by building typology [2.1] 23

Figure 13 Share of total energy demand in retail buildings 24

Figure 14 Process of design and integration of mixed-mode ventilation solutions 25

Figure 15 Percentage of hours within a year when direct ventilative cooling is required, useful or not useful in the ten reference building climates considering different values of internal gains [2.5]. 26

Figure 16 Path chart to identify the most suitable ventilative cooling system according to architectural features. Source: [1.21] 27

Figure 17 Pictures of the openable windows and skylights considered in the ventilation strategy [2.10] 29

Figure 18 Control strategy scheme for mixed-mode ventilation in common areas in DonauZentrum [2.10] 30

Figure 19 Monthly trend of electricity consumption for ventilation and cooling for Baseline scenario and Mixed-mode scenario [2.10]. 31

Figure 20 Change in thermal sensation vote (TSV) over time in response to temperature steps from 32 ºC (left), 28 ºC (middle), and 20 ºC(right) to 24 ºC [3.10]. 37

Figure 21 Relation between PMV and PPD [3.4] 38

Figure 22 Comparison of the RP-884 adaptive models' predicted indoor comfort temperatures with those predicted by the static PMV model [3.15] 40

Figure 23 Clockwise, from top left: shopping mall plants of Katané (Gravina di Catania, CT) and Donau Zentrum (Wien),interior of Donau Zentrum [Unibail-Rodmanco] and large atrium of Katané 47

Figure 24 Mobile environmental monitoring cart (right) and definition of parameters measured at different levels 50

Figure 25 Sensor used for measuring indoor environmental parameters, from left to right : omnidirectional anemometer omnidirectional anemometer, radiation shielded thermistor, 40 mm -globe thermometer 50

Figure 26 Screenshot from the questionnaire. 52

Figure 27 Reference clothing values used for the analysis on the base of EN ISO 7730 [3.4] 53

Figure 28 Localization of the case studies (left). Pictures of three different shopping malls 54

Figure 29 Pictures and diagram of Shop Center Valsugana (left), Millenium Centre (middle) and Katanè (right) 54

Figure 30 Some pictures of the pilot measurement campaign in SC01. Set-up of MEMO (left) and interview with customers (right) 55

Figure 31 Frequency distribution of the Indoor parameters measured during the three campaigns: air temperature, Operative temperature, indoor air velocity and relative humidity 59

Figure 32 Frequency distribution of the outdoor parameters measured during the three campaigns: Dry-Bulb temperature and relative humidity 59

Figure 33 Frequency distribution of the difference between outdoor and indoor temperature during the three campaigns 60

Figure 34 Comparison between the actual (field study) and predicted (from Fanger) number of people not satisfied with the operative temperature 61

Figure 35 Comparison between comfort temperature calculate according to adaptive model (EN 15251) the average operative temperature measured during measurements days and the percentage of customers satisfied 63

Figure 36 Bar Chart of the distribution of customer's thermal acceptability over operative temperature intervals 65

Figure 37 Bar Chart of the distribution of thermal sensation over operative temperature intervals [ºC] 66

Figure 38 Distribution of satisfied, warm dissatisfied and cold dissatisfied over operative temperature intervals [ºC] 67

Figure 39 Distribution of customers with TSV equal to neutral, warmer than neutral and cooler than neutral over operative temperature intervals [ºC] 67

Figure 40 Bar Chart of the distribution of customer's thermal preference over operative temperature intervals 68

Figure 41 Distribution of the customer's thermal preference over operative temperature ranges 68

Figure 42 Bar graph distribution related to the thermal comfort questions 69

Figure 43 Permanence period within the three case studies 71

Figure 44 Percentage of preference against sensation depending on permanence period 74

Figure 45 Effect on thermal sensation of different outdoor-indoor temperature for operative temperature equal to 25ºC 75

Figure 46 Effect on thermal sensation of different outdoor-indoor temperature for operative temperature equal to 26ºC 75

Figure 47 Effect on preference of different outdoor-indoor temperatures for operative temperature equal to 25ºC 76

Figure 48 Effect on preference of different outdoor-indoor temperatures for operative temperature equal to 26ºC 77

Figure 49 Outdoor temperature trends. April (left) and July (right) 78

Figure 50 Bar Chart of the distribution of thermal sensation over outdoor-indoor temperature differences for SC01 and SC03 with average operative temperature close to 25 ºC 79

Figure 51 Bar Chart of the distribution of thermal preferences over outdoor-indoor temperature differences for SC01 and SC03 with average operative temperature close to 25 ºC 80

Figure 52 Building view from the outside (left), an internal view of the central atrium (right) 85

Figure 53 A 3D sketch of Seixal city Hall showing the night ventilation strategy (left) and an outdoor view of the second row of inlet windows on west side (right) 85

Figure 54 Location of the sensors used for the experiment and CO_2 release point location 88

Figure 55 Location of the installation of the weather station marked with the red asterisk 89

Figure 56 Location of the sensors used during the long-term measurements campaign 90

Figure 57 Wind distribution, wind speed and pressure generated by the wind during the experiment 93

Figure 58 Temperature distribution during the experiment and buoyancy pressure 93

Figure 59 Physics of the pressure during the experiment 93

Figure 60 Phase of the experiment on the bases of CO_2 distribution 94

Figure 61 *CDH* and Solar Gains for all the days of the measurements campaign. Days identified with the star are the one in which the direct thermal comfort assessment with guests and workers took place. 96

Figure 62 Wind rose based on the data recorded by the weather station installed close to the building in the period between July 4th and July 31th 2017 96

Figure 63 Comparison of the normalized cooling demand (N1and N2) between mode *NV & RFC* and *RFC*. The graph also show the average indoor and outdoor temperature during occupied hours (8 a.m.-7 p.m.) and the maximum outdoor temperature recorded for the four measurements days 98

Figure 64 Indoor and Outdoor temperature trends during the three different modes (NV-14th July, NV & RFC-26th July, RFC-28th July) 99

Figure 65 Temperatures and CO_2 trend during night under NV mode (night between 13th and 14th July) 100

Figure 66 Temperatures and CO_2 trend during night under RFC mode (night between 27th and 28th July) 101

Figure 67 Bulk airflow and pressure (NV mode) during the night between 13th and 14th of July 101

Figure 68 Bulk airflow and pressure (NV & RFC mode) during the night between 25th and 26th of July 102

Figure 69 Interior view of the central atrium of Seixal City Hall 103

Figure 70 Distribution of thermal acceptability between guests and workers under mode NV and NV & RFC 105

Figure 71 Distribution of thermal sensation votes between guests and workers under mode NV and NV & RFC 105

Figure 72 Distribution of thermal preferences between guests and workers under mode NV and NV & RFC 106

Figure 73 Distribution of thermal comfort votes between guests and workers under mode NV and NV & RFC 106

List of Tables

Table 1 Information about the selected case-studied 12

Table 2 ASHRAE seven-point thermal sensation scale[3.2] 36

Table 3 Field studies related to transitional spaces 41

Table 4 Recommended design criteria for department stores 49

Table 5 Measured indoor environment parameters and sensors characteristics 51

Table 6 Measured outdoor environment parameters and MEMS integrated portable data logger characteristics 51

Table 7 Characteristic of three case studies 53

Table 8 Statistics of the sample 56

Table 9 Mean error and standar deviation between 58

Table 10 Indoor and outdoor environmental conditions for the three case studies 58

Table 11 Intervals of operative temperature considered for the whole analysis 61

Table 12 Means Bias, standard deviation and standard error between predicted PMV and actual TSV 62

Table 13 Central limit Theorem assumption check for different operative temperature interval 70

Table 14 Correlation values among TS, TC, TP with the indoor and outdoor environmental parameters through Kendall non-parametric test (* statistical significance with 95% confidence interval, ** statistical significance with 99% confidence interval) for customers who have spent less than 10 minutes 72

Table 15 Correlation values among TS, TC, TP with the indoor and outdoor environmental parameters through Kendall non-parametric test (* statistical significance with 95% confidence interval, ** statistical significance with 99% confidence interval) for customers who have spent more than 10 minutes 72

Table 16 Average values of the relevant indoor and outdoor environmental parameters the April 5th and the July 18th 77

Table 17 Correlation coefficient among clothing level with the outdoor and operative temperature through Parson parametric test (* statistical significance with 95% confidence interval, ** statistical significance with 99% confidence interval).............. 78

Table 18 Features of the windows used in the ventilation strategy 85

Table 19 Control modes for windows operations 86

Table 20 Operation modes tested during the long-term measurments 87

Table 21 Specification of the measurement equipment used for indoor 89

Table 22 Specification of the measurement equipment used for the weather station 89

Table 23 Specification of the measurement equipment used for the long term monitoring 91

Table 24 Pressure coefficient at inlet, outlet and difference 92

Table 25 Comparison in term of normalized cooling demand between mode NV & RFC and RFC 98

Table 26 Bulk airflow and pressure during the mode NV and NV &RFC.................. 101

Table 27 Statistics of the sample of thermal comfort assessment in Seixal City Hall . 103

Table 28 Environmental characteristics (indoor and outdoor) and clothing level under modes NV and NV & RFC during the thermal comfort assessment............................ 104

Table 29 Comparison between thermal sensation prediction (PMV) and actual (TSV) 104

Table 30 Tabulation of the data plot in Figure 35 117

Table 31 Distribution of preference over thermal sensation for customers with “less than 10 minutes” permanence period 117

Table 32 Distribution of preference over thermal sensation for customers with “more than 10 minutes” permanence period 117

Abstract

Transitional spaces are pivotal in non-residential architecture. Depending on the building typology, the proportion of such areas may vary between 10% up to 40% of the total volume. Because of their features transitional spaces are independent dynamic spaces with various physical conditions and behaviour which may that have different thermal comfort requirements. Being integral part of the non-residential architecture, their HVAC design and controls follow however guidelines intended for indoor space. No current comfort guidelines that are specific for this peculiar building zones exists. Nevertheless, if designed with appropriate energy saving strategies as mixed-mode ventilation solution and flexible controls of HVAC, these peculiar building spaces can help achieve more energy efficient buildings.

With the aim of a deeper understanding of these peculiar building zones, this PhD dissertation focuses on three aspects related to transitional spaces: *mixed-mode ventilation design, thermal comfort* and *actual thermal performance*.

Information about 17 non-residential building, which integrate a transitional space in their architecture and mixed-mode ventilation strategy, were analysed and collected in a small databased. Within the building typologies considered, shopping centres resulted to be a very interesting one for the implementation of mixed-mode ventilation strategies. From the analysis of recent examples of shopping centres conversion from fully mechanical into mixed-mode operation, a design procedure was proposed.

The conversion from fully mechanical into mixed-mode operation is further encouraged by the findings related to thermal comfort in shopping centers common areas. Within the studies about thermal comfort in transitional spaces, an investigation of human response within shopping centres common areas was missing. With the scope of understanding actual comfortable ranges in these spaces, around 700 customers were interviewed about their state of comfort while measuring environmental parameters. For this scope a specific questionnaire and a Mobile Environmental Monitoring cart (MEMO) were developed. The measurements were performed in spring and summer 2016 in three different Italian shopping centres, fully-mechanical operated. The results show a wider range of indoor thermal comfort conditions than in typical indoor spaces. The necessity of a tailor-made model to assess thermal comfort in transitional spaces is also disclosed. The model could correlate indoor comfort temperatures with outdoor temperatures on the basis of the direct observation of users' thermal sensation. In order to expand the database of evidence and the creation of such model, further field studies are required, gathering together a conspicuous number of data which cover all the seasons.

These findings unlock important energy use implication. If shopping centre HVAC systems are operated in a more flexible way and natural ventilation potentialities are exploited, the final goal of achieving more energy efficient buildings without sacrificing users' comfort seems closer.

With the objective of verifying the level of comfort provided by a mixed-mode solution in a transitional space, the thermal comfort and airflow performance of an atrium located in a warm temperate climate were investigated. The measurements campaign lasted over four-weeks in summer 2017. The thermal comfort evaluation of the atrium users' was performed under different operational modes. The results showed that users' state of comfort was independent from the way the atrium was conditioned. Specific to this case, the result opens possibilities for the use of just natural ventilation to provide comfortable conditions in summer. This would reflect in a consistent reduction of the operation costs for cooling.

In the perspective of the reduction of building energy consumption without compromising thermal comfort, the results of this thesis confirm and booster the interest towards mixed-mode operated building. The potentialities of transitional spaces expressed in the thesis need to be taken into account in non-residential building design.

The nature of the results for shopping centers transitional spaces can be extended to all those non-residential buildings that have transitional spaces with similar features.

Acknowledgments

There have been many people who have walked alongside me during this last three years. They have guided me, supported me and placed opportunities in front of me. The completion of this research work would not be possible without those precious people.

My greatest thanks goes to my supervisors Annamaria Belleri and Wilmer Pasut who patiently drove me along this path. I want to thank for their positive and supportive guidance (both technical and psychological).Without their help the completion of this work would have been more difficult. In particular I want to thank with Annamaria: my thanks is proportional to the number of grammar mistakes I made during these years, which means A LOT!

My gratitude goes also to Roberto Lollini who gave me opportunity to be part of his team, a great stimulating working environment.

I would also like to thank to Prof. De Carli for having offered me this opportunity.

A huge thanks goes also to Prof. Guilherme Carrilho da Graça who patiently and enthusiastically supported the work we performed in collaboration during my stay in Lisbon.

One simply does not spend three year of her life pursuing her PhD without forming valuable interpersonal relationship. A special thanks goes to all the people who shared their time with me in these last three years (and for some of them even longer…). Thanks for not having walked away from me especially in the moments I was probably not that lovable.

I want to thank all the past and present EURAC colleagues for making the work environment such enviable.

Last but not least, I want to thank my parents for the support, the patience and the understanding of my "hunger for knowledge" who brought me far away from home. Without you none of this would be possible. Thanks.

Introduction

A transitional spaces is meant as

"*a space in between indoor and outdoor climate, or between two indoor environments, which thermal characteristics can be or not modified by mechanical control system and where occupants may experience the dynamic effect of this change*"

Nowadays, transitional spaces are pivotal in non-residential architecture. The proportion of such areas may vary between 10% up to 40% of the total volume depending on the building typology [1.1]. Most of the time, transitional spaces are meant as buffer zones and they do not necessarily accommodate the main activity of the building. But nonetheless they are operated as an extension of the interior environment. As consequence, for reaching the same level of comfort as indoor environment, they consume more energy than the other parts of building of similar size [1.2]. The energy demand of transitional spaces per unit area or volume might be three times as high as that of the remaining of the building interior [1.3].

The necessity of reducing buildings' energy demand and consumption is a tangible fact after the entry into force of the EPBD directive 31/2010/EU. Buildings design consequently went through the improvement of thermal envelope proprieties. In particular, for non-residential buildings this aspect combined with the increased level of internal gains has changed the energy balance. The low heating demand is compensated by an increased cooling demand often not restricted to the only summer season.

This evidence has stimulated a renewed interest in designers for the exploitation of natural ventilation as passive cooling solution. Transitional spaces can rely on a great potential for natural ventilation exploitation [1.4]:

- they have direct connection with the outside;
- their architecture based on large volume suites with the principles for an effective natural ventilation;
- users of transitional spaces tolerate warmer thermal environments under summer conditions, as proved by the few studies about thermal comfort in transitional spaces [1.1], [1.2], [1.5].

Because of the awareness of natural ventilation limitations [1.6], the interest has progressively moved towards mixed-mode buildings. Mixed-mode buildings are indeed designed in such a way that the HVAC system help to prevent uncomfortable conditions when natural ventilation is not sufficient to guarantee a comfortable environment. Nevertheless the penetration of natural ventilation solutions and the energy use intensity of new non-domestic buildings was almost constant during the last decade, even in locations suitable for natural ventilation [1.7].According to Da Graça and Linden [1.7], one of the reasons why the integration of natural ventilation has become rare in modern non-domestic building design is the lack of knowledge and confidence in natural ventilation system possibilities. This lack of information is keeping designers and building owners to follow a traditional design based on reliable mechanical and air conditioning systems.

Within non-residential building stock, shopping centres could have a great potential for mixed-mode implementation. Their architecture is indeed based on shops with interconnecting walkways that enable customers to walk from a shop unit to another. Shopping centres' common areas are good examples of transitional spaces with a high variability in occupancy and thermal conditions. Generally, shopping centres are conditioned by means of standard HVAC systems. The use of natural ventilation potentiality to guarantee the minimum air change rate required by IAQ standards and to reduce cooling demand is not considered. Mechanical ventilation systems are also preferred to natural ventilation because more controllable and reliable, since they are not affected by the uncertainty of natural forces. Thereby, within the design process the team never focused neither on opening sizing nor on control strategies definition for ventilative cooling systems (natural or hybrid). So far, shopping centres design has included a small proportion of automated windows, sized for smoke ventilation only. There are only few examples of shopping centre designed for natural ventilation like the Ernst August Galerie in Hannover (Germany), the Blue Water shopping mall in Dartford (United Kingdom) and the Eastgate shopping mall in Harare (Zimbabwe).

No relevant studies related to thermal comfort in shopping centre transitional spaces at the moment exist. As consequence no current guidelines on thermal comfort have been identified that are specific to retail transitional space. Most of the time, temperature set points are based on the experience of the facility/energy manager which are most of the time different from the design set-point for heating and cooling. Based on direct experience of shopping centre environment, it is easy to experience high internal temperature in winter while low temperature in summer. This way of conditioning is meant to promote longer permanence periods with a consequent increase of the shopping activities and also the customers' satisfaction within the shopping centre. Nevertheless, the reality is far from expectation. This way of space conditioning works against an efficient use of energy. Furthermore it generates thermal shocks increasing the possibility of generating discomfort in customers that visit the shopping centre. Understanding the comfortable ranges in these spaces, will open to improvements and further investigation about mixed-mode operation for these peculiar building zones.

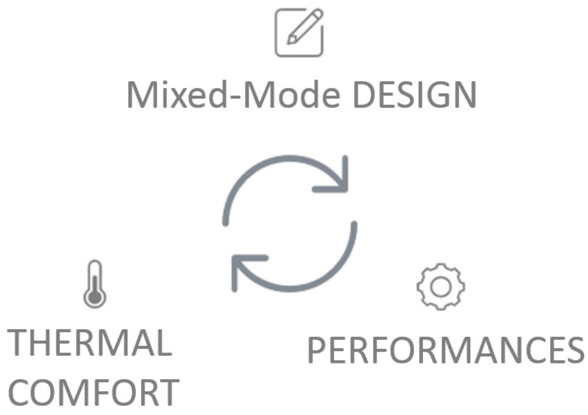
Under the light of these considerations, the research activities presented in this PhD dissertation focus on investigating three linked aspect related to transitional spaces: *mixed-mode ventilation design, thermal comfort* and *actual thermal performance*.

The topics I faced during the research are:

1. Mixed-mode ventilation design in transitional spaces of non-residential buildings and shopping centers;

2. Assessment of thermal comfort in shopping centers' common area based on direct customers' thermal comfort evaluation;
3. Assessment of actual thermal comfort and energy performances of a mixed-mode transitional space.

This PhD is financed by the European project "CommONEnergy" (www.commonenergyproject.eu/) [1.8] coordinated by Eurac Research, which focuses on transforming shopping centers into energy efficient and high-indoor-environmental-quality buildings, by developing smart renovation strategies and solutions, supporting their implementation and assessing their environmental and social impact.



The research questions of this work can be therefore formulated as:

- Is the conversion from fully-mechanical into mixed-mode operation of transitional spaces feasible?
- How thermal comfort can be assessed in shopping centre common areas and what are the actual thermal comfort ranges?
- Do mixed-mode transitional spaces guarantee comfortable conditions to users?

The thesis is organized as follows:

Chapter 1 introduces transitional spaces features and how their use is changed throughout history. After the presentation of basics mixed-mode ventilation schemes, the role of transitional spaces in the mixed-mode design is investigated. A database with 17 non-residential buildings which integrate a transitional space in their mixed-mode ventilation design was created. The mixed-mode operation of shopping centre was analysed in details.

Chapter 2 proposes a design procedure for the conversion of shopping centre transitional spaces from fully-mechanical into mixed-mode operation.

Chapter 3 presents the basic concepts of indoor thermal comfort. Thermal comfort models mostly used in building design and an overview of the previous studies related to thermal comfort in transitional spaces are discussed.

Chapter 4 presents the study related to the thermal comfort assessment in shopping centres common areas I performed in summer 2016. 724 customers were interviewed about their comfort while experiencing three Italian shopping centre common areas. The purpose of the study was to explore direct human response within shopping centres transitional spaces with the ultimate goal of finding the actual thermal comfort ranges under summer and mid-season.

Chapter 5 presents the thermal comfort and energy performance assessment methodology applied to a mixed-mode atrium in a warm temperate climate. The aim of the study is to verify the level of comfort provided by a mixed-mode solution

Chapter 6 provides overall conclusions of this work.

1 Transitional Spaces

This chapter introduces transitional spaces features and how their use is changed throughout history. Basics of mixed-mode ventilation schemes are presented and the role of transitional spaces in the mixed-mode design is investigated through the analysis of some examples. A database with 17 non-residential buildings which integrate a transitional space in their mixed-mode ventilation design is presented. Some of the case studies are analysed in details with the aim of addressing the use of transitional spaces, the main ventilation strategies and mixed-mode schemes and the main controls.

1.1 Definition and main features

A transitional space is a building zone that has an intermediate position between the external and internal spaces, or within two internal spaces. For their characteristics transitional spaces may be considered as a "limit": *«the limit does not consist in the end of something but, as the Greeks had already figured out, it is rather the point where something begins to assert its presence»*[1]. In architecture, the concept of limit should not be understood as a clear separation between two areas, but rather as a partition which allows a dialogue between different spheres: indoor/outdoor, private/public.

Transitional spaces have been existing across different cultures throughout the history of architecture. From the thermal point of view, they are important since they can temper the thermal condition of people moving from outside to inside and vice versa. Researchers use a variety of terms when referring to environmental conditions within a space. The expression *transitional,* however, is often used synonymously with the term *transient*. This leads to confusion about whether we are talking about the architectural space, the response and behaviour of the human occupant, the physical conditions, or some combination of these meanings [1.1].

People may use transitional spaces as areas to sit and relax or as a passage way to walk about, stop shopping or dash to catch a train, and other activities. The most important factors distinguishing transitional spaces from internal and external ones are:

- big volumes that when conditioned results to be high energy demanding;
- the variability of the thermal conditions (presence of areas in the sun and in the shade), for which it is not possible to think in stationary terms;

---

[1] Martin Heidegger, German philosopher (1889-1976).

- short-term exposure which however depends on the building use;
- multisensory perception that involves all the senses in relation to the social and cultural sensibilities of the people;
- low impact of users behaviour on the energy consumption;
- low building-user interaction;
- presence of openable glazed area, usually designed for fire safety reason only;
- big volumes and high spaces are particularly effective for displacement ventilation.

Because of the plurality of their uses, transitional spaces design faces different climatic, functional, aesthetic and social challenges.

For the scope of these dissertation, a transitional space is *"a space in between indoor and outdoor climate, or between two indoor environments, which thermal characteristics can be or not modified by mechanical control system and where occupant may experience the dynamic effect of this change"*.

1.2 Typological classification and functional value

According to existing literature [1.1], transitional spaces have a wide range of different features. A revised typological classification is proposed in Figure 1.

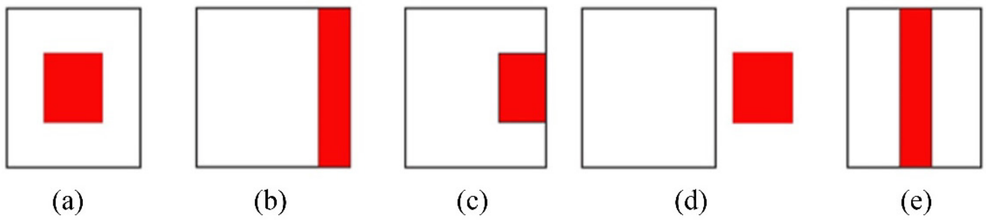


Figure 1 Types of transitional spaces: Type (a)-central, Type (b)-perimetral, Type (c)-lobby space, Type (d)-not attached, Type (e)-passing

Transitional spaces can be classified into:

- ***Type (a) central:*** totally enclosed by the building's walls and opened to the sky, such as courtyards, patios, atria;
- ***Type (b) perimetral***: a covered transitional space connected to the building, where outdoor conditions predominate, such as porches, corridors, arcades and balconies;
- ***Type (c) lobby space***: a transitional space contained within a building, where conditions are constantly mixed as people move in and out the building. A lobby space is defined as the first visual and spatial contact that people have with the inside of a building. Examples of lobby spaces are the atria of hotel entrances and foyers, which are spaces located before the projection rooms in cinemas or performance halls in theatres, where people entertain before and after the show;

- ***Type (d) not attached***: an outdoor room not attached to a building, entirely influenced by how the design of the structure modifies the outdoor climate, such as pergola, bus station, pavilions;
- ***Type (e) passing***: a covered transitional space closed longitudinally by building walls. It has two openings on the shorter sides, such as a galleria.

In their origin, transitional spaces born to meet needs related to protect from sun, wind and rain depending on the different climates. In hot-humid climates, the need is both to protect from solar radiation and to ensure a certain level of ventilation. To meet both needs, an extension of roofs is usually adopted, also functioning as protection from the rain called "veranda". In dry-hot climates, the need is to protect from large solar radiation that is almost entirely perpendicular to the horizon for most of the year. A major characteristic of these climates is the perimeter transitional space called "mashrabyia" (Figure 2). It modulates the passage of light and the air flow and is usually made of a wood structure dressed with interstices. In traditional Japanese houses, the perimeter type is called "engawa"(Figure 2). This is a transitional space between the house and the external environment that serves several functions: to protect the building from the outside climate, to welcome guests and to connect different parts of the house [1.9].

Figure 2 Example of "mashrabyia" (left) and "engawa" (right) [Source: Google]

In Mediterranean Countries, characterized by a temperate climate, people are inclined to spend most of their time in outdoor environment. By shading outdoor spaces, a new social space where to meet was born, the so-called atria. Ancient atrium examples are the courtyard of the Roman *domus* and the cloisters in religious architecture. Atrium provides impressive aesthetic space, exposing adjacent indoor spaces to daylight, maximizing benefits from direct solar gain and increasing inhabitants' socialization and interactions. Other examples of transitional spaces used in temperate climate are porches, loggias and pergolas. Traditionally, the archetype of such space is the porch that, in some cases, was integrated by curtains or other shading system along the squares and streets, to extend the shaded space. A lot of Italian cities were characterized by the presence of porches, such as Torino, Bologna and Bolzano. Porches play an important support to activities of adjacent open space, mitigating summer weather conditions and promoting social interactions, especially through commercial activities. The modern concept of the commercial transitional spaces in particular derives from porch.

Starting from early 19th century, transitional space design for both residential and non-residential buildings was deeply influenced by the use of glass. The use of glass, especially in cold climates has positively influenced thermal comfort of inhabitants in residential building during daytime. An example is the "solar greenhouse" or "buffer space", used in European cold temperate climates. These are completely glazed perimeter transitional spaces, placed on the southern side of the building, exploiting the greenhouse effect for heat storage. If equipped with shadings to limit solar gain, especially in summer, this architectural feature could be also used in the Mediterranean climate.

The increased use of wide glazed façades combined with the higher permeability of buildings had risen the necessity, especially in summer, to mechanically control the indoor conditions. This solution avoids indoor overheating maintaining a certain level of indoor thermal comfort also for non-residential transitional spaces.

Transitional spaces are nowadays pivotal in the architecture of big retails building such as shopping centers and malls but also in airports, train station and other typologies of non-residential buildings.

1.3 The role of transitional spaces in mixed-mode ventilation design

In this paragraph the role of transitional spaces within the mixed-mode ventilation design is investigated.
Firstly a definition and different operation scheme of mixed-mode buildings are presented. Then with the help of 17 examples of non-residential mixed-mode buildings which integrate a transitional spaces in their architecture and mixed-mode strategy, an overview of their use is given. A small database with information related to, transitional spaces typology, mixed-mode scheme, natural ventilation strategies and controls and integration with HVAC system was created. The database is free and accessible through [1.10]. The role of the transitional spaces is investigated though the analysis of some of the examples that goes from office buildings to shopping centres.

1.3.1 Mixed-mode schemes

In recent years, concerns about global warming and greenhouse gas emissions [1.11], have motivated designers to reduce building energy consumption through the implementation of passive solutions without compromising users' thermal comfort. The continuous improvements of building thermal envelope proprieties combined with the increased level of internal gains changed the non-residential building energy balance. These effects led to a lower heating demand while raising the problem of increased cooling demand during the whole year. Besides, outdoor temperatures increase as a result of warmer climate .This has progressively produced an increment of the demand for electricity, which is the main source of energy for air conditioning [1.11]. This evidence has stimulated a renewed interest in designers for the exploitation of natural ventilation as means of passive cooling solutions. For non-residential buildings, their architecture commonly based on the presence of large open space such as lobbies and atria, helps the implementation of passive cooling solutions though natural ventilation strategies. Before the uptake of air conditioning, especially in Eastern countries, indeed, large open atria property of air stratification were used. The warm air flushing out from the top allows the colder air entering from lower level providing comfortable condition [1.3].

Nowadays, the practice of using natural ventilation for cooling purpose falls into the Ventilative cooling practice. Ventilative cooling [1.12] can be defined as "*the use of natural or mechanical ventilation strategies to cool indoor spaces. This effective use of outside air reduces the energy consumption of cooling systems while maintaining thermal comfort. The most common technique is the use of increased ventilation airflow rates and night ventilation, but other strategies may be considered as well*".

The international research project Annex 62 of the International Energy Agency (IEA) [1.13], focuses its research activity on Ventilative cooling.

Because of the awareness of natural ventilation limitations, which relies on natural forces, the interest has moved towards mixed-mode buildings. Mixed-mode buildings are indeed designed in such way that the HVAC system help to prevent uncomfortable conditions when natural ventilation is not sufficient to guarantee a comfortable environment. By following this compromised approach, the benefits of both systems are maximized achieving two important results. On one side the anxiety concerning the performance of fully naturally ventilated buildings under extreme condition is overcome and, electricity costs and CO_2 emissions are limited on the other.

Today there is not a "standard" mixed-mode approach. The mixed-mode solution need to be thought and designed in relation to the climate, the available natural sources of the building site and the building use. The Chartered Institution of Building Services Engineers (CIBSE) [1.14] published a classification schemes that describe the integration of natural ventilation and air-condition control strategies. The classification scheme was originally proposed by Max Fordham and Partners, revised and further explored by Bill Bordass, Adrian Leaman, Erik Ring and others.

In the simplest terms, the classification is based on whether natural ventilation and air-conditioning are operating in the same or different spaces in a building, and at the same or different times.

In Figure 3 a flow chart that help in the classification of buildings within the different mixed-mode scheme is presented.

The first difference is between ***zoned*** and ***complementary*** mixed-mode buildings. A zoned mixed-mode building might have spaces that are either exclusively naturally ventilated, or exclusively mechanically cooled. Zoned systems can have, for example, natural ventilation on the perimeter and mechanical ventilation in the core. An example is the Ecoport Office building [1.15], located in Wien, where the natural night ventilation is applied just in the central atrium while for the office a mechanical night cooling solution is considered.

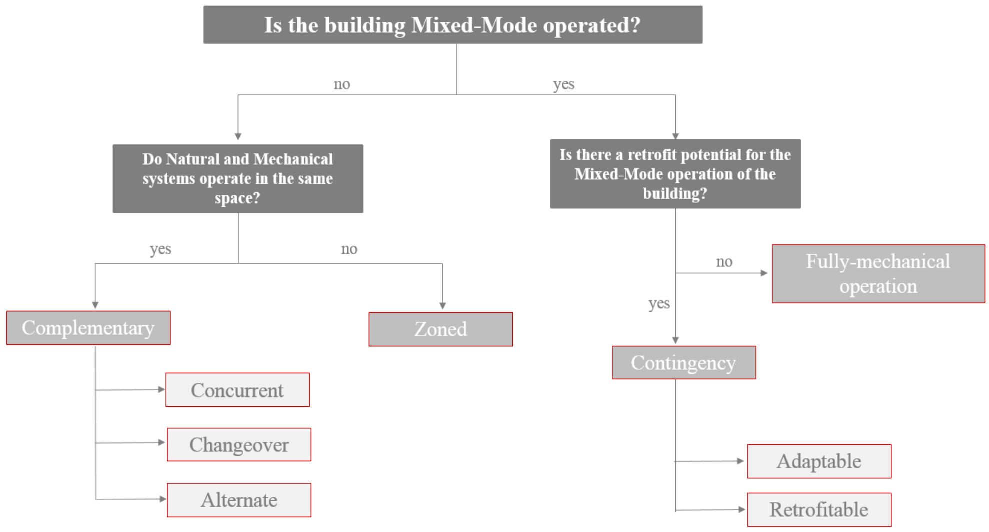


Figure 3 Flow chart for the classification of the mixed-mode scheme (Source of information then re-elaborated is [1.14])

Oppositely, for a complementary mixed-mode building there are both systems in the same space. Depending on the operation time of natural ventilation and mechanical ventilation and cooling, a further distinction within the complementary category is possible. We talk about ***concurrent*** mixed-mode solutions when the systems work in the same space and at the same time. An example is the Gap Office Building, located in San Bruno, California [1.16]. It utilizes an underfloor air distribution system (UFAD) and occupant have control of both operable windows and floor diffuser. Occupants can use the operable windows at their discretion, and there are no controls connecting their use to the mechanical system.

With concurrent system a common concern is about the risk of an higher energy demand because of the need of conditioning the air coming thought the windows. This situation can be avoided or restrained letting the building working first under passive mode and then switching to active when the comfortable conditions inside the space are overtaken. This results can be, for example, simply achieved by running the building with higher cooling set point than the usual one. By operating the building in this way we are progressively moving to the ***changeover*** mixed-mode scheme. In the same building or building zones we have both passive and active solution which however work within different temporal framework. By means of climate-base controls, the two systems work separately. The aim is still to provide a comfortable indoor environment reducing the energy consumption. A good examples of climate and time-based control strategies is a ten-storey office building located in Tokyo [1.17]. The building owner has indeed established four different operational modes to accommodate different comfort expectation of the building tenants. The modes basically works prioritizing, on the base of ambient conditions, the use of natural ventilation. At certain time of the day (12:00, 18:00 and 22:00), the system is reset, turning off all the fan and opening all the openings. This action is made in case occupants have manually shut openings, but have not re-opened them after ambient conditions have changed.

The use of climate-base controls which detect the optimal outdoor-indoor conditions for running the building under either passive or active mode, allows preventing energy drawback as seen for the concurrent mode. It should anyway considered that despite the possibility of losing energy if windows are open when the mechanical cooling is running, the energy savings due to the use of natural ventilation for cooling purpose can outshine this waste.

When the turnover between natural ventilation and air-conditioning is based on seasonal variation but the controls is purely manual we talk about ***alternate*** mixed-mode building.

In relation to the potential of mixed-mode exploitation, a building can be also addressed as a ***contingency*** mixed-mode building. All the buildings built entirely with either mechanical ventilation or natural ventilation, but with a good retrofit potential to become mixed-mode belong to this group. Depending on the available investment for turning the building into mixed-mode operation, the level of contingency can be further dissociated into retrofitable (moderate investment) or adaptable (small additional investment).

Shopping mall building typology has a big potential in term of retrofitable or adaptable mixed-mode solutions. The topic will be further analyzed in paragraph 1.3.3 and 2.1.

1.3.2 Database of mixed-mode operated transitional spaces

With the aim of a better overview about the role of transitional spaces in mixed-mode design, technical information about 17 non-residential mixed-mode buildings among Europe have been recovered and analysed. All the information have been categorized and collected in a small database which have open access [1.10].The buildings include a transitional space in their architecture which has been classified according to the typology classification presented in paragraph 1.2 (Figure 1).

The mixed-mode scheme was instead identified according to the solutions presented in paragraph 1.3.1. A climate classification was also adopted on the basis of Köppen-Geiger climate classification principles [1.18]. Part of the information related to typology, climate, and transitional space type and mixed-mode scheme are collected in Table 1. Figure 4 shows the buildings location within Europe.

Except for City Sid shopping mall located in the snow climate of Trondheim (Norway), all the other buildings are located in warm and temperate climates.

Table 1 Information about the selected case-studied

Building	Typology	Climate	Transitional space	Mixed-mode
Powergen Headquarters (Coventry, UK, 1994)	Office	CFB [2]	type e (atrium)	changeover
Barclaycard (Northampton, UK, 1997)	Office	CFB	type e (atrium)	concurrent
Blue Water Shopping Mall (Dartford, UK,1999)	Shopping mall	CFB	type e (galleries)	concurrent
Oststeiermarkhau (Großwilfersdorf, AT,2005)	Office	CFB	type b (winter garden)	changeover
Københavns Energi (Copenhagen, DK,2005)	Office	CFB	type a (atrium)	concurrent
Earn August (Hannover, DE,2008)	Shopping mall	CFB	type a/ e (atria and galleries)	changeover
Seixal City Hall (Lisbon, PT, 2010)	Multi-service building	CSA [3]	type a (atrium)	concurrent
Ecoport Saubermacher (Feldkirken, AT, 2011)	Office	CFB	type e (atrium)	zoned
Justizzentrum (Korneuburg, AT,2012)	Office	CFB	type a (atrium)	zoned
DTU building 324 (Kgs. Lyngby, DK,2013)	Educational	CFB	type a (atrium)	concurrent
Windkraft Simonsfeld AG (Ernstbrunn, AT,2014)	Office	CFB	type b	concurrent
Pakhus (Copenhagen, DK,2015)	Office	CFB	type a (atrium)	concurrent
City 2 (Høje Taastrup, Copenhagen DK,2010)	Shopping mall	CFB	type e	contingency-retrofittable
Forum Kloster (Gleisdorf, AT, 2010)	Multi-service building	CFB	type b (hall)	changeover
Field's (Copenhagen, DK, 2004)	Shopping mall	CFB	type a/e (atrium-galleries)	contingency-retrofittable
City Sid (Throndeim, NO, 2016)	Shopping mall	DFC [4]	type a (atrium)	contingency-adaptable
Marcado dal Val (Valladolid, ES,2016)	Shopping mall	CSB [5]	type e	contingency-retrofittable

---

2 Warm temperate climate, fully humid (warmest temperature ≤ 22 ºC; mean monthly temperature ≥ 10 ºC for at least four months) [1.18]

3 Warm temperate climate with dry summer (Warmest temperature ≥ 22 ºC) [1.18]

4 Snow climate, fully humid (warmest temperature lower than 22 ºC ; mean monthly temperatures ≤ 10 ºC for more than 8 months; coldest temperature > - 38 ºC) [1.18]

5 Warm temperate climate with dry summer (warmest temperature ≤ 22 ºC; mean monthly temperature ≥ 10 ºC for at least four months) [1.18]

Figure 4 Location of the 17 mixed-mode non-residential building considered for the analysis

Differently for warm and hot climate where, the frequency of high temperature during summer periods, makes necessary the use of active cooling system in order to reduce the risk of compromising users' thermal comfort. A suitable solution for both climates, with a different degree of application, is night ventilation. This technique utilizes the thermal mass of the building for cooling storage at night [1.4] .At night, heat gains are much lower or even negative, and colder outdoor air can be used to remove heat from the surfaces, cooling down the building structure. Within the office building typology, six buildings over eight, consider night ventilation coupled with thermal mass, as solution for keeping comfortable conditions.

The main features in terms of typology of transitional space used and mixed-mode scheme are summed up in Figure 5.

The typologies mainly used are three: the great part of the buildings analysed integrate in their architecture *type a* and *type e* while a small percentage integrate *type c*. In relation to mixed-mode scheme, concurrent solution is the mostly adopted followed by changeover and contingency. Just for two case studies (zoned) there is no integration between the transitional space and the rest of the building in term of mixed-mode solution. The four case studies which belong to category *contingency* are shopping centers. A detailed analysis of these peculiar building and their potentiality of conversion from fully mechanical to mixed-mode operation of their common areas is presented in paragraph 1.3.3 . Therefore in this paragraph the attention is focused on the other buildings typologies. For office solutions indeed *type a* and *e*, are most of the time medium-size or big atria that have a central position between rows of office floors. Figure 6 collect three examples of central atria used in three different mixed-mode strategies.

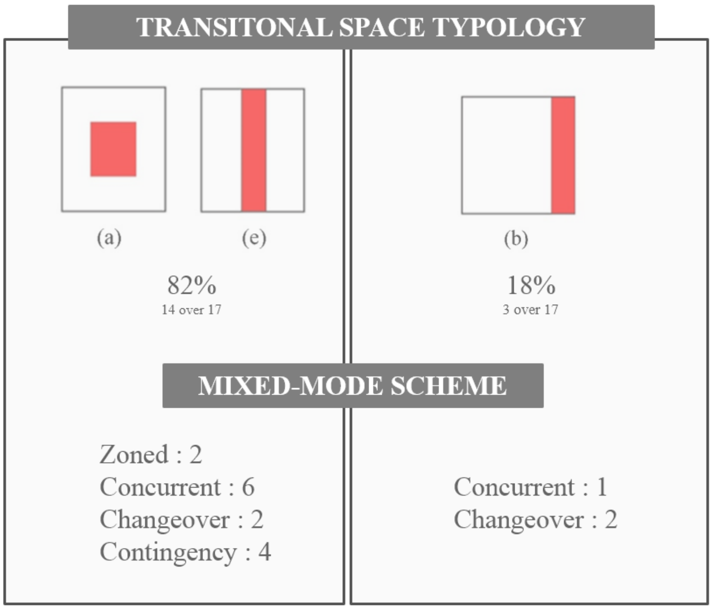


Figure 5 Statistics of the transitional space typology and mixed mode schemes adopted in the 17 cases studies (Table 1)

Figure 6 Examples of transitional space *type a* and *e* included into mixed-mode solution. From left to right: PowerGen Headquarter central atrium (source: here), Ecoport (source: IEA EBC Annex 62 Ventilative Cooling International Ventilative Cooling Application Database [1.15]) and Seixal City Hall (source: Natural Works)

A common feature of the three buildings in Figure 6 is the ventilation strategy, mainly based o stack effect. Air from the lower level of the building is driven by buoyancy in the upper part of the atria where the presence of openable windows allow its outflow. In the case of Seixal City Hall, the ventilation strategy was also designed considering the prevailing wind direction on the site which at night usually comes from the ocean, namely from North-West orientation. The natural ventilation solutions is therefore wind-driven stack ventilation.

For the three buildings, the inlet openings location is different. For Ecoport (zoned) and Seixal City Hall (concurrent) the mixed-mode solution involves just the atrium and therefore inlet openings are locate within the atrium perimeter. Contrarily for Powergen Headquarter (changeover) the big central atrium is open to the lateral offices where perimeter windows function as inlet. The windows have three level of openings. During daytime the middle and the lower windows can be manually opened by the occupants and working in conjunction with automatically operated ventilators high in the atrium. When it is not naturally ventilated, an underfloor ventilation ductwork (UFAD) provides up to three air changes per hours in the offices. The system acts as cooling system on hot days and also ensures background ventilation in winter when the occupants have the windows closed. At night the lateral windows are kept closed and just the roof windows are opened to allow cool air to flow over the coffered concrete ceiling. A warm-water heat bus that gathers heat from various sources including IT equipment, the atmosphere and a diesel generator is used to cover the heating demand. The heat is distributed to the heather batteries of the UFAD system, to underfloor pipes in the atrium and also to anti-downdraught radiations located at roof level. This last is a very interesting solutions that allow the use of natural ventilation also when the outdoor temperatures being too low, can potentially create discomfortable conditions.

Coupled night ventilation with thermal mass is also used in Ecoport and Seixal buildings where it is mainly controlled on temperature and time.

For Ecoport, when natural night ventilation is not enough to offset the cooling demand, free cooling effect of ground water is used. The ventilative cooling strategy in the office is totally mechanical recirculating up to three air change per hour.

Seixal city hall has a dedicated HVAC system for the atrium: a radiant floor feed by a reversible heat pump, positioned on building roof, covers the cooling demand. During daytime a cross-ventilation system also help to cool the atrium. Two rows of nine windows located in the upper part of the atrium, on opposite orientation (North-South), allow the replacement of the warm exhaust air that stack under the ceiling with fresh one coming from the outside. Daytime ventilation is most of the time running during the period between April and October. Although all the windows are equipped with electric actuators connected to the general Building Management System (BMS) of the building, the controls is manual. This means that the technical engineer decides, based on outdoor and indoor conditions, or on atrium worker feedback, the best moment for natural ventilation operation.

Night cooling is operated more or less within the same seasonal period and again the control is based on the technical engineer decisions. No automated climate-based controls are considered.

The three buildings that incorporate *type c* transitional spaces in their architecture and in the mixed-mode solution are presented in Figure 7.

While for Forum Kloster and Oststeiermarkhau the perimentral transitional space was part of the original architecture, for the Forum Kloster the entrance hall was added in 2001 as part of a retrofit process. The ventilation principle is also for these buildings, based on stack ventilation with opening located at different heights. Night ventilation coupled with thermal mass is again the main ventilative cooling solutions.

Figure 7 Examples of transitional spaces *type b* adopted into the mixed-mode solution. From left to right: Forum Kloster and Oststeiermarkhau (source: IEA EBC Annex 62 Ventilative Cooling International Ventilative Cooling Application Database [1.15]), Windkraft Simonsfeld AG (source: IEA EBC Annex 62 Ventilative Cooling International Ventilative Cooling Application Database [1.15])

In Windkraft Simonsfeld AG night ventilation effect is supported by the central massive wall that can be thermally activated by ground water freecooling. Powerless rotating extract ventilators also enhance the air changes during nights. The control of the system is based on indoor and outdoor temperature and humidity. A manual override of the control system is however left.

For Oststeiermarkhau the night ventilation strategy consider also the adjacent office zones. By means of special designed doors, the air can circulates in the whole buildings. The natural ventilation is controlled in temperature and time with a degree of freedom for possible future changes. Heating and cooling demand is covered by a biomass plant and with connection to district heating. The mechanical ventilation system takes advantage of an air-soil-heat exchanger for preheating and precooling the outdoor air. Same solution is adopted in the Forum Kloster: an air-soil-heat exchanger preconditions the incoming air. Because the base load are covered by means of a passive solution, a size reduction of the conventional cooling system was possible. The air pre-treated air is injected at floor and wall level and exhausted the top of the atrium where a shed opens automatically controlled by temperature. Considering that the building is used for different events which involve a high internal loads and a high cooling demand to be offset, this solution allow to save an important slide of energy for cooling. Night ventilation in the hall is effective considering the extensive thermal mass due to the historical structure of the building.

On the basis of the mixed-mode solution presented, transitional spaces such atria or hall are mainly used as buffer zone. They are most of the time integrated in the mixed-mode strategy as collector for the exhaust air that is then purged out through opening in their upper part. Night ventilation coupled with thermal mass is a well-established solutions. It is a reliable solution to cut the temperature peak of the following day of application guarantying comfortable conditions. Free cooling associate to air-to soil heat exchanger or directly by exploitation of ground water is an interesting solution for middle and norther European cold climates. Controls are either automated or manual and they are basically based on temperatures and time of the day.

1.3.3 Mixed-mode operation in shopping centre transitional spaces

Shopping centre represent a good examples of contingency mixed-mode buildings. In their typical layout, shopping mall are organized on small individual stores connected by common areas such as atrium and galleries. Generally, these spaces are conditioned by means of HVAC systems. The potential of natural ventilation to guarantee the minimum air change rate required by IAQ standards and to reduce cooling demand is most of the time not considered. The presence of openable skylights for fire safety regulations combined with the large volumes and height of these shopping centres zones, however makes the exploitation of natural stack ventilation very attractive.

The Danish company Windows Master has been the first to design and integrate natural ventilation solutions for shopping mall common areas. The Ernst-August Galerie located in Hannover [1.19] is indeed the first shopping centre in Europe, where controlled natural ventilation has completely replaced the mechanical centre-cooling. At initial design only the smoke ventilation was planned. The presence of windows actuators in the central area would have to ensure the exhaust of the smoke and heat in case of fire. However, Window Master was able to demonstrate, via dynamic thermal analysis of the building, that with an intelligent control system, the temperature within the centre could be kept stable all year round. This would reduce the need for additional mechanical cooling. Just the original roof lights together with some additional vertical windows in the facades were employed [1.19]. In total, the ventilation strategy involves 10 zones within galleries and atria that can be separately controlled. The control is based on indoor and outdoor temperature, the CO_2 concentration in the zones, wind speed and direction, and rain detection. During summertime, night ventilation coupled with thermal mass is chosen to prevent temperature peak of the following day. The shops are maintained at a 10-20% over pressure compared to the gallery. Therefore, the air flows from the shops to the central atrium and out through the skylight openings. The stack ventilation concept is shown in Figure 8.

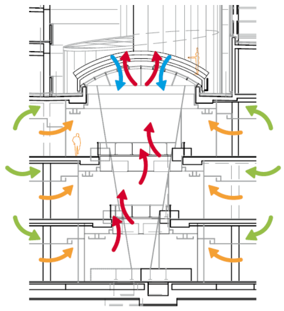



Figure 8 Ventilation concept (left) and a detail of the gallery roof openings (right) for the Ernst-August-Gallerie Source: Window Master

After this successful design example, Window Master started to propose similar solutions but for the retrofit of shopping centre. Examples are the City2 and Field's (Figure 9) shopping centres ([1.10] and [1.15]) where the openable windows on façades and skylights are used to recirculate fresh air from outside during shoulder and summer seasons. In summer then, when the operative temperatures are over the 26 ºC comfort threshold, the mechanical cooling is operated.

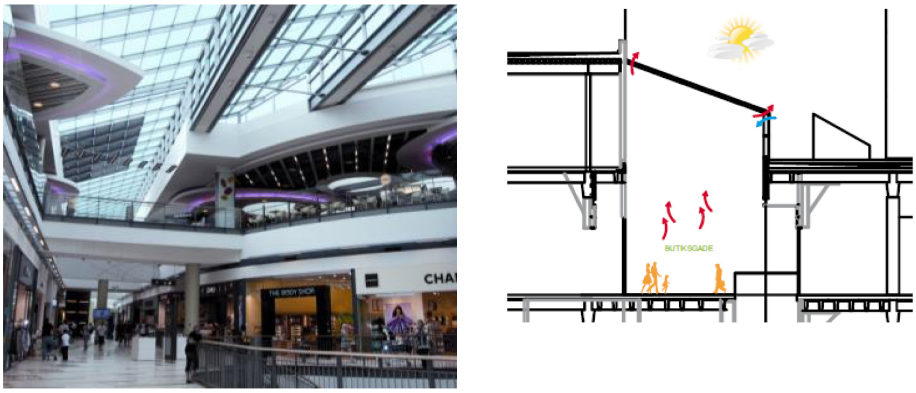


Figure 9 Picture of Field´s common area (left) and ventilation strategy (right)

Most recent examples of shopping mall common areas conversion into mixed-mode operation are CitySid in Norway and Mercado dal Val in Spain ([1.20] and [1.21]). Both shopping malls were demonstration case studies of the CommONEnergy project [1.8].

The central atrium of CitySid mall was already equipped with openable windows in the skylight. The operation of those windows was however very limited. The building manager was not able to modify the control algorithm, exclusively propriety of the windows manufacturer. Belleri et. al, [1.20] proposes a natural ventilation strategy combining the effect of existing sliding doors and skylight openings to enhance stack ventilation and ventilate/cool the common areas. Climate-based control strategies have been initially studied through an airflow network model coupled with the energy model of the building [1.22]. At a second stage they were implemented in a brand new iBEMS that controls in a smart way the operation of either natural ventilation or HVAC system in the atrium. This is an example of how an *adaptable* building (see paragraph 1.3.1) can turn into a changeover mixed-mode building with a capital investment just related to the installation and commissioning of a new BMS[6].

Oppositely to CitySid, for Mercado dal Val the mixed-mode design was part of a deeper refurbishment intervention. The municipality of Valladolid planned to transform the market into an innovative and contemporary commercial building keeping its historic representativeness. The goal was reached thanks to a newly developed modular climatic adaptive [1.23]. This new façade system aimed at integrating thermal, daylighting and ventilation functions, being responsive when internal and external loads change [1.24], was adapted to the existing iron structure.

[6] Building Management System

Because of the deep retrofit and the multifunctional facade, a sizing of the openable windows in the façade was possible. The ventilation strategy (Figure 10) considered also the existing skylight openings located at ca. 10 m height from the ground level where air can exhaust [1.21].

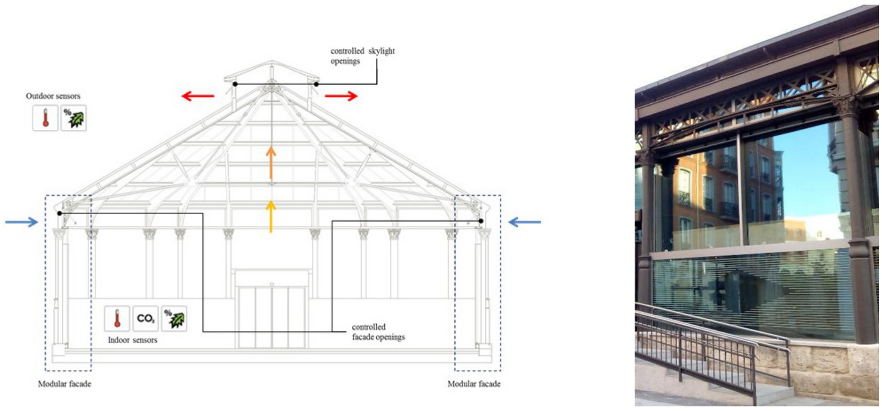


Figure 10 Ventilation strategy for Mercado dal Val (left) and details of the modular multifunctional façade used.

For the definition of the number of openings, a parametrization study to optimize the investment cost was conducted. The study took into account not only the potential energy saving due to natural ventilation but also thermal comfort and indoor air quality issues.

The optimization was possible thanks to a coupled thermal Trnsys model with airflow model by means of the Trnflow plugin [1.25].

The thermal-airflow model was further used to define a detailed control strategy. The control strategy is climate-based. This means that it takes into consideration the outdoor temperature measured by the weather station and the indoor temperatures measured by temperature sensors located within the building. Rain and wind speed are considered as well. Mercado dal Val represents a successful example of mixed-mode conversion proving how a retrofit process that includes a mixed-mode cooling solution is a fact even for buildings under heritage protection.

In all the shopping mall presented so far, the ventilation strategy was mainly based on stack ventilation because of the favourable architecture. Another way to provide thermal comfort inside the common areas is to exploit a strategy based on wind-induced ventilation as in the Blue Water shopping mall [1.26]. The galleries are mixed-mode ventilated by using 39 rotating wind catcher located on the roof of the building (see Figure 11). The operation of the wind catchers is based on outdoor weather conditions and indoor thermal conditions. They can operated in two ways:

- as supply in summer with outside temperature range of 16 ºC -25 ºC;
- as extract in winter and other mild weather conditions for external temperature in the range of -4 ºC -16 ºC [1.26].

Figure 11 Wind scoops application on Blue Water shopping centre, Kent Source: http://www.battlemccarthy.com/bluewater-shopping-centre-kent

Bibliography

[1.1] Chun C., Kwok A., Tamura A. Thermal comfort in transitional spaces - basic concepts: literature review and trial measurement. Building and Environment,(2004) 1187-1192.

[1.2] Kwong, Q. J., Tang, S.H., Adam, N. M. Thermal comfort evaluation of the enclosed transitional space in tropical buildings: subjective response and computational fluid dynamic simulation, Applied Sciences, 9(19), 3480-3490.2009

[1.3] Kuppaswany I. Sustinable Architecture desing : An overview. Tayor & Francis, 2015.

[1.4] Spindler H.C., Norford L.K.. Naturally ventilated and mixed-mode buildings - Part II: Optimal control. Building and Environment 44: 750-761,2009

[1.5] Hui, S. C. M. and Jiang, J., 2014. Assessment of thermal comfort in transitional spaces, In Proceedings of the Joint Symposium 2014: Change in Building Services for Future, 25 Nov 2014, Kowloon Shangri-la Hotel, Tsim Sha Tsui East, Kowloon, Hong Kong, 13 pp.

[1.6] P.F. Linden, The fluid mechanics of natural ventilation, Annu. Rev. Fluid Mech. 31 (January 1999) 201e238, http://dx.doi.org/10.1146/annurevfluid.31.1.201. ISSN 0066-4189.

[1.7] G.C. da Graça, P. Linden. Ten questions about natural ventilation of non-domestic buildings. Building and Environment 107 (2016) 263-273.

[1.8] European FP7 project CommONEnergy

[1.9] Poggi C. Potenzialità di uno spazio di transizione microclimatica: il portico nel clima mediterraneo- temperato. Tesi finale di Dottorato di Ricerca in Tecnologia e Progetto per l'ambiente costruito. Politecnico di Milano.2015

[1.10] doi:10.5281/zenodo.1011230

[1.11] IPCC, 2014: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.

[1.12] INIVE-EEIG, 2013-last update, Venticool platform

[1.13] IEA EBC Annex 62. Ventilative cooling. s.l., 2014-2017.

[1.14] AM13- Mixed-mode ventilation systems. Chartered Institution of Building Services Engineers (CIBSE), 2000

[1.15] IEA EBC Annex 62. Ventilative Cooling Application Database.

[1.16] Centre for the Built Environment (CBE).Mixed mode: case studied and project database.

[1.17] Ray, Stephen D., Masashi Fukuda, Maria-Alejandra Menchaca- Brandan, Iwao Hasegawa, Leon R. Glicksman, and Natsuko Ochiai. "Overview of Hybrid Ventilation Control System and Full Scale Monitoring." ASHRAE Transactions. 2013, Vol. 119 Issue 2, 1-8

[1.18] Kottek M., Grieser J., Beck C., Rudolf B., Rubel F. World Map of the Köppen-Geiger climate classification updated. Meteorologische Zeitschrift, Vol. 15, No. 3, 259-263, June 2006

[1.19] Ernst-August-Galerie http://www.windowmaster.com/building-types/shopping-centres

[1.20] Belleri A., Haase M., Papantoniu S., Lollini R. Delivery and performance of a ventilative cooling strategy: the demonstration case of a shopping centre in Trondheim, Norway. 38th AIVC Conference, Nottingham, 13-14 September 2017

[1.21] Belleri A, Avantaggiato M., Lollini R. Deliverable 3.3: Ventilative cooling, CommONEnergy project (FP7-2013 grant agreement no 608678), 2017

[1.22] Haase M., Stenerud Skeie K., Belleri A., Dipasquale, C. Modelling of a complex shopping mall in Norway, Proceedings of BS2015: 14th Conference of International Building Performance Simulation Association, pp. 2264, 2015

[1.23] Attia S.G., Favoino F., Loonen R.C.G.M., Petrovski, A., Monge-Barrio A., Adaptive façades system assessment: An initial review. 10th Conference on Advanced Building Skins 2015, pp. 1275-1276-1283.

[1.24] Rozanska M., Mata G., F.J., in progress. Deliverable 3.4: Concept of modular multifunctional façade. CommONEnergy project (FP7-2013 grant agreement no 608678) , 2017

[1.25] Holst S., Hille M., Weber A., Koschenz M. “TRNFLOW: Integration of COMIS into TRNSYS TYPE 56”. In: 23rd AIVC and EPIC 2002 Conference "Energy efficient and healthy buildings in sustainable cities (2002) (cit. on p. 74).

[1.26] Elmualim A.A. , Awbi H.B. Evaluating a control strategy for a hybrid air-conditioning and windcatchers ventilation system. CIB 2004, World Building Congress, Toronto, Canada.

2 Retrofitting shopping centres transitional spaces into mixed-mode operation

A BPIE report released in 2011[2.1] stated that 28% of the European non-residential building stock is covered by wholesale and retails (see Figure 8).This implicates that the majority of European shopping centres are already built, but there is still a huge potential for energy savings due to the practice of regular retrofitting and redesign.

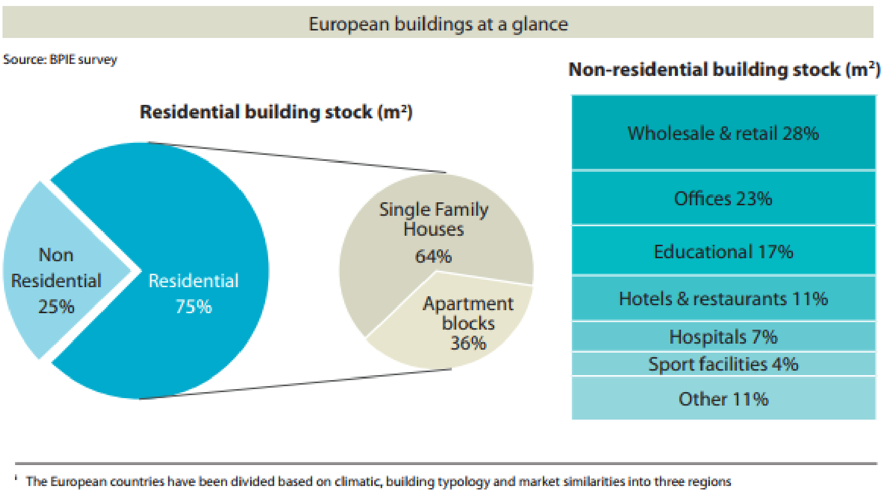


Figure 12 Distribution of the European building stock according by building typology [2.1]

This state of constant change offers regular opportunities to improve the technical systems, such as lighting, ventilation, the building envelope and monitoring systems, and more. In shopping centres, differently from residential buildings where energy is mainly consumed by heating, cooling, hot water, cooking and appliance [2.1], the major consumption is due to lighting and air-conditioning and ventilation system (HVAC) as showed in Figure 13 ([2.2]). Therefore energy retrofit solutions should consider actions able to reduce both specific lighting power installed and the energy used for the HVAC. Lighting power installed always affects the HVAC consumption. While during winter internal gains have a beneficial effect in decreasing the heating demand, in summer they cause an increase of the cooling demand.

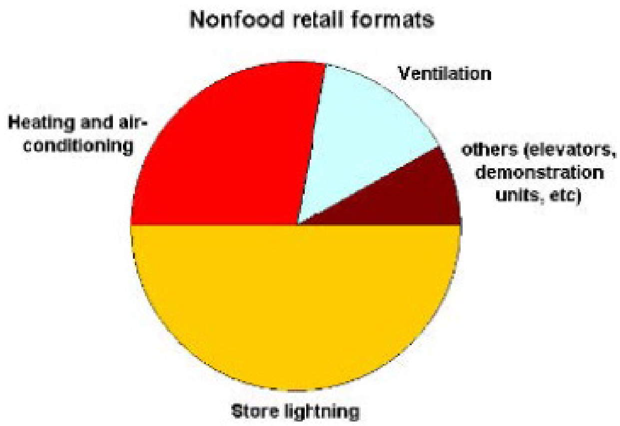


Figure 13 Share of total energy demand in retail buildings

Next paragraph reports a design procedure for the conversion of shopping centre common area into mixed-mode operation. The procedure is discussed with reference to a practical example.

2.1 Design procedure

In paragraph 1.3.1 several mixed-mode operation schemes were presented. Further in paragraph 1.3.2 and 1.3.3 different examples of how these schemes are applied for both new buildings or retrofitted one were discussed.

Natural ventilation needs a specific design service dealing with building shape, internal layout distribution and airflow paths along the building. Therefore its integration shall be ideally considered in the early design stage of an Integrated Design Process (IDP) [2.3].When this kind of retrofit action are considered for shopping centres, the building shape cannot be modified and internal layout can be only partially remodelled. However, typical architectural archetypes of shopping centres makes the exploitation of natural ventilation strategies very attractive. This fact was already proved by the examples presented in paragraph 1.3.3. Typical suitable features are the presence of openable skylights for fire safety regulations and the large volumes and height in the common areas. Furthermore shopping centres common areas are managed by a unique referent (e.g. owner, energy manager) which is also the one who makes the decisions during a retrofit process. Different situation in the "leasing" area, where each shop is managed by franchising companies and most of the time standardized protocols restrain the applicability of general retrofit solutions (e.g. installation of a defined lighting technology, centralized HVAC controls). Beside the architecture suitable features, it is therefore easier to just consider the common areas because of the higher degree of freedom in the applicability of the solutions.

The design of mixed-mode solution for shopping centres should follow several steps which are graphically summarized in Figure 14.

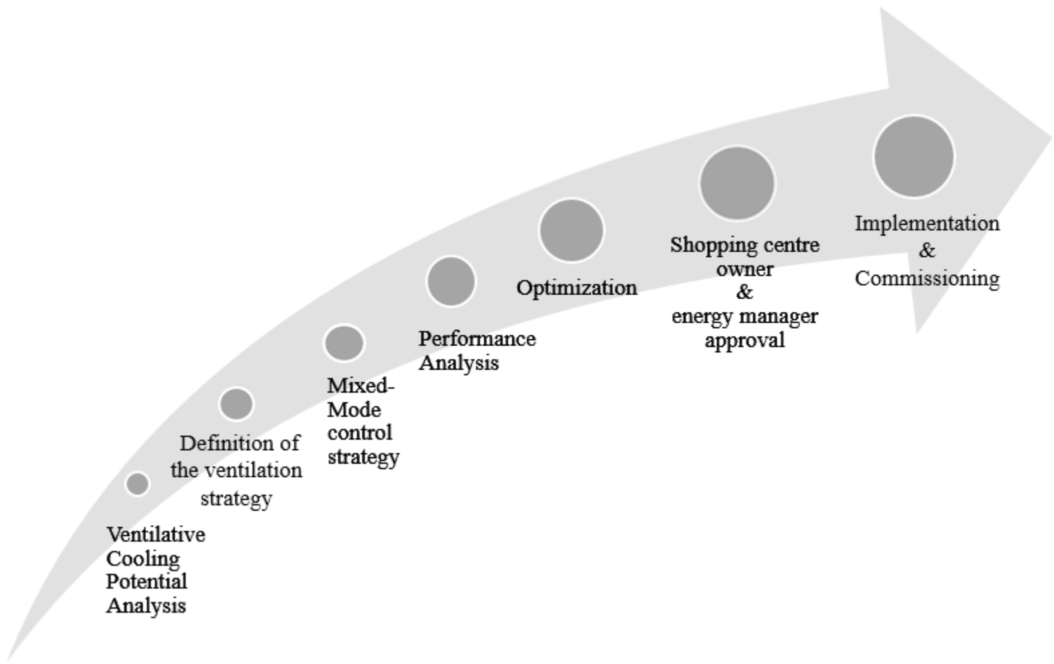


Figure 14 Process of design and integration of mixed-mode ventilation solutions

2.1.1 Step 1 – Ventilative cooling potential analysis

First of all, since the retrofit process may include different solutions, their synergies need to be evaluated. The reduction of the lighting density level is proved to be one of the cost-effective retrofitting solution [2.4] therefore is likely to be chosen as first option. The reduction of the internal gains for lighting affects the energy balance of the buildings and as a consequence the potential of natural ventilation for ventilative cooling purpose. This is what came out from a parametric study the author conducted, correlating lighting level in shopping mall common areas with the ventilative cooling potential [2.5]. The analysis was supported by the ventilative cooling potential tool [2.6], developed within the research activities of the IEA EBC Annex 62 research project [1.13].The performance of a single zone, representative of a shopping mall common area, was analysed for ten different climate within Europe[7] , under different lighting levels. The results showed a linear dependence between the level of lighting power density and the percentage of hours of direct ventilative cooling use, as showed in Figure 15. Overlooking this interdependency could lead to discomfort conditions because of increased airflows and to extra investment costs for openings´ actuators, which might not be necessary.

[7] The ten climates are the ones of the ten reference shoppingmall of the CommONEnergy project [1.8]. Three of the reference buildings (CitySyd, Studlendas, Pamarys) are located in heating dominated climates, three of them (Katane', Coop Valbisagno, Coop Canaletto) are located in cooling dominated climates and the others (Mercado del Val, Brent Cross, Donauzentrum, Waasland, Grand Bazaar) are located in mixed dominated climates [2.7].

Furthermore since the exploitation of mixed mode ventilative cooling can significantly reduce the cooling load, the impact of more efficient cooling systems could happen not to be relevant anymore. This suggests also that when approaching both retrofit and a new design, ventilative cooling should therefore be considered before any HVAC improvements or before a new detailed design of any HVAC equipment [2.5].

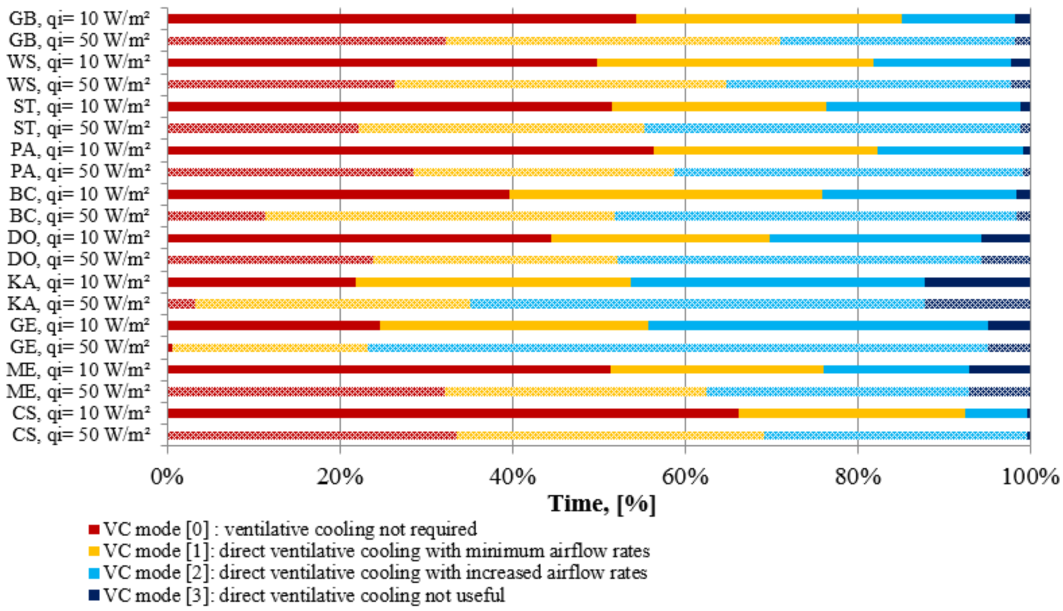


Figure 15 Percentage of hours within a year when direct ventilative cooling is required, useful or not useful in the ten reference building climates considering different values of internal gains [2.5].

Once the retrofitted lighting level is defined, a verification of the climate suitability for natural ventilation and ventilative cooling exploitation need to be performed. The analysis consists in the identification of the number of occupied hours when the ventilative cooling is useful to provide comfortable condition inside the building. The before-mentioned ventilative cooling potential tool (VC tool) [2.8] helps in this sense. It can be used to evaluate the climate suitability for ventilative cooling exploitation. By taking into account location, building envelope thermal properties, occupancy patterns, internal gains and ventilation needs an algorithm identifies, over the occupied time, the number of hours when ventilative cooling is useful. The tool also estimates the airflow rates needed to prevent building overheating. The analysis is based on a single-zone thermal model applied to user-input climatic data on hourly basis

Further analysis related to the exploitation of natural ventilation could include the analysis of the wind distribution around the buildings. Depending on the degree of details needed by the analysis, it can go from a simple analysis of the wind speed direction and distribution based on local climate data to a more detailed analysis involving CFD simulation. CFD simulation are used to define the pressure coefficient on different building facades. They are however time consuming, therefore theirs application is suggested when the site is particular suitable for the definition of a ventilation strategy that counts on wind pressure e.g. coastal areas. If the shopping mall is located in the inland

and no particular effect of the wind speed is foreseen, the static analysis of the wind distribution and speed frequency can be considered enough detailed.

2.1.2 Step 2 – Definition of the ventilation strategy

Once step 1 is accomplished, the most suitable ventilation strategy can be defined by identifying possible airflow paths and the locations for air intake and exhaust. Natural ventilation needs to be integrated in the overall building design, especially in relation to area partitioning (shops, common areas, areas closed to visitors), air tightness, building geometry, and HVAC system and envelope characteristics. The path chart presented in Figure 16 helps in the definition of the most suitable ventilation strategy according to architectural features [1.21]. Nevertheless, depending on the climate and shopping centres typology, the variability of the architecture can open to different ventilation solutions. In relation to that the author conducted an analysis of the architectural features of shopping centres that influence and drive the selection of a ventilative cooling solution. Because a ventilative cooling strategy involves the whole building its selection is strictly dependent on building design and indoor spaces layout. Considering the internal layout and taking into account interconnected galleries and atria, number of levels and ceiling height and the location of parking areas, a decision scheme, shown in Figure 16, was created [1.21].

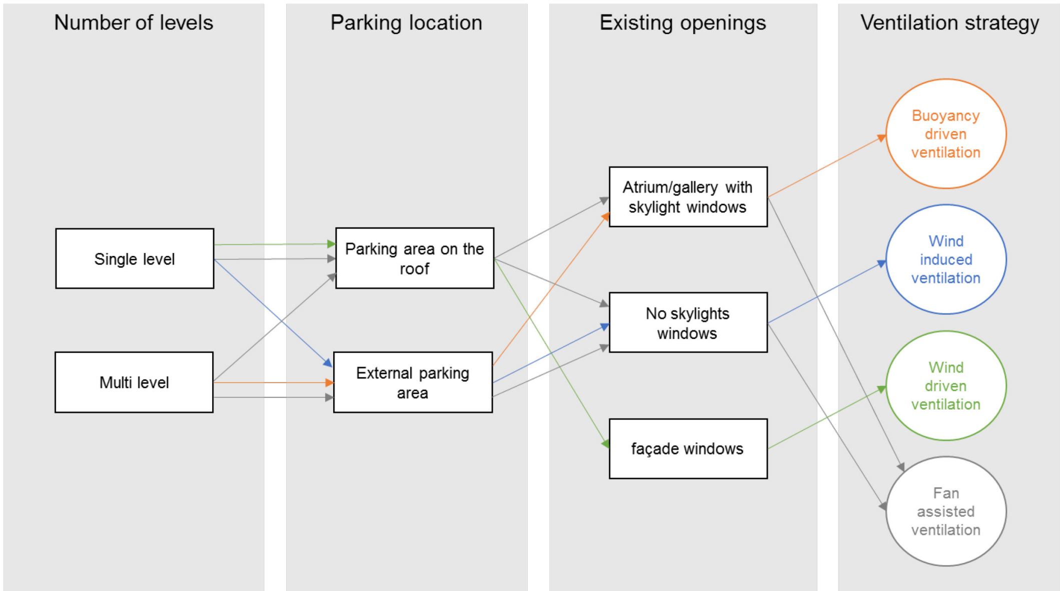


Figure 16 Path chart to identify the most suitable ventilative cooling system according to architectural features. Source: [1.21]

Further factors to be taken into account by designers when designing natural ventilation are:

- Urban regulation (historical, landscape...);
- Noise and pollution;
- Indoor comfort need;
- Responsibility on actual building indoor air quality;

- Aesthetic appearance;
- Building standard and regulations (acoustic, fire, zoning...);
- Safety;
- Operative and maintenance costs;
- Need to maintain building in operation during the retrofitting.

Those constraints depend on the design complexity. An integrated design process can however help in the identification and the overcome of such constraints. An integrated design process indeed foresees a continuous discussion and interface between the design team, building owner, energy manager and other actors directly involved, which should favour the design process.

At this stage the ventilation strategy is the output needed in order to go on in the design process.

2.1.3 Step 3&4 – Mixed-mode control strategy and performance analysis

Once the suitability in terms of climate and architectural integration and ventilation strategy is addressed, building simulations models give help in assessing the thermal, airflow and energy performance of the proposed solution. Considering that indoor areas of a shopping centre highly interacts among each other, a multi-zones based analysis of airflows is needed to evaluate the mixed-mode strategy effectiveness and to assess the potential energy savings.

Within the CommONEnergy project [1.8] activities a TRNSYS-based simulation environment namely Integrative Modelling Environment (IME) was developed [2.9]. It can be coupled with an airflow network model (Trnflow plug-in) that allows to solve the airflows throughout a building. Those kind of models have been proven to be effective in early design stages to assess energy savings and size building components [2.3].

Control strategies for the operation of both natural ventilation systems and HVAC systems need to be developed and tested. They can be implemented in the IME or in a generic modelling environment to test their effectiveness.

The control strategies has to be shaped accordingly to the necessity and objective of the specific shopping centre. As a general guideline, control strategies need to modulate the use of either natural ventilation and mechanical ventilation and cooling depending on the outdoor conditions, the level of comfort to be provided to users and common areas condition of use.

The author conducted a feasibility study for the conversion of the Donau Zentrum shopping centre[8] common areas into mixed-mode operation [2.10] which included the first four steps of the design procedure presented in Figure 14.

---

[8] The Donau Zentrum shopping center is one of the ten reference buildings of the CommONEnergy project [1.8].

In Donau Zentrum shopping centre, natural ventilation was already applied in the shopping centre common areas. The openable windows and skylights already presented (Figure 17) were however activated just on the basis of the energy manager judgment. A robust control strategy based on indoor-outdoor climatic condition, thermal comfort and building use was missing.

The author performed a feasibility study which aimed at defining and testing the thermal and economic performances of a new control strategy for the automation of the windows..

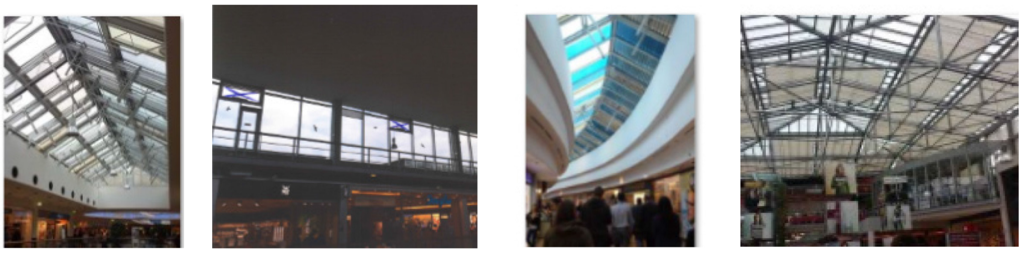


Figure 17 Pictures of the openable windows and skylights considered in the ventilation strategy [2.10]

The control rules for the mixed-mode operation of Donau Zentrum common areas have been developed taking into account both indoor and outdoor parameters. As a general guideline, the parameters that should be taken into consideration in the definition of the control strategies are:

- Indoor air temperatures in the common areas and outdoor temperatures;
- Minimum outdoor temperatures for the operation of the windows;
- Temperatures threshold for night cooling activation;
- Heating and cooling temperatures set-point;
- Common areas occupancy.

Based on the input conditions different operational modes were defined depending on the activation of the natural and mechanical ventilation systems and the active cooling system.
The mixed-mode control developed for Donau Zentrum includes four operation modes:

- MODE 0: during opening hours, when the outdoor temperature is below the minimum outdoor temperature for windows opening, T_{ext_min}, the minimum airflow rates are provided by mechanical ventilation and cooling demand is covered through mechanical cooling system;
- MODE 1: during opening hours, when the outdoor temperature is higher than the T_{ext_min} and when we are out of the heating season, the windows involved in the ventilation strategy are operated with a variable opening factor. When windows are operated, the HVAC system is off;
- MODE 2: out of the opening hours and between 3 a.m. and 6 a.m., if the temperatures inside the zones in the previous eight hours ($T_{zone\_avg\_8h}$) were higher than the threshold temperature for night cooling application (T_{set_NC}), natural night cooling can be operated. Under this mode, windows are used with maximum opening;

- MODE 3: during not occupied period and out of the interval between 3 a.m. and 6 a.m., just infiltration are considered, for all the year.

A scheme of the control strategy is reported in Figure 18 and detailed information about the control strategy can be retrieved in [2.10].

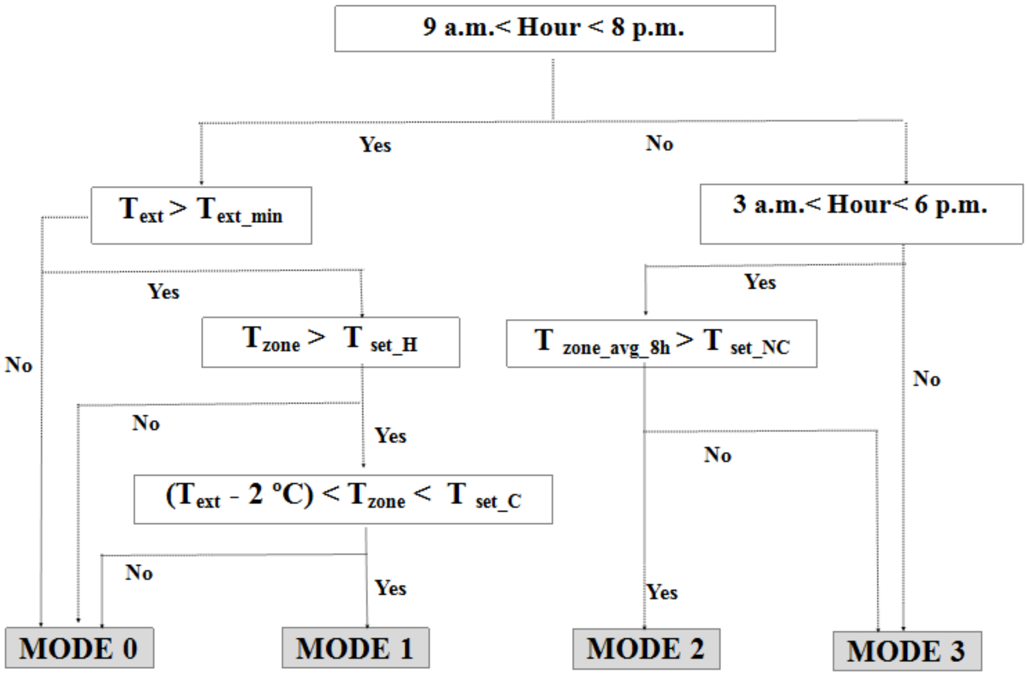


Figure 18 Control strategy scheme for mixed-mode ventilation in common areas in Donau Zentrum [2.10]

By potentially running the common areas with the new control strategy, the retrofitted Donau Zentrum can be then classified as a *changeover* mixed-mode building (see paragraph 1.3.1).The operation of the mechanical active system and natural ventilation is indeed disjointed.

Following the design process, once the control strategies are defined, they can be implemented in the building energy model in order to assess the performance in term of energy saving on cooling need, number of activation hours of the mechanical ventilation system and therefore electrical savings. The potential level of comfort provided to the users can be also assessed.

For Donau Zentrum shopping centre as example, the operational modes were implemented in the building energy model and the energy, thermal and airflow performance were tested. The simulation results showed that running the common area with a mixed-mode strategy, 265 MWh can be saved over a year, cutting by 23% the common areas electrical consumption. Figure 19 shows the simulated monthly electricity consumption of the mixed-mode solution in the common areas of Donau Zentrum in comparison with a fully-mechanical baseline. Considering an electricity price of 0.10 €/kWh, savings for around 26500 €/year are foreseen. With an estimation of initial investment cost of 100 € per window module or entrance door which takes into account of the connection of windows automation to a building management system, installation and engineering and permitting costs, the solution turns to be very cost effective. Over an expected working period of 25 year, the estimated Pay Back Time is less than one year (with a discount factor lower than 8%). Further information about the economic analysis assumption can be found in [2.31]. The whole feasibility study related to mixed-mode conversion of Donau Zentrum common area into mixed-mode operation can be retrieved in [2.10].

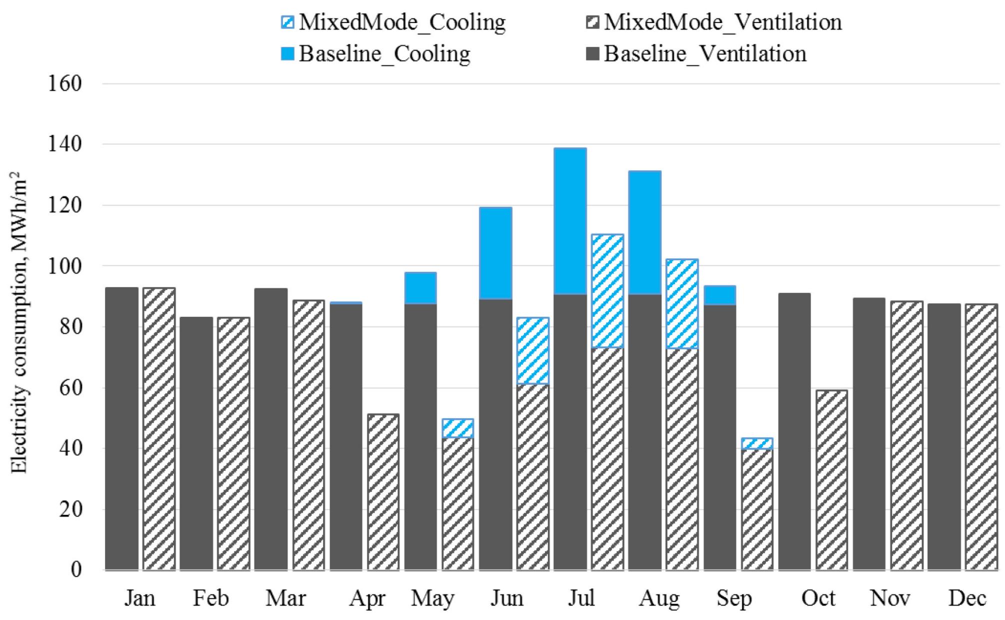


Figure 19 Monthly trend of electricity consumption for ventilation and cooling for Baseline scenario and Mixed-mode scenario [2.10].

2.1.4 Step 5&6 –Optimization and approval

At this stage, if the proposed solution does not accomplish regulation requirements, expected performance and initial goals, an optimization process should be performed.

The optimization process can involve either the design of additional airflow components, either the redefinition of control strategies, or both. The modelling environment is a powerful tool at the optimization stage since it allows to test and compare different solutions. An iterative process leads indeed to the identification of the optimal retrofitting solution. The modelling results are used as basis for discussion with the building owner and/or the energy manager of the shopping center. It is important that the optimization process is supported by an economic analysis since the return of the investment is one of the driving force in the decision process.
The design of mixed-mode solution for Mercado dal Val [1.21] is a valid example on how this interaction and discussion between owners, architects and building physics consultant was successful for the identification of the cost-effective retrofit solution.

2.1.5 Step 7 – Implementation and commissioning

Once the retrofit solution is approved by the shopping centre owner and energy manager, the implementation phase can start.

Depending on the level of retrofit, this phase could simply regard the implementation of the new control strategies in the Building Management System (BMS) as for City Syd shopping centre [1.20] or the implementation of airflow components as openable windows and actuators as for Mercado del Val [2.11].

The implementation phase need to be followed by a commissioning period in order to verify that the building is operated and it performes as designed and expected. This phase is crucial for the whole success of the mixed-mode retrofit solution. It can happen indeed that, if not operated in the right way, mixed-mode building does not perform as expected, resulting in extra energy cost. The benefits of the commissioning phase involve not only the proper operation of the building itself and the occupants but also the designers that can easily rectified some operational issue hard to estimate during the design.

According to Lomas et al. [2.12], commissioning trials are valuable because an "*accurate communication between design team members that achieves real mutual understanding is more difficult*". This can also reflect in gained experience exploitable in the next design projects. Also Ray et al. [2.13] stressed the importance of commissioning "*Extended commissioning of the NV system is highly recommended to ensure all system components work properly and the building control system accurately follows the designed control algorithm. Since the NV system relies on natural driving forces that vary throughout the year, it should be commissioned in each season. Even if it will not be used in the winter, the NV system should be inspected to ensure all openings are properly sealed and remain closed and that no unexpected drafts occur in the building due to airflow paths"*.

The conversion from fully mechanical to mixed-mode operation of shopping centre common areas is further encouraged by the new findings related to thermal comfort in shopping centres common areas which are going to be summarized and discussed in chapter 4.

All the considerations about mixed-mode retrofit solution for shopping centres can be broaden to all the building typologies with the same features e.g. airport, educational buildings.

2.2 Acknowledgements

The research leading to these results about DonauZentrum shopping mall has received funding from the European Community's Seventh Framework Programme (FP7/2007-2013) under grant agreement n° 608678. I would like to thank Drazen Ivanis and Sojka Ratislav, technical managers of the Donau Zentrum shopping centre, for their help and collaboration.

Bibliography

[2.1] BPIE. Europe´s buildings under the microscope, A country-by-country review of the energy perfomance of buildings .2011

[2.2] Schönberger, H. (2013). Best Environmental Management Practice in the Retail Trade Sector, European Commmission, Joint Research Centre-Institute for Prospective Technological Studies, Pubblications Office of the European Union, Scientific and Technical Research Series- ISSN 1831. Luxemburg

[2.3] A. Belleri. Integrated desing methods for natural ventilation.PhD final dissertation.Università degli Studi di Bergamo.2014 http://hdl.handle.net/10446/30436

[2.4] Cambronero Vàzquez M.V., A. Belleri, M.Avantaggiato, C. Dipasquale, J.A. Gutierrez, M. Haase, K.S. Skeie. D5.1-Systemic solution-sets; CommONEnergy project (FP7-2013 grant agreement no 608678). 2017

[2.5] Avantaggiato M., Belleri A., De Carli M., Lollini R. Ventilative cooling strategies to reduce cooling and ventilation needs in shopping centres. Madrid 2015. 36th AIVC Conference, 5th TightVent Conference, 3rd Venticool Conference. pp. 633-644. Madrid 2015

[2.6] Belleri A., Psomas T., Heiselberg P. Evaluation tool of climate potential for ventilative cooling. 36th AIVC- 5th TightVent- 3rd venticool. Madrid, 2015

[2.7] Bointner R., Toleikyte A.. Deliverable 2.1 Shopping mall features in EU-28 + Norway.; Environment; CommONEnergy project (FP7-2013 grant agreement no 608678). 2014

[2.8] A. Belleri, M. Avantaggiato, T. Psomas, P. Heiselberg, Evaluation tool of climate potential for ventilative cooling, International Journal of Ventilation, Pages 1-13, 25 October 2017 https://doi.org/10.1080/14733315.2017.1388627

[2.9] Dipasquale C., Belleri A., Lollini R. D4.1-Integrative Modeling Environment; CommONEnergy project (FP7-2013 grant agreement no 608678). 2016.

[2.10] M. Avantaggiato, A. Belleri, M.De Carli, R. Lollini. Mixed-mode ventilative cooling opportunity for an existing shopping mall retrofit. 38th AIVC Conference-7th TightVent- 5rd venticool, 2017,pp 816-826, 13-14th September Nottingham, United Kingdom

[2.11] Belleri, M. Avantaggiato, R. Lollini, Ventilative cooling in shopping centers' retrofit: the Mercado del Val case study, Energy Procedia, Volume 111, March 2017, Pages 669-677 https://doi.org/10.1016/j.egypro.2017.03.229

[2.12] LOMAS, K.J., COOK, M.J. and SHORT, C.A., 2008. Commissioning hybrid advanced naturally ventilated buildings: a US case study. 5th Windsor Conference of the Network-for-Comfort-and-Energy-Use-in-Buildings on Air Conditioning and the Low Carbon Cooling Challenge, Cumberland Lodge, Windsor, UK, 27-29 July 2008

[2.13] Ray, Stephen D., Masashi Fukuda, Maria-Alejandra Menchaca-Brandan, Iwao Hasegawa, Leon R. Glicksman, and Natsuko Ochiai. "Overview of Hybrid Ventilation Control System and Full Scale Monitoring." ASHRAE Transactions. 2013, Vol. 119 Issue 2, 1-8.

3 Thermal comfort in transitional spaces

We spend 90% of time in indoor spaces. Indoor environment has a great impact on occupants, including their productivity, health and emotion etc [3.1].This is a fact easy to believe. Therefore, designing a high quality internal space is a driving pattern in modern architecture. It is well-agreed in the international scientific and design community that thermal comfort is essential aspects of the indoor environmental quality.

This chapter gives an overview of indoor thermal comfort model used for building design. In the final part a literature review of the main studies about transitional spaces of the last fifteen years is presented. The contents are preparatory for the study about thermal comfort in shopping mall transitional spaces which will be later presented in chapter 4.

3.1 Definition of Thermal comfort

Thermal comfort is a state people strive for when they feel discomfort and it influences behaviour. When comfortable conditions are reached, there will be the minimum drive for change.

The reasons why a person reports thermal comfort (or discomfort) or related feelings of warmth, freshness, pleasure and so on are complex and not fully understood. What is demonstrated is that thermal environments affect such feelings. When thermal comfort conditions are not achieved people may complain, health and productivity may be affected and workers may refuse to work in an environment that they judge uncomfortable [3.2],[3.3]. For these reasons, in the twenty-first century research and society interests has been the understanding of the conditions that produce thermal comfort and acceptable environment [3.2].

An international recognized definition of thermal comfort can be found in the European standard EN ISO 7730 [3.4] which settles thermal comfort as “that condition of mind which expresses satisfaction with the thermal environment”. For the American standard (American Society of Heating, Refrigerating and Air-Conditioning Engineers-ASHRAE) thermal comfort is defined as “the condition of the mind in which satisfaction is expressed with the thermal environment” [3.2].

Personal difference such as mood, culture and other individual, organization and social factors affect thermal comfort. The judgment of comfort or not is a cognitive process involving many inputs influenced by physical, physiological, and other factors

Clearly, subjects' diagnosis of the experienced environment is an indispensable tool for thermal comfort assessment [3.5]. Most of the times thermal comfort studies, both in controlled environment (climatic chambers) and fields' studies, involve human subjects, investigating their thermal sensation, comfort and preference under different indoor conditions.

3.2 Other important definitions

3.3.1 Thermal sensation and Comfort temperature

Thermal sensation of people is quantified through the ASHRAE seven-point thermal sensation vote (TSV) scale. The mean thermal sensation vote of a group of people in neutral temperature is neutral or at the middle point of the seven-point thermal sensation scale (Table 2).

Table 2 ASHRAE seven-point thermal sensation scale[3.2]

-3	-2	-1	0	1	2	3
cold	cool	slightly cool	Neutral	slightly warm	Warm	hot

Comfort temperature is the temperature at which the subjects express comfort feelings voting with the three middle categories of the comfort scale (Table 2). Therefore the comfort temperature can be the same as the neutral temperature.

Nevertheless, there could be a difference between the neutral temperature and what a group of people may prefer. McIntyre [3.6] found indeed that the preferred temperature of a group of people might be below or above middle category (neutral). Later in 2007, Humphreys and Hancock [3.7] portrayed this discrepancy explaining that "*people prefer sensation on the warm side of neutral if it is warm indoors and cool outdoors, while they prefer sensations cooler than neutral if it is warm outdoors and cool indoors*". Information about the preferred temperature can be gained using the McIntyre or 3 three-point scale. The subject is asked to rate how he/she would like to be in that moment between Cooler, No Change and Warmer [3.6].

Generally people who voted in the three central categories (-1,0,1) of the seven-point thermal sensation scale are assumed to accept the thermal environment and therefore to be in comfort [3.6].This method of thermal comfort assessment is widely used especially when direct interview of people is considered.

ASHRAE standard 55 defines an acceptable thermal environment as one that satisfies at least 80% of the occupants [3.2].

3.3.2 Thermal neutrality

Thermal neutrality is defined as the situation in which subject would prefer neither warmer nor cooler surroundings [3.1]. When people judge the environment they experience as neither too cold nor too warm, they are in a neutral condition and no feeling of discomfort are felt.

According to Liu et al.[3.8], a period of at least 30 minutes need to be considered to reach a new state of neutrality when experiencing a change in the thermal environment or when moving between two environments with different thermal characteristics. During this period, thermoregulation processes act and people gradually adjust to the change in thermal condition. According to Nagano et al. [3.9] it takes 50 min to achieve a new steady state conditions after experiencing a temperature step from hot to neutral.

If in simple term we refer to the variation of the thermal sensation over time as a way to assess the achievement of a steady state condition, the considered period of acclimatization[9], after a change in thermal condition, can be notably reduced. This is what come out from the results presented by Chen et al. [3.10]. In this study, a sample of people was asked to assess their thermal sensation every two minutes for a period of 20 minutes, experiencing an indoor temperature of 24ºC. In the previous 30 minutes the sample was exposed to a simulated outdoor environment of 32 ºC, 28 ºC and 20 ºC. The thermal sensation trends, reported in Figure 20, show that around 10 minutes are sufficient for a thermal sensation stabilization, for all the three preconditioning conditions. The variation of the thermal sensation, namely *thermal sensation overshoot phenomenon,* is what happen within the first two-three minutes of exposition to the indoor environment. Within this time frame a sudden variation of thermal sensation is observed.

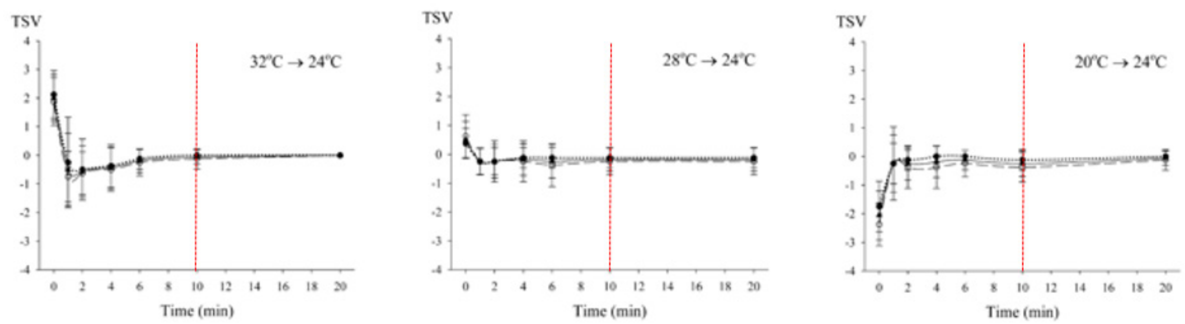


Figure 20 Change in thermal sensation vote (TSV) over time in response to temperature steps from 32 ºC (left), 28 ºC (middle), and 20 ºC(right) to 24 ºC [3.10].

3.3 Thermal comfort approach

In term of indoor thermal comfort, two different approaches exist:

- Rational or heat-balance approach, based on laboratories and chamber studies;
- The adaptive approach, based on field studies.

3.3.3 The rational or heat-balance approach

The rational or heat-balance approach is the steady-state model developed by Fanger in the 1970s for air-conditioned spaces. It is based on the heat balance model of the human body. Heat is generated in the body and lost from skin and lungs. It is then transferred through clothing where it is lost to the environment. Heat balance conceptual equation can be expressed in the following way:

---

[9] or acclimation if referred to climate-chamber studies

$$F(v_a, I_{cl}, T_a, T_{mr}, \varphi_a, M) = 0$$

Air temperature (T_a), air speed (v_a), mean radiant temperature (T_{mr}), relativity humidity (φ_a) are the environmental variables, while thermal resistance of clothing (I_{cl}) and metabolic activity are subjective variables.

Fanger's model [3.1] aims to predict the mean thermal sensation of a group of people and their respective percentage of dissatisfaction with the thermal environment. It is expressed through the indices Predicted Mean Vote and Predicted Percentage Dissatisfied (PMV–PPD). PMV is calculated through six variables: metabolism, clothing, indoor air temperature, indoor mean radiant temperature, indoor air velocity and indoor air humidity which are the ones presented in the heat balance model.

Fanger's experiments were conducted in controlled climate chamber on 1296 young students (in USA at the KSU[10] and in Denmark at the DTU[11]). Participants were dressed in standardized clothing and completed standardized activities, while exposed to different thermal environments. While exposed to different thermal environments the participants were asked to state their thermal sensation using a seven-point scale (Table 2).

Based on experimental data, Fanger was able to derive an equation to express the PMV index stating the six variable before-mentioned and an empirical relationship between PMV and the predicted percentage of dissatisfied (PPD), which graphical expression is shown Figure 21.

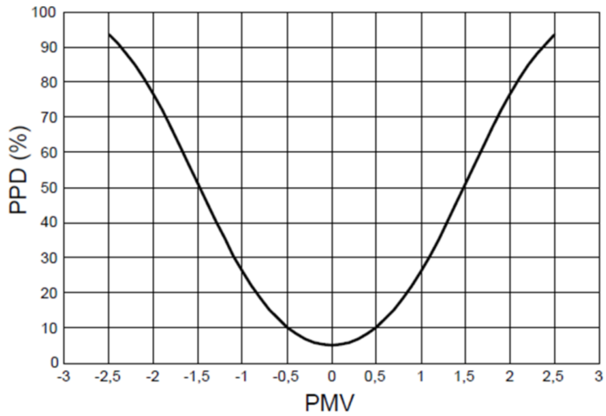


Figure 21 Relation between PMV and PPD [3.4]

Considering a group of people, thermal neutrality happens when PMV index is equal to 0. Nevertheless, from the experimental studies came out that, even under general neutral condition (PMV=0), there were some individual cases of dissatisfaction with the indoor environment. Although all participants were dressed in a similar way and with same level of activity, perception was different from one person to another. PMV-PPD relationship takes into account of this evidence considering a 5% minimum rate of dissatisfied at PMV=0 while at PMV=± 0.5, comfort range, a 10% dissatisfied is accounted (Figure 21).

Fanger's PMV-PPD model on thermal comfort has been a path breaking contribution to the theory of thermal comfort and to the evaluation of indoor thermal environments in buildings.

---

[10] Kansas State University

[11] Denmark Technical University

As reported in a recent publication [3.12], a memorial of his contribution on thermal comfort research, Fanger's research started by "*recognizing that existing knowledge of thermal comfort was quite inadequate and unsuitable for practical applications and that the creation of thermal comfort for man is one of the principal aims in environmental engineering and indeed in the entire heating and air-conditioning industry*". Ten years after his death, his theory is still widely used and accepted for design and field assessment of thermal comfort for mechanically conditioned indoor environment. PMV-PPD method is indeed on the basis of the ISO 7730 [3.4] and ASHRAE 55 [3.2] standards which are used in practice.

3.3.4 Adaptive approach

In the late 90s the adaptive approach arose from dissatisfaction linked with the narrow band of temperature controls used in building as consequence of the static comfort model (PMV). This way of controlling indoor environment was not anymore in line with the renewed interest in climate-responsive and energy-conserving building designs.

According to this approach, building occupants are not passive recipient of the thermal environment but they play an active role in creating their own thermal preferences. They adapt themselves to the indoor condition in order to reach a comfortable condition. Therefore, if there is any discomfort due to changes in the thermal environment, people would tend to act to restore their thermal comfort. This turned to be even more relevant in naturally ventilated buildings, were occupants can operate windows as possible measure to reach "satisfaction with the thermal environment". This new approach, widely spread with the studies of Nicol and Humphreys [3.13] and De Dear and Brager [3.14], was proved by means of fields' studies.

Three different categories of adaptation were introduced [3.14]:

- *Physiological adaptation* (in terms of acclimatization);
- *Psychological adaptation* refers to the effects of cognitive, social and cultural variables, and describes how and to what extent the habits and expectations might change people's perceptions of the thermal environment. Psychological adaptations are identified as playing a significant role in explaining the difference in responses in air-conditioned versus naturally ventilated buildings;
- *Behavioural adaptation* is by far the most dominant factor in offering people the opportunity to adjust the body's heat balance to maintain thermal comfort. The adaptation may go from changing the activity and clothing levels and/or opening/closing windows and switching on fans.

By collecting actual votes from fields' studies in 160 office building (located in 9 countries- 4 continents) the ASHRAE RP-884 database was created [3.15]. From the collected data linear regressions relating indoor operative temperatures to pre-vailing outdoor air temperatures were established, differentiating between buildings with centralized HVAC and ones naturally-ventilated. Figure 22 shows how the static PMV model works well in air-conditioned buildings but definitely not in naturally ventilated ones.

In 2004 the adaptive thermal comfort model was introduced in the ASHRAE 55 as optional method for evaluating naturally ventilated buildings.

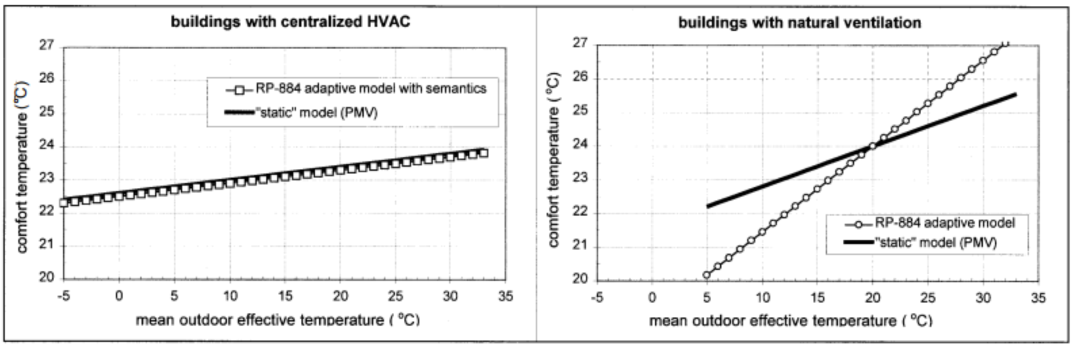


Figure 22 Comparison of the RP-884 adaptive models' predicted indoor comfort temperatures with those predicted by the static PMV model [3.15]

In 2007 the adaptive model also landed in Europe standards with its introduction in the EN 15251[3.16]. The model was developed within the SCATs project [3.17]. Data from field studies in 26 office buildings located in 5 countries within Europe where collected in a database.

Findings from the field studies on adaptive models have unlocked important energy use implications. The direct interview of people in their usual "habitat" have revealed an increased range of temperature acceptability, because of the adaptation measures that can take place. The acceptance of higher indoor temperatures in summertime conditions lead to less prevalence use of cooling systems. And even in situations/locations where air conditioning is unavoidable, a wider range of indoor thermal comfort conditions would mean less cooling demand and hence less electricity consumption for the air conditioning systems.

3.4 Previous findings on transitional spaces

In paragraph 1.1, the main features of transitional spaces have been presented. Their differences from a typical indoor environment such as offices or educational buildings were underlined. Thermal comfort research traditionally focuses on either the indoor environment of buildings or outdoor comfort. Thermal comfort research in buildings assume steady-state conditions, while in real condition the thermal environment is often transient and dynamic over time. Little has been discussed in previous work about people's thermal perception and comfort standard in indoor transitional spaces, where transient and dynamic conditions happen.

Literature review discloses indeed few studies on thermal comfort in transitional spaces. As a consequence, current comfort standards do not clearly address this kind of spaces treating them as typical indoor spaces. It should be considered that these spaces are frequently placed in the perimeters of buildings with large glazed areas. Because of their characteristics, they also experience significant air change with outdoor climatic conditions. Therefore, for reaching the same comfort level, it is truly credible that transitional spaces consume more energy than the other part of building of similar size [3.18] . According to Pitts and al.[3.19] the energy demand of transitional spaces per unit area or volume may be three times as high as that of the remaining of the building interior. Understanding real comfortable conditions also in these spaces is essential for facing the European building energy reduction challenge. Table 3 collects studies related to thermal comfort in transitional spaces in the last fifteen years. Only field studies have

been selected because representative of transitional spaces peculiar conditions which disclose in real operation.
The common methodological approach is to combine objective measurements and subjective questionnaire.

Table 3 Field studies related to transitional spaces

Author	Building typology	Research Method	Location	Year	Ref
Jitkhajornwanich et al.	Educational building, Office	Questionnaire Physical Measurements	Bangkok, Thailand	2002	[3.22]
Chun et al.	Lobbies, Balconies, pavilions	Physical Measurements (long & short term) Observation (activities)	Yokohama, Japan	2004	[3.20]
Pitts et al.	Educational Buildings	Questionnaire Physical Measurements	Sheffield, UK	2008	[3.19]
Hwang et al.	Entrance Atrium. Service center	Questionnaire Physical Measurements	Taichung, Taiwan	2008	[3.23]
Kwong et al.	Lobby-Educational Building	Questionnaire Physical Measurements CFD simulations	Serdang, Malaysia	2009	[3.18]
Hui and Jie	Lift lobbies corridors Educational building	Questionnaire Physical Measurements Energy simulation tool	Hong Kong	2014	[3.21]
Kotopouleas A., Nikolopoulou	Airport Terminal	Questionnaire Physical Measurements	Manchester London, UK	2016	[3.24]
Mishra et al.	Museum	Questionnaire Physical Measurements	Amsterdam, Netherlands	2016	[3.25]
Vargas	Lobby	Questionnaire Physical Measurements	Sheffield, UK	2016	[3.26]
Hou	Atria - Educational buildings, Business Center	Questionnaire Physical Measurements	Cardiff, UK	2016	[3.27]

Chun et al [3.20] gave a literature review trying to address transitional spaces and setting order between the terms *transitional* and *transient*, often used indistinctly by researches to address environmental condition within these spaces. They defined the *transitional* zones as “in between” architectural spaces where the indoor and outdoor climate is modified, without mechanical control systems and the occupant may experience the dynamic effect of this change. In transitional spaces, *transient* conditions are meant as a consequence of outdoor conditions. They defined three transitional space typologies, with different proximity to the indoor space, and performed pilot physical measurements. None of the case studies was mechanically conditioned. The typical behaviours they observed were walking, standing, and sitting which are different and varied compared to the sedentary behaviour in offices or homes. They concluded that PMV cannot be used for transitional spaces thermal comfort prediction because of its unstable and dynamic physical and MET value. They also observed that the most efficient architectural shape of transitional spaces is related to the corresponding regional climatic condition. In general transitional spaces can help to relieve the thermal shock to humans and reduce the energy loss.

In 2008, at the 25th Conference on Passive and Low Energy Architecture, Pitts et al. [3.19], presented a further study related to thermal comfort in transitional spaces and its energy implications. 120 occupants of six buildings located in UK were interviewed whilst passing through transitional spaces.

While physical measurements were recorded (air temperature, mean radiant temperature, relative humidity and air velocity) occupants were asked about their thermal sensation, preference and comfort. The study highlighted how users were inclined to accept less stringent environmental conditions, compared to the one predicted by the PMV model. The causes were unclear but speculated by several factors as the fact of non-equilibrium conditions because of the movements within the spaces. Also users were still influenced by the previous place and were not concerned about the upcoming environment because of the awareness they would be moving into a further zone within a short space of time. Based on this evidence the authors suggest to expand the PMV limit for transitional spaces beyond the conventional indoor limit of ±0.5. The impact of widening effective PMV boundaries for transition spaces would be reductions in winter heating demand and summer cooling demand.

Hui and Jie [3.21] studied semi-opened and fully enclosed lift lobbies and corridors in The University of Hong Kong (HKU) campus. Environmental parameters related to the body thermal balance were measured at 1.1 m above the floor level in the centre of each site. The results obtained from the objective measurements were tabulated and applied for the calculation of PMV and PPD and compared with the information gathered with the questionnaires. This study also disclosed that people can accept a wider range of thermal environmental conditions. Their thermal responses varied with dressing, activity level, past thermal experience and prior thermal preference. According to the authors changes in the current design guidelines and standards could be beneficial. And they conclude, "*If the transitional spaces are designed with appropriate energy saving strategies such as passive design, hybrid ventilation and flexible HVAC controls, it can help achieve more energy efficient and healthy buildings in the future*".

Jitkhajornwanich et al.[3.22] performed a field study in buildings in Bangkok, Thailand. They selected four groups of people: those moving from external environments into both air-conditioned and naturally ventilated transitional spaces, and those going outdoors from the same environments. From the thermal comfort assessment of whole sample group, they reported a neutral temperature of 27.1ºC in the cool season, and of 26.5ºC in the warm season.

By observing that in previous studies on transitional spaces only guests were interviewed, Hwang et al. [3.23] decided to investigate if differences between guests and staff occur.
In a time frame between June and September both guests and staff of a service center located in Taichung (Taiwan) were surveyed about their thermal sensation, thermal preference, and thermal acceptability. The service centre was air-conditioned with a centralized HVAC system. The results showed that the guests and staff had the same span for comfortable zone. Moreover, the PMV-PPD model seems to accurately estimate the percentages of unacceptability for both guests and staff. Within the considered study, this is [3.23] the only one to accept the applicability of the PMV-PPD model for transitional spaces.

A similar study was recently conducted in three UK airport terminals investigating both passengers and terminal staff [3.24]. Passengers demonstrated higher tolerance of the thermal conditions and consistently a wider range of comfort temperatures, whereas the limited adaptive capacity for staff allowed for a narrower comfort zone. As a consequence of these results, the authors indicate little scope for increasing the cooling systems set-points in summer and suggest alternative methods. They however identified a greater potential for energy savings by lowering the heating set-points. As a final consideration they suggest more flexible dressing codes for staff to improve their thermal comfort.

The theme of the changing thermal comfort level according to time spent within a transitional space is faced by Mishra et al.[3.25]. The study was performed in a museum located in Amsterdam. They analysed the subjective thermal comfort responses of users to bring to the fore any underlying trends and differences for visitors who had spent different durations of time indoors. They observed that for the first 20-30 minutes, visitors still retained a connection with the outdoor environment. According to the authors, the discernment of this buffer period in buildings open up possibilities for flexible and less energy intensive indoor conditioning. As examples, if the entrance area "*are conditioned in manner so as to "encourage" visitors to modify their clothing ensembles more in accordance with the settings being maintained"* in the bulk of the building, substantial energy savings can be reached throughout the year.

The effect of thermal sequences on users' thermal comfort was investigated by Gloria Vargas in her Doctoral Thesis [3.26]. She studied how the use of a lobby space could positively modify people's short thermal history by analysing temperature order, people's thermal direction, and temperature changes when people move from the outdoor to an interior seminar room. She concluded that "*an appropriate temperature order in spatial connections can positively conduct people towards a gradual thermal adaptation in the short term, allowing a reduced set temperature in AC buildings and consequently reducing energy demand*"

In 2016 another Doctoral thesis related to transitional spaces have been released. Guoying Hou [3.27] investigated thermal comfort requirements and the use of three transitional spaces located in Sheffield, United Kingdom. The method is still the combination of objective and subjective measurements. He demonstrated how that heat balance indices (PMV) cannot explain the thermal preferences of subjects in UK climates. The predicted percentage of dissatisfied people (PPD) was always higher that the real conditions. This provides evidence that people in indoor transitional space have a higher tolerance of their thermal environment. Operative temperature appeared to be the most important predictor of thermal sensation in three cases.

The main findings of literature review of the field studies on transitional spaces in the last fifteen years can be therefore summarized:

- the approach that combine measurements of environmental parameters affecting thermal comfort with direct interview of users is the one mostly followed;
- transitional spaces are independent dynamic spaces with various physical conditions and behaviour [3.20] which may that have different thermal comfort requirements;
- because of their dynamic features, the Fanger's model based on steady-state conditions seems to overestimate the discomfortable condition with respect of the real perception of transitional space users (with the exception of the study conducted by Hwang et al. [3.23]);
- people in indoor transitional space have a higher tolerance of thermal environment which reflect in the possibilities in more relaxed set-point temperatures with consequent air-conditioning energy savings;

- further investigation at different time of the year are required in order to expand the database of evidence.

Bibliography

[3.1] P.O. Fanger. Thermal Comfort : An Analysis and Application in Environmental Engineering, Danish Technical Press, Copenhagen, 1970

[3.2] ASHRAE Standard 55. Thermal Environment Condition for Human Occupancy. American society of Heating, Refrigeration and Air-Conditioning Engineers. Atlanta, 2010

[3.3] D.P. Wyon, P.Wargocki. How indoor environment affects performance Ashrae J., 55 (2013), pp. 46-52

[3.4] EN ISO 7730. Ergonomics of the thermal environment – Analytical determination and interpretation of thermal comfort using calculation of the PMV and the PPD indices and local thermal comfort criteris, International Standards Organization, Geneva, 2005

[3.5] Djongyang N.,Tchinda R.NjomoD. Thermal comfort: A review paper. Renewable and Sustainable Energy Reviews 14 (2010), 2626-2640,

[3.6] D.A. McIntyre. Indoor Climate. Applied Science Publishers, London. 1980

[3.7] M.A. Humphreys, M. Hancock. Do people like to feel ‘neutral’?: exploring the variation of desired thermal sensation on the ASHRAE scale. Energy Build 39 (7), pp. 867-7. 2007

[3.8] H. Liu, J. Liao, D. Yang, X. Du, P. Hu, Y. Yang, B. Li. The response of human thermal perception and skin temperature to step-change transient thermal environments. Building and Environment 73 (2014) 232-238.

[3.9] Nagano K, Takaki A, Hirakawa M, Tochihara Y. Effects of ambient temperature steps on thermal comfort requirements. International Journal of Biometeorology 2005;50:33-9.

[3.10] C-P Chen, R-L Hwang, S-Y Chang, Y-T Lu. Effects of temperature steps on human skin physiology and thermal sensation response. Building and Environment 46 (2011) 2387-2397

[3.11] H. Zhang, Human thermal sensation and comfort in transient and non-uniform thermal environments, PhD thesis, University of California, Berkeley, 2003.

[3.12] D’Ambrosio Alfano F.R., Olesen B.W., Palella B.I. Povl Ole Fanger’s impact ten years later. Energy and Buildings 152 (2017) 243-249

[3.13] Nicol F., Humphreys M., Roaf S., Adaptive Thermal Comfort: Principles and Practice, Routledge, Abingdon, 2012.

[3.14] De Dear, R.,Brager, G . Developing an adaptive model of thermal comfort and preference. ASHRAE Transactions. 104 (1): 145–67, 1998

[3.15] R. de Dear, G. Brager, D. Cooper, Developing an adaptive model of thermal comfort and preference, in: Final Report ASHRAE RP-884, 1997

[3.16] ISO EN 15251. Indoor Environmental input paramenters for design and assessment of energy perfomance of building addressing indoor air quality, thermal environment,lighting and acustics.2008

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

[3.18] Kwong, Q. J., Tang, S.H., Adam, N. M. Thermal comfort evaluation of the enclosed transitional space in tropical buildings: subjective response and computational fluid dynamic simulation, Applied Sciences, 9(19), 3480-3490.2009

[3.19] Pitts A. , Bin Saleh J., Sharples S. Building Transition Spaces, Comfort and Energy Use. PLEA 2008- 25th Conference on Passive and Low Energy Architecture, Dublin, 22nd to 24th October 2008, Paper No 591

[3.20] Chun C., Kwok A., Tamura A. Thermal comfort in transitional spaces - basic concepts: literature review and trial measurement. Building and Environment,(2004) 1187-1192.

[3.21] Hui, S. C. M. and Jiang, J., 2014. Assessment of thermal comfort in transitional spaces, In Proceedings of the Joint Symposium 2014: Change in Building Services for Future, 25 Nov 2014, Kowloon Shangri-la Hotel, Tsim Sha Tsui East, Kowloon, Hong Kong, 13 pp.

[3.22] Jitkhajornwanich K, Pitts A. Interpretation of thermal responses of four subject groups in transitional spaces of buildings in Bangkok.Building and Environment 2002;37:1193–204.

[3.23] Hwang R.L., Yang K-H.,Chen C-P.,Wang S-T. Subjective responses an comfort reception in transitional spaces for guests versus staff. Building and Environment, 2008. 43(12): p. 2013-2021.

[3.24] Kotopouleas A., Nikolopoulou M.. Thermal comfort conditions in airport terminals: Indoor or transition spaces? Building and Environment 99 (2016), 184-199

[3.25] Mishra A. K., Kramer R.P., Loomans M.G.L.C., Schellen H.L. Development of thermal discernment among visitors: Results from a field study in the Hermitage Amsterdam. Building and Environment 105 (2016), 40-49

[3.26] G.A .Vargas Palma. Short-term thermal history in transitional lobby spaces. The University of Sheffield. Faculty of Social Sciences. School of Architecture. November 2015

[3.27] G. Hou. An investivation of thermal comfort and the use of indoor transitional spaces. Thesis for the degree of Doctor of Philosophy. Cardiff University.2016

4 Thermal comfort in shopping centres transitional spaces

4.1 Introduction

Large shopping centres are based on a model of small individual stores connected by common areas. These walkways enable customers to move from a shop unit to another staying in the indoor. They can be shaped as galleries, atria or in a sort of ring, as shown in Figure 23, and can be located on a single level or connect multiple levels. Shopping centres common areas possess all the characteristics of transitional spaces described in chapter 1 .

Figure 23 Clockwise, from top left: shopping mall plants of Katané (Gravina di Catania, CT) and Donau Zentrum (Wien),interior of Donau Zentrum [Unibail-Rodmanco] and large atrium of Katané

Use of common areas is not constant but affected by the high variability of people walking through them. Observed users' activity is dynamic even though the permanence period deeply differ depending on the motivation in visiting the shopping centre. This creates a very unstable and variable occupancy.

Generally, shopping centres are conditioned by means of basic all-air HVAC systems that can handle both the individual stores and the retail units, or have separate individual systems for each of the retail units. In both cases, the temperature set point inside the single shops are controlled by managers or workers. Most of the time this results in indoor temperature that are different from the temperature experienced in the common areas. This means that by moving within the shopping centre, customers experience several temperature differences.

Moreover, the indoor temperatures experienced by the customers are generally independent from the actual outdoor temperature conditions. Indoor air temperature set-points are based on guidelines intended for more traditional indoor environment, or set up based on the experience of the system manager. The variability in term of clothes worn by customers and their activity is not taken into consideration, sometimes resulting in discomfort conditions throughout the year.

Nevertheless considering their features, common areas, as other typology of transitional spaces analysed in paragraph 1.1, may not require the same high level and close control as indoor or fully occupied areas. A more relaxed range of interior conditions may be allowed without compromising (or improving) customers' comfort.

According to Coleman [4.1] customers who feel comfortable will shop longer and spend more. This proves the importance of customers' thermal comfort also from profit point of view. The no profit association GreenSense has released the results of a survey conducted in ten shopping malls in Hong Kong [4.2]. The study is part of a so-called "awareness raising project" with the aim to let drop the common idea of shopping mall managers that "colder the better". The results of the study have indeed disclosed that one third of the interviewed customers would leave a shopping centre if the conditions inside are judged "too cold". According to the authors the judgement derives from a direct comparison with the previous experienced temperature, usually the outdoor one. Furthermore, high temperature steps between inside and outside not only create potential discomfort conditions but also generate a not necessary waste of energy. Indoor temperatures and indoor-outdoor temperatures steps affect the time customers spend inside the shopping centre and consequently on the probability of shopping. The connection between thermal comfort and shopping centre profit, indicates that improving the first, the beneficial effect will be recovered on the second.

In 1998 Chun and Tamura presented comparative results of a thermal comfort field study in underground shopping mall and department store in Japan [4.3]. The objective was to assess any difference in thermal comfort requirements between the two typologies. They found that customers were more tolerant about indoor condition in underground shopping mall than in the department store. No others studies related to shopping mall were found in literature in the past twenty years.

To date, no current guidelines on thermal comfort have been identified that are specific to transitional spaces. Being integral part of the building architecture, their HVAC design and control follows guidelines intended for indoor space, even though the utilization conditions differ from a common indoor space. In Table 4 the recommended design criteria for department stores according to standards are presented.

Moving from one shop to another, shopping centres' customers experience different indoor temperatures. It is important to avoid excessive temperature steps that may cause thermal discomfort. The investigation of optimal outdoor-indoor temperature differences based on customers actual thermal perception will lead to a better control of air conditioning inside transitional spaces and to the exploitation of natural ventilation with sub sequential potential energy saving.

Table 4 Recommended design criteria for department stores

	EN 7730			EN 15251		
		Operative temperature, ºC			Operative temperature, ºC	
Department store Standing walking- 1.6 met	Category	Winter (heating season)	Summer (cooling season)	Category	Maximum for heating (winter season)- 1.0 clo	Maximum for cooling (summer season)- 0.5 clo
	A	19.0 ± 1.5	23.0 ±1.0	I	17.5	24
	B	19.0 ± 3.0	23.0 ± 2.0	II	16	25
	C	19.0 ± 4.0	23.0 ± 3.0	III	15	26

4.2 Methods

For the content of the study, the common approach of combining the environmental monitoring with direct questionnaire to users was followed.

During the measurement campaigns while the customers were asked to complete the questionnaire, a mobile monitoring cart was placed close to them recording indoor environmental parameters. At the same time, outdoor environmental parameters were recorded as well.

4.2.1 Environmental monitoring

The measurements campaign considers the monitoring of both indoor and outdoor environmental variable as described in the next paragraphs 4.2.1.1 and 4.2.1.2.

4.2.1.1 Indoor environmental monitoring

For the scope of the study, a tailor-made mobile monitoring cart named MEMO (Mobile Environmental MOnitoring) was built in EURAC Research laboratory.

MEMO can be easily moved within the indoor environment and the height of the sensors can be modified, resulting in a very flexible device to monitor indoor environment quality in different building typologies.

For this field study, MEMO was set up to measure both global thermal comfort at 1.1 m (abdomen level) and to record air velocity and air temperature at 1.6 m (head level), in order to evaluate possible local discomfort. The ankle level (0.1m) was disregarded because the relative air velocity generated by people when walking. In Figure 24 a scheme of the sensors used is reported.

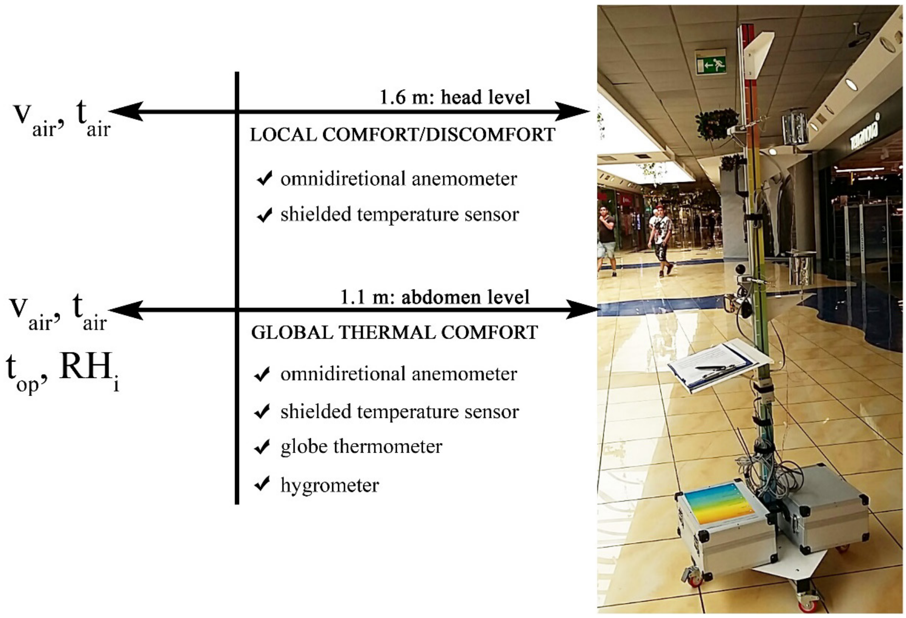


Figure 24 Mobile environmental monitoring cart (right) and definition of parameters measured at different levels

The accuracy of the sensors meets the recommendations of the European standard EN ISO 7726 [4.4]. Air temperature is measured using radiation-shielded Pt100. As suggested by Humphreys in the late 1977[4.5], later stated by the European normative [4.4] and then proved by Simone et al.[4.6], for indoor application, the operative temperature approximates closely to the temperature at the centre of a 40mm black painted globe. Thus, operative temperature refers to the globe temperature. The 40mm globe thermometer was built using a ping-pong ball, which was painted in grey in the inside and black on the outside (Figure 25). Mean radiant temperature was then determined starting from the temperature measured by the globe thermometer through the procedure suggested by the European standard EN ISO 7726 [4.4].

An Omni-directional hot wire sensor was used to measure air speed, and a portable probe for the indoor relative humidity.

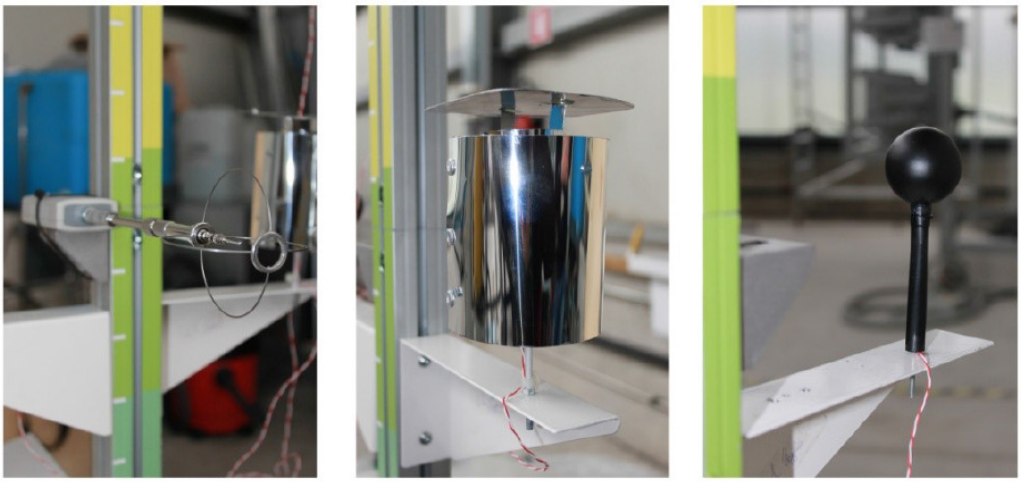


Figure 25 Sensor used for measuring indoor environmental parameters, from left to right: omnidirectional anemometer omnidirectional anemometer, radiation shielded thermistor, 40 mm -globe thermometer

The thermal parameters where measured and recorded every 10 seconds. In Table 5 the characteristic of the sensors used to measure the environmental parameters are presented.

Table 5 Measured indoor environment parameters and sensors characteristics

Parameter	**Sensor types**	**Measuring range**	**Accuracy**
Air temperature, Ta	Pt100 class A Radiation-shielded	-50..+150°C	± 0.2 °C (-25..+74.9°C)
Mean radiant temperature, T_{mr}	Pt100 class A and 40mm diameter globe	-50..+150°C	± 0.2 °C (-25..+74.9°C)
Air speed, V_a	Anemometer Sensor electronics SensoAnemo 5130LSF	0.05 to 5.0 m/s	0.02 m/s + 1.5% of reading
Relative humidity RH% (at ambient pressure)	EE EE08 series HC101 sensor	0-100%	±2% RH (0-90% RH) ±3% RH (90-100% RH)

4.2.1.2 Outdoor environmental monitoring

Outdoor temperature and relative humidity at 10 seconds frequency were also measured. To this aim, we used a MEMS (MicroElectroMechanical System) integrated portable data logger whose features are listed in Table 6.

Table 6 Measured outdoor environment parameters and MEMS integrated portable data logger characteristics

Parameter	Sensor & Brand Type	Measuring range	Accuracy
Outdoor temperature T_{out}	MEMS Integrated portable data logger	-30...+70°C	± 0.5°C
Outdoor Relative Humidity RH%	MEMS Integrated portable data logger	0-100%	± 2%

4.2.2 Questionnaires with customers

Customers were interviewed through a questionnaire structured into three sections: Background, Thermal comfort field survey and Clothing.

4.2.2.1 Background

In the first section of the survey, general questions such as age and gender, and other questions related to the physiological condition (health conditions, if customers had eaten or drunk, previous activities) were asked to customers. They were also asked about their permanence period within the shopping mall which means the duration of their stay inside the building before taking the survey.

4.2.2.2 Thermal comfort field survey

In the second part of the survey customers were asked about their acceptability (TAV), sensation (TSV) and preference (TPV) regarding the indoor temperature and their level of thermal comfort (TCV). Thermal acceptability was directly assessed on a 2-point scale (acceptable, not acceptable). Customers were asked to assess their thermal sensation with respect to the thermal environment on a 7-point scale according to ASHRAE standard 55 [3.2]. Customers' thermal preference was surveyed using the McIntyre 3-point scale [3.3] (Right now I want to be: cooler, no change, warmer).

Finally, interviewees were asked to evaluate their thermal comfort status on 6-point scale (very comfortable, comfortable, just comfortable, just uncomfortable, uncomfortable, and very uncomfortable). A screenshot from the questionnaire is shown in Figure 26 while the full version in English and Italian language can be found in Annex A and B.

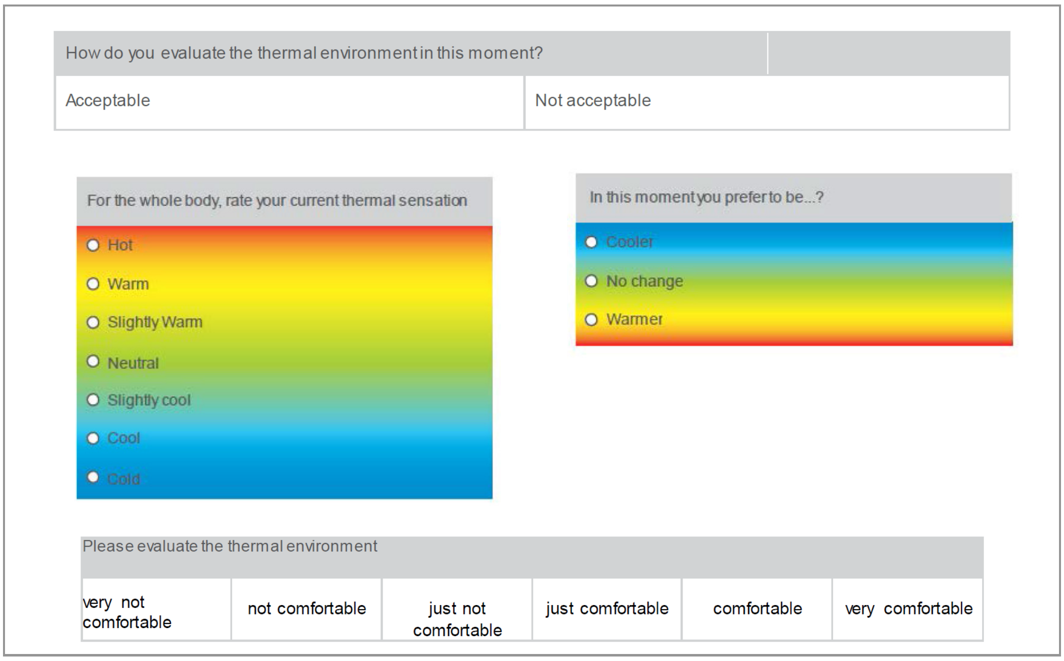


Figure 26 Screenshot from the questionnaire.

4.2.2.3 Clothing

Helped by the customers, we recorded interviewee's clothing ensemble to estimate the thermal resistance according to EN ISO 7730 standard [3.4]. Clothing level is one of the parameters needed to calculate the PMV value. In Figure 27 the reference values for clothing that have been used for the study are reported.

Physiological parameters were not measured, thus the metabolic activity was assumed to be 1.6 met (shopping) according to the EN 7730 [3.4].

4.3 Case studies

The measurement campaigns were conducted in the transitional space of three Italian shopping centres. Two located in the north (Trento) and one in the south (Catania).The main features of the shopping centres are presented in Table 7, while Figure 28 shows their geo-localization. Figure 29 shows pictures of the three shopping centres.

The first row of measurements was conducted in the "Shop Center Valsugana" (Trento Province) over four days: 4^{th}, 5^{th}, 6^{th} April 2016 and 10^{th} June 2016. The centre was built in 2000 and it has a total area of 9774 m^2, laid out over two floors. The common areas of the shopping centre are mainly shop galleries and there are 55 retail units. The main entrance atrium has a fully glazed façade (with sun control film) oriented towards south-west. The field study was performed in different locations within the common areas, which included shop galleries and atria on the ground and first floor.

Figure 27 Reference clothing values used for the analysis on the base of EN ISO 7730 [3.4]

Table 7 Characteristic of three case studies

Case study	Location	Reference	Typology	Climate	Level
Shop Center Valsugana	Pergine Valsugana (TN)	SC01	nighborhood centre	H &CD	2
Millenium Center	Rovereto (TN)	SC02	community centre	H &CD	3
Katanè	Gravina di Catania (CT)	SC03	super regional centre	CD	1

The second measurement campaign was at "Millennium Center over two consecutive days: 21st and 22nd June 2016. The centre is arranged over three floors. The common areas of the shopping centre are mainly shop galleries, with a total area of 6898 m^2 and it contains 47 retail units. The main entrance is an atrium with a fully glazed façade oriented towards south-east. The field study was performed in different locations within the shop gallery on the first floor.

The last measurement campaign was conducted in "Katané", over six days: 13rd, 14th, 15th, 18th, 19th and 20th July 2016. The centre was built in 2009 and it contains a two-storey gallery with more than 60 retail units, offering a gross leasable area of 27521 m^2 of which 8.000 m^2 are dedicated to a hypermarket. The shorter building axis is rotated of 27.5° from absolute north. Therefore, the main building façade is oriented towards south- east. The field study was performed in different locations within the shop gallery at the second floor.

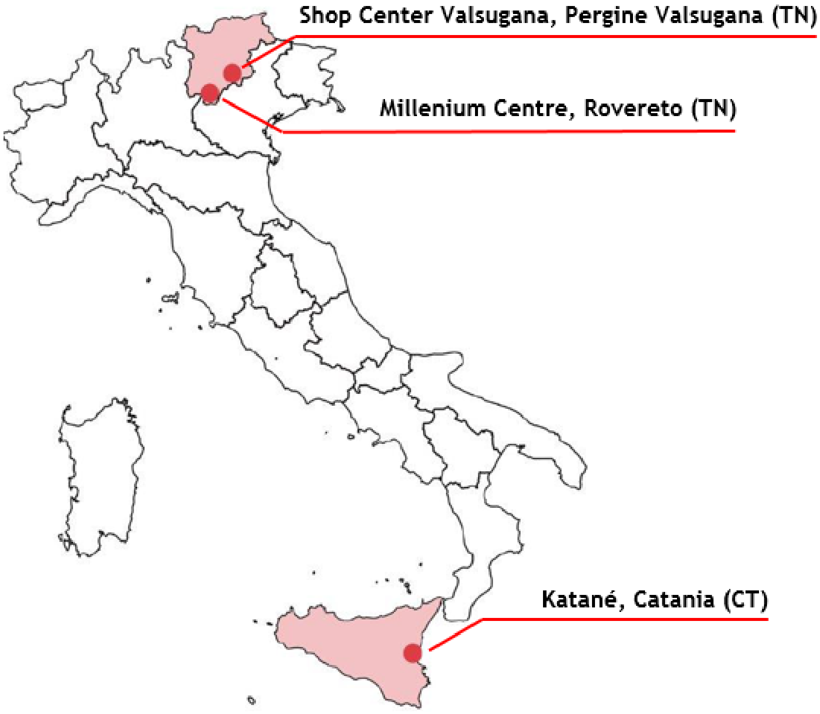


Figure 28 Localization of the case studies (left). Pictures of three different shopping malls

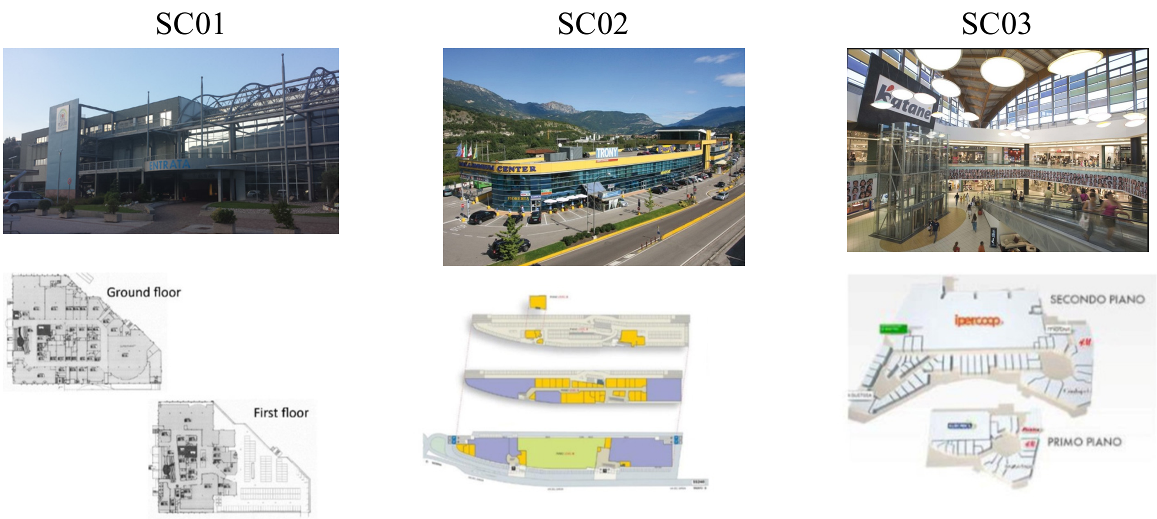


Figure 29 Pictures and diagram of Shop Center Valsugana (left), Millenium Centre (middle) and Katanè (right)

A one-day pilot study was also performed in August 2015 in Shop Center Valsugana (Figure 30). From the pilot study we learned the best approach for conducing the interview with the customers. We also gained awareness about possible problems that could happen during the measurements.

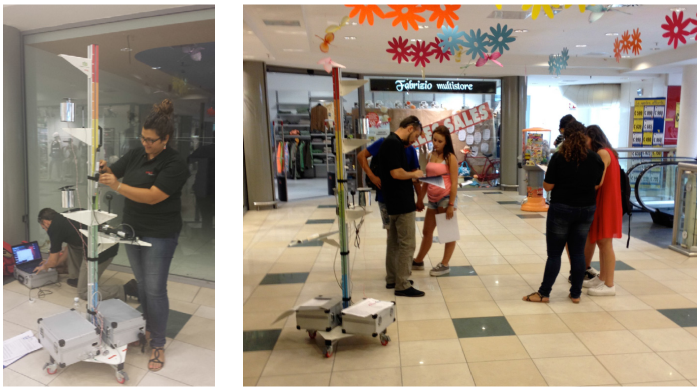


Figure 30 Some pictures of the pilot measurement campaign in SC01. Set-up of MEMO (left) and interview with customers (right)

4.4 Research Process

A total of 724 customers where interviewed during the three measurements campaigns. All of them were included in the sample, also those with critical physiological conditions, i.e. those who have eaten or drunk in the previous twenty minutes before the questionnaire. This to have a better representation of typical shopping centre customers, who are used to drink coffee or eat ice-cream before shopping, especially during summer season.

The research process consisted on different steps. Firstly, the applicability of the two thermal comfort models (see paragraph 4.5.4) on transitional spaces was evaluated. To do that, PMV and PPD parameters were calculated applying Fanger's model equations and using the data collected by MEMO and the clothing ensembles recorded during the interview. The metabolic activity was assumed at 1.6 met for all the customers. The R package "comf" was used [4.7] for the PMV-PPD calculation.

The rough data collected by MEMO were processed using both Microsoft excel [4.8] and the R software [4.9].

For the application of the adaptive algorithm, I refer to the method presented by Nicol and Humphreys [4.10].The equations are the same included in the European standard EN 15251 [3.16]. As described in paragraph 3.3.4 the adaptive method was derived to assess comfort in free running or naturally ventilated buildings. The measurements were performed in mechanically ventilated and cooled transitional spaces. Nevertheless, because thermal comfort in shopping centre is not yet addressed, the applicability of the adaptive model was tested as well. In order to calculate the mean running temperature (t_{rm}), data coming from weather stations located closer to the three case studies [4.13] were used. This was necessary because the outdoor temperatures during the days before the measurement campaign were not recorded by the MEMS. The evaluation of the thermal environment using the two thermal comfort models was compared with the real customers' satisfaction votes coming from the survey.

In a second step, the customer perception of the thermal environment was deeply investigated by analysing their answers related to thermal acceptability, sensation, preference and comfort in relation with the operative temperature experienced.

The last step was the investigation of the effect of temperature down-step (outdoor-indoor temperature difference) on customers' thermal sensation and preference trying to identify an optimal temperature that minimizes the percentage of dissatisfied people with the indoor environment.

By following this approach, a characterization of the actual thermal comfort conditions inside shopping centres transitional spaces was performed.

4.5 Analysis and Results

In this paragraph the main results of the study are presented. The paragraph is structured as follows:

- statistics of the sample;
- validation of operative temperature measurements;
- environmental characterization;
- application of the thermal comfort models: Fanger's and adaptive model;
- investigation of the customers' perception of the thermal environment;
- investigation of the temperature-initiated thermal overshoot.

4.5.1 Statistics of the sample

The selection of the customers was completely random and a total of 724 people were involved in the study and directly interviewed. Customers participate voluntarily. After a brief explanation about the content of the study, they could decide to be part of it or not. Because of the followed approach, the percentage between man and woman is unbalanced. Female gender indeed accounts for 59% of the sample. In relation to the age, 44% of the people were less than 30 year old, followed by the range between 31 and 50 years old (33%) and just 23% were more than 50 year old. The statistics of samples for the three case studies is showed in Table 8.

Table 8 Statistics of the sample

		Total sample	Female	Male
SC01	Number of interviews	204	130	74
	less than 30 years old	76	45	32
	between 31-50 years old	55	37	18
	more than 50 years old	72	48	24
SC02	Number of interviews	180	115	65
	less than 30 years old	88	51	37
	between 31-50 years old	57	38	19
	more than 50 years old	35	26	9
SC03	Number of interviews	340	185	155
	less than 30 years old	150	77	73
	between 31-50 years old	128	75	53
	more than 50 years old	62	33	29

SC01:the sample is composed by 204 customers (130 females and 74 males) distributed among three age groups: 77 interviewees were less than 30 years old, 55 interviewees were between 31 and 50 years old and 72 interviewees were over 50 years old.

SC02: the sample is composed by 180 customers (115 females and 65 males) distributed among three age groups: 88 interviewees were less than 30 years old, 57 interviewees were between 31 and 50 years old and 35 interviewees were over 50 years old.

SC03: the sample is composed by 340 customers (185 females and 155 males) distributed among three age groups: 150 interviewees were less than 30 years old, 128 interviewees were between 31 and 50 years old and 62 interviewees were over 50 years old.

4.5.2 Validation of operative temperature measurements

The operative temperature, t_o is defined, according to the EN ISO 7730 [3.4] as:

"uniform temperature of an imaginary black enclosure in which an occupant would exchange the same amount of heat by radiation and convection as in the actual non-uniform environment"

The exact equation for the operative temperature is showed in Eq. (1):

$$t_o = \frac{h_c \cdot t_a + \bar{h}_r \cdot \bar{t}_r}{h_c + h_r} \qquad (1)$$

where:
t_a is the air temperature, °C;
$\bar{t}_r$ is the mean radiant temperature, °C;
h_c is the heat- transfer coefficient by convection;
h_r is the heat- transfer coefficient by radiation.

For the direct measurement of the operative temperature, MEMO was equipped with a black painter 40 mm globe thermometer.

The operative temperatures measured with the globe thermometer were compared with the operative temperatures calculated according to the procedure described by the EN ISO 7726 [4.4].

Based on EN ISO 7726 the operative temperature is calculated as:

$$T_o = \frac{T_a \cdot \sqrt{10 \cdot V_{air}} + \bar{T}_r}{1 + \sqrt{10 \cdot V_{air}}} \qquad (2)$$

where:
V_{air} is the air velocity, m/s
Ta is the air temperature, K;
$\bar{T}_r$ is the mean radiant temperature, K.

The mean radian temperature of equation (2) is calculated converting the temperature measured by the globe by using equation (3)

$$\bar{T}_r = \sqrt[4]{T_g^4 + \frac{h_{cg}}{\varepsilon_g \cdot \sigma} \cdot |T_g - T_a|} \qquad (3)$$

where:

T_g is the temperature of the black globe, K;

ε_g is the emissivity of the black globe;

σ is the Stefan-Boltzmann constant equal to 5.67 x 10^{-8} W/($m^2 \cdot K^4$).

In Table 9 the mean errors and standard deviations of the two operative temperature values for each day of measurements are reported.

Table 9 Mean error and standar deviation between

Day of measurement	bias ± std	Day of measurement	bias ± std
4-Apr	0.06 ± 0.07	13-Jul	0.08 ± 0.14
5-Apr	0.06 ± 0.05	14-Jul	0.03 ± 0.05
6-Apr	0.05 ± 0.05	15-Jul	0.03 ± 0.04
10-Jun	0.06 ± 0.07	18-Jul	0.04 ± 0.04
21-Jun	0.18 ± 0.15	19-Jul	0.27 ± 0.11
22-Jun	0.08 ± 0.01	20-Jul	0.04 ± 0.04

Considering the accuracy of the Pt100 (Table 5), it is possible to consider the temperature measured by the globe thermometer as the operative temperature defined by the EN ISO 7730 [3.4].

4.5.3 Environmental characterization

Table 10 reports a statistics of the indoor and outdoor physical measurement in the three different shopping centres.

Table 10 Indoor and outdoor environmental conditions for the three case studies

		Indoor			Outdoor		Clothing
		$t_{op.}$ (°C)	V_{air} (m/s)	RH (%)	$t_{dry,out.}$ (°C)	RH (%)	Clo
SC01	Mean	25.1	0.12	48	24.3	43	0.64
	SD	0.9	0.06	7	2.1	7	0.2
	Min	22.9	0.00	59	19.4	31	0.18
	Max	26.7	0.33	33	29.5	55	1.41
SC02	Mean	25.3	0.12	48	30.8	40	0.45
	SD	0.5	0.08	2.9	1.3	2	0.1
	Min	24.4	0.00	43	28.5	35	0.23
	Max	26.3	0.40	53	32.6	46	0.85
SC03	Mean	26.1	0.14	42	30.1	42	0.38
	SD	1.1	0.08	3	1.7	14	0.1
	Min	21.7	0.00	33	27.4	17	0.22
	Max	29.6	0.41	49	34.6	62	0.67

The operative temperatures (t_o) recorded during the measurement campaigns range between 21.7°C and 29.6 °C. Both extreme values of the range were recorded in SC03. Indoor Relative humidity (RH) was well controlled by the HVAC system in all the three shopping centres with measured values ranging between 33% and 59%. The air speed measurements generally showed very limited values, with a maximum of 0.41 m/s recorded in SC03.

Regarding outdoor conditions, the air temperature ($t_{dry,out}$) ranges between 19.4°C and 34.6 °C measured respectively in SC01 during the mid-season campaign (April 2016) and in SC03 in July 2016.

The data collected in the three shopping centres were aggregated to investigate the frequency distribution of the main environmental parameters.

Figure 31 reports the frequency distributions of the indoor parameters while Figure 32 shows the ones of the outdoor parameters.

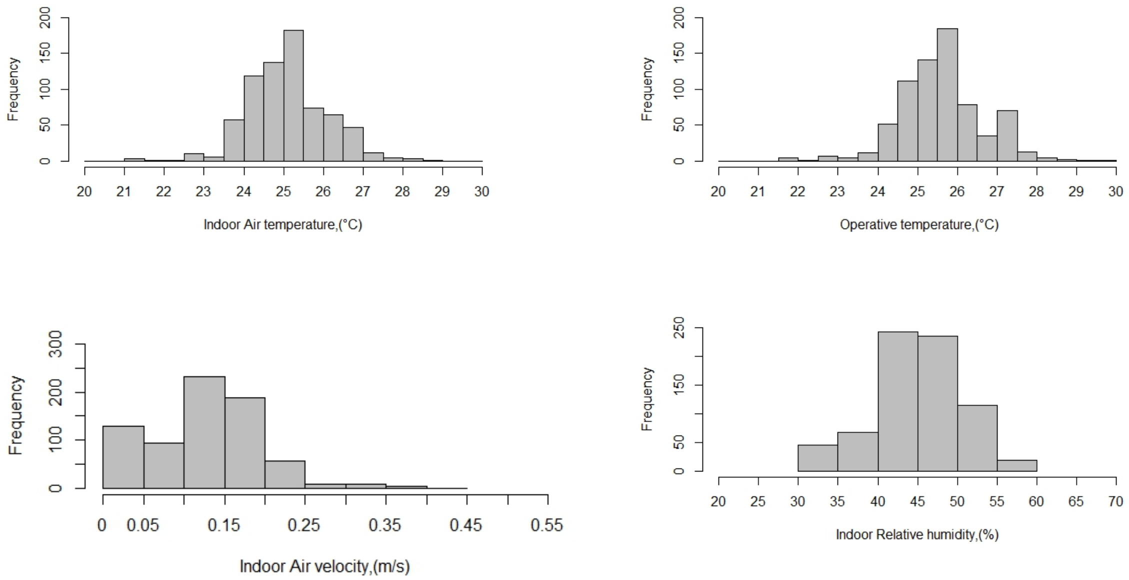


Figure 31 Frequency distribution of the Indoor parameters measured during the three campaigns: air temperature, Operative temperature, indoor air velocity and relative humidity

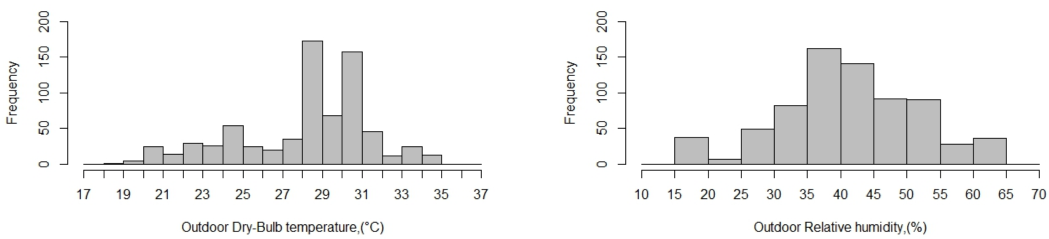


Figure 32 Frequency distribution of the outdoor parameters measured during the three campaigns: Dry-Bulb temperature and relative humidity

The highest frequency (around 45% of the time) of dry-bulb outdoor air temperature distribution ranged between 28 °C and 31 °C. The indoor air temperature frequency distribution is centred between 24.5 °C and 25.5 °C, accounting for around 45% of the total. The highest frequency of the operative temperature distribution ranged between 25 °C and 26 °C, accounting for around 47% of the total. Most of the measured indoor air velocities were lower than 0.25 m/s. This value is low because of the big volume involved. Measured indoor relative humidity is normally distributed with peak between 40% and 50%. Finally, the difference among the outdoor relative humidity distribution was relatively small, with the highest frequency ranging from 35% to 45%.

The distribution of indoor air temperatures is slightly different from the distribution of the operative temperatures. This is due to the radiant effect of internal gains such as lights and the effect of solar radiation passing through the wide glazed façades that characterize shopping centre transitional spaces.

The measurements were performed in both mid-season and summer conditions. This is visible from the frequency distribution of the outdoor-indoor temperature difference shown in Figure 33.

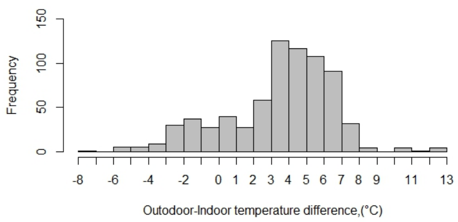


Figure 33 Frequency distribution of the difference between outdoor and indoor temperature during the three campaigns

From Table 10 differences in the average clothing level in the three shopping centres is observed. In SC01 the measurements took place in both April and June. This justified an average value of clothing higher than for SC02 and SC03 where the measurements were performed just under summer conditions. The lowest average clothing level is recorded for SC03 were the highest outdoor temperatures were recorded. The average clothing level are anyway lower than 0.50 clo, the standards references value for the calculation of the comfort temperatures under summer condition [3.4].

4.5.4 Thermal comfort model applied to transitional spaces

4.5.4.1 PMV-PPD model

By merging the data collected with MEMO, the information about the clothing level gained through the questionnaire and assuming 1.6 met as metabolic activity, Fanger's indicators, PMV and PPD, were calculated for each interviewee using the validated package "comf" [4.7] developed in R environment.

To assess the applicability of Fanger's model, the predicted and actual number of people dissatisfied were compared over 1 K operative temperature intervals. The interval of operative temperature considered are shown in Table 11. The value of operative temperature in the first column is the centre value of ± 0.5 ºC interval with respect of the value showed.

The actual dissatisfied people were considered the ones whose TSV was out of the interval [-1; +1], [3.3]. As predicted dissatisfied people were considered the customers which PPD is above

20% which is the considered threshold for comfortable conditions by both EN 7730 [3.4] and ASHRAEE 55 [3.2].

Table 11 Intervals of operative temperature considered for the whole analysis

interval t_o ,ºC	range ºC
22	$21.5 \leq t_o < 22.5$
23	$22.5 \leq t_o < 23.5$
24	$23.5 \leq t_o < 24.5$
25	$24.5 \leq t_o < 25.5$
26	$25.5 \leq t_o < 26.5$
27	$26.5 \leq t_o < 27.5$
28	$27.5 \leq t_o < 28.5$
29	$28.5 \leq t_o < 29.5$

The comparison between the two values, the customers' samples size and the average clothing levels, are reported in Figure 34. As it can be seen in the figure, for operative temperatures between 25ºC and 28ºC, Fanger's model tends to overestimate the number of dissatisfied customers. When the operative temperature is in the 24 ºC interval, the trend is reversed with a slight underestimation of the comfortable conditions.

The discomfort overestimation increases with the increase of the operative temperature. This suggests that users of transitional spaces can stand higher operative temperatures than predicted by the steady state model.

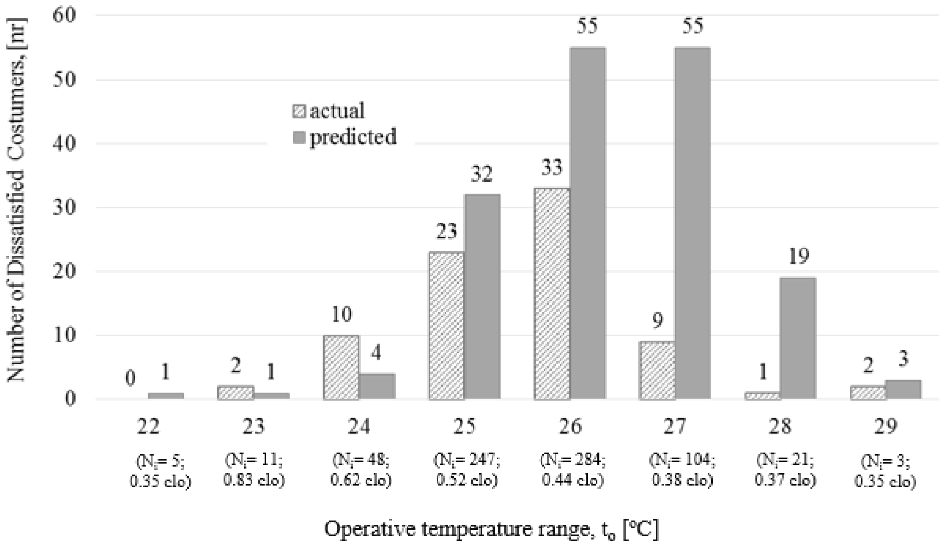


Figure 34 Comparison between the actual (field study) and predicted (from Fanger) number of people not satisfied with the operative temperature

Because of the nature of the seven –point scale used to assed customers' thermal sensation, the TSV is a categorical variable which is not directly comparable with a continuous variable as the PMV. A direct comparison between actual TSV and PMV is however possible with a categorization of the PMV. Taking advantage of the function "cutTSV" of the package "comf"

[4.7] the categorization was realized: e.g. all values lower and equal then -2.5 were set to a value of -3, higher than -2.5 and lower or equal -1.5 to -2, and so on.
Once the categorization was completed, the calcBias function [4.7] was applied in order to compare the prediction of PMV with respect of the actual sensation of customers (TSV). The function calculates the mean bias and its standard deviation and standard error between predicted thermal sensation votes (coming from the categorization of the PMV) and actual thermal sensation votes (TSV).

The differences between the Fanger's model and the actual thermal sensation of customers are confirmed by looking at the mean bias between the PMV and the TSV reported in Table 12. For operative temperatures between 25 ºC and 27 ºC the error in prediction is between 0.4 and 0.6 thermal sensation unit. At 24 ºC there is still an error prediction of 0.3 thermal sensation unit but in opposite direction. This means that the actual thermal sensation of customers is towards cool compared to the prediction. The inaccuracy of PMV model in predicting thermal sensation for transitional spaces finds explanation in the assumptions at the base of this model. The method is indeed based on the assumption that people are in steady-state condition, which is not the case of shopping centre transitional spaces. As explained in the introduction, subjects are under a constant thermal transient because of moving within different zones of the shopping centres (shops, common areas, food store, ecc..). Furthermore, they experience an initial thermal sensation overshoot due to the temperature difference between outdoor and indoor, parameter that is not taken into account by Fanger's theory and model.

Table 12 Means Bias, standard deviation and standard error between predicted PMV and actual TSV

t_o [ºC]	N_i	mean Bias	sdt Bias	se Bias
22	5	0	1.73	1
23	11	-0.45	0.93	0.28
24	48	-0.29	0.87	0.13
25	247	0.40	0.93	0.06
26	284	0.60	1.04	0.06
27	104	0.54	0.85	0.08
28	21	0.57	0.81	0.18
29	3	0	1.73	1.0

4.5.4.2 EN 15251 Adaptive comfort model

The adaptive comfort model was also tested. In particular, it was verified how far the average operative temperatures recorded during the measurements days were from the predicted comfort temperatures. The data were crossed-checked with the level of satisfaction of customers with respect of these temperatures.

For each day of measurement the daily comfort temperature has been calculate as shown in equation (4)

$$t_{comf} = 0.33 t_{rm} + 18.8 \ \text{ºC} \quad (4)$$

Where t_{rm} is the mean running temperature calculated according to the procedure described in the EN15251 [3.16].

The mean running temperature is an index introduced by Nicol and Humpreys [4.10] as improvement on the monthly mean temperature that was originality used by Humpreys [4.11] to predict neutral temperature in free-running buildings. Considering that the temperature within a month can be very variable, they suggested the use of an exponentially weighted running mean of the daily mean air of the previous days. The formula is therefore express in the form of a series [4.11].The weather data of the three sites in the days before the measurements, used for the calculation of the t_{rm} were retrieved from weather station closed to each shopping centre [4.12].

The customers are assumed to be satisfied when their TSV is within the range of slightly cool (-1) and slightly warm (1). Their percentage is calculated over the total respondent of each measurement day.

For the graph reported in Figure 35 some interesting consideration about the applicability of the adaptive model to shopping centre transitional spaces.

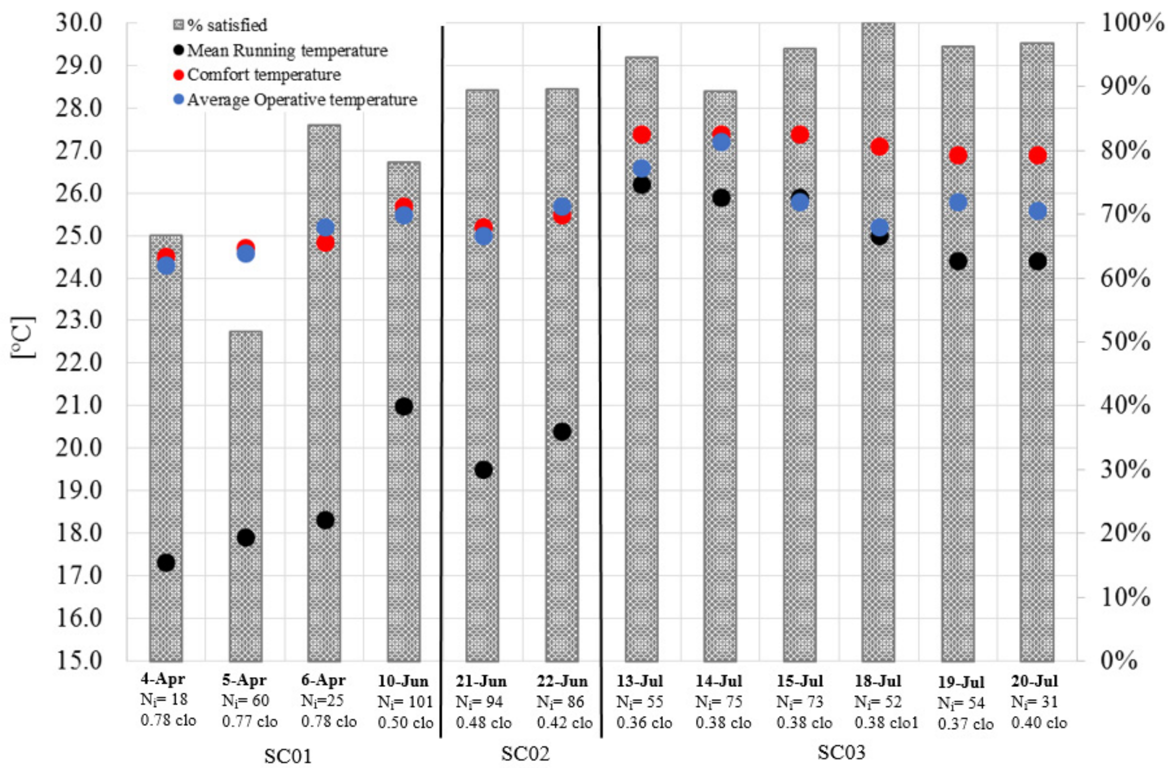


Figure 35 Comparison between comfort temperature calculate according to adaptive model (EN 15251) the average operative temperature measured during measurements days and the percentage of customers satisfied

During the 4th, 5th and 6th of April in SC01, the active cooling system was off. The mechanical ventilation system was providing just the minimum hygienic airflow rates.

For the measurements days in SC01 and SC02 the estimated comfort temperatures are in line with the actual average operative temperatures experienced by the customers. While for SC01 on summer period (21th and 22th of June) these temperature allow for 90% of satisfied customers, for SC01 the percentage of satisfied customers cross the 80% just one day (6th April).

On April 5th, 60 customers were interview and just 50% of them were satisfied with the thermal environment.

The almost same level of operative temperature is experienced on July 18th in SC03 by 52 customers and the percentage of them being satisfied reached the 100%.There are two main reasons creating this difference on customers' thermal sensation:

- the first one is the clothing level: in April, customers of SC01 have an average level of clothing equal to 0.78 clo (April 5th) which quite well represents a mid-season situation. In July the average level of clothing in SC03 is equal to 0.38 clo (July 18th).Therefore, experiencing the same operative temperature, the level of satisfaction is higher when the clothing level is lower[12].
- the second factor in creating such difference in satisfaction is the effect of the temperature step between outdoor and indoor. While in April an up-step temperature difference is experienced, in July we have a down-step temperature difference. This subject will be further analysed in paragraph 4.5.6 where the effect of the temperature difference on customers' thermal sensation and preference during the day of measurements before mentioned will be investigated.

The average operative temperatures recorded in SC02, which was mechanically conditioned during the measurements, are almost equal to the predicted comfort temperatures. The percentage of satisfied customers was around 90%. Looking at the data from SC03, the percentage of satisfied people are quite high but at lower average operative temperature than the predicted comfort temperatures.

Based on the analysis, the direct application of the adaptive thermal comfort model for transitional spaces is judged not recommended. This conclusion was reached especially for the conditions of dissatisfaction that such predicted comfort temperature can create in mid-season period.

In order to derive a model to assess thermal comfort in shopping centre transitional spaces, it is first of all necessary to better understand the range of operative temperature judged as comfortable by the customers. This aspect will be further investigated in the following paragraphs 4.5.5. and 4.5.6..

A tabulation of the data shown in Figure 35 is reported in the Annex C, Table 30.

4.5.5 Investigation of customers' perception of the thermal environment

In the following paragraph the distribution of the customers' answers related to thermal acceptability, preferred thermal sensation, and comfort are presented and discussed. The data have been grouped and binned over 1 K operative temperature intervals. From the direct observation of the data, it will be possible to understand the thermal perception of the customers and to understand what the comfortable ranges are.

---

[12] We can assume from the measurement that the other parameter affecting thermal comfort are almost comparable (paragraph 4.5.3).

4.5.5.1 Customers thermal acceptability

In Figure 36, thermal acceptability for each temperature range is presented. In case of indoor operative temperatures up to 28ºC the percentage of people not accepting the thermal environment is below 20%. The situation is completely different, with 100% of non-acceptance when the operative temperature is over 29 ºC. It has to be highlighted that for this interval the sample is made just by 3 customers, therefore no solid considerations can be derived, as well as for temperature intervals 22 ºC and 23 ºC (because of the same reasons)[13].

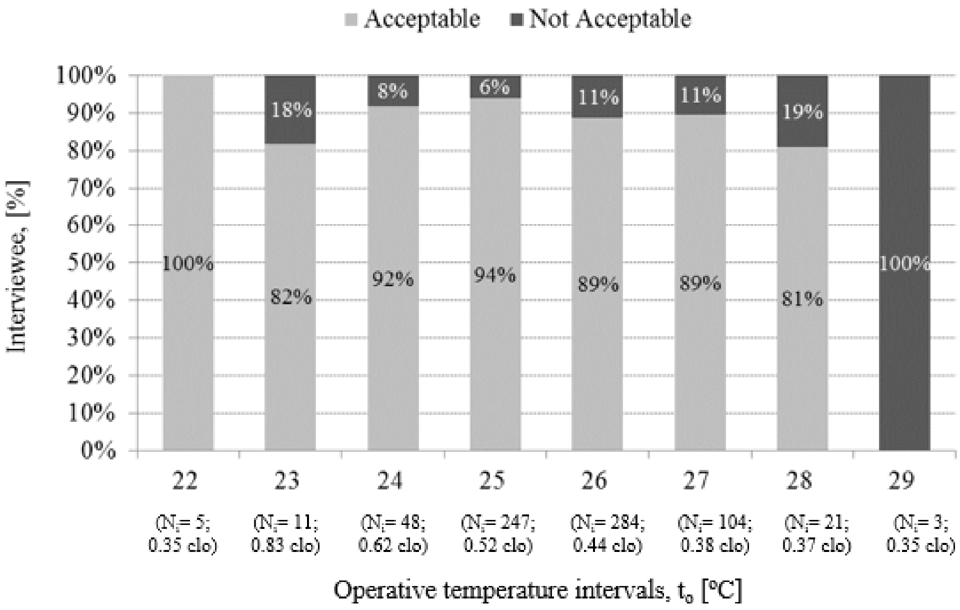


Figure 36 Bar Chart of the distribution of customer's thermal acceptability over operative temperature intervals

4.5.5.2 Customers thermal sensation

Thermal sensation votes were divided into three subcategories:

- TSV(-1,0,1) stands for customers that are satisfied with the thermal environment;
- TSV (-3-2) stands for customers that are cold dissatisfied;
- TSV (+3,+2) stands for customers that are warm dissatisfied.

By grouping in this way the thermal sensation votes, for each operative temperature interval, it was possible to identify the reason that generates discomfort (too cold or too warm).

A general satisfaction with the environment is observed, from 22 ºC up to 28 ºC (Figure 37). A great adaptation/tolerance to a wide range of operative temperature is hence demonstrated. When the operative temperature is 29 ºC the environment is perceive as too warm.

---

[13] Statistical validation for the temperatures ranges is presented in paragraph 4.5.5.4.

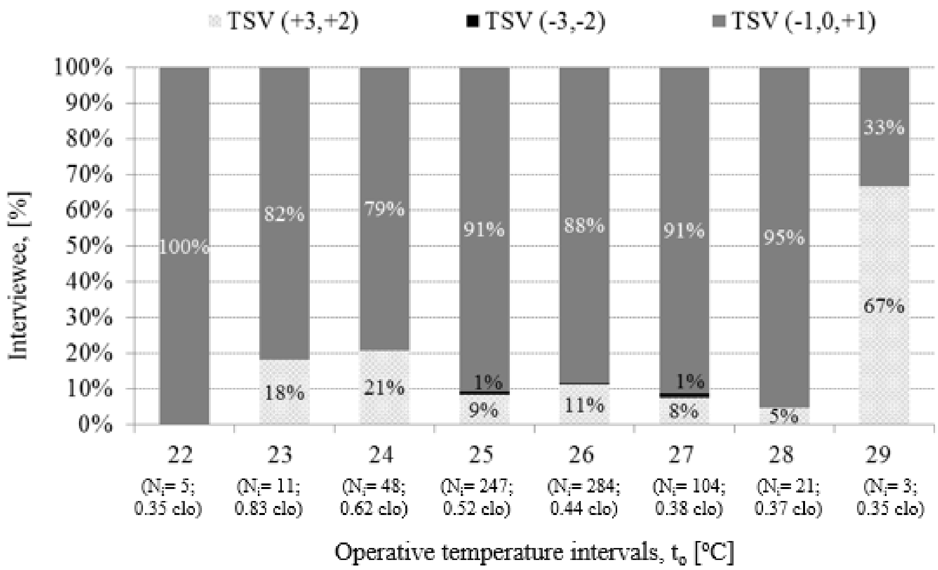


Figure 37 Bar Chart of the distribution of thermal sensation over operative temperature intervals [ºC]

By adopting the same aggregation of the TSV the percentage of satisfied, cold dissatisfied and warm dissatisfied were plotted in the graph in Figure 38. The aim is to find the optimal operative temperature which minimizes the number of dissatisfied customers. Since there is no significant variation in the percentage of the dissatisfied, a range of optimal operative temperature can be assumed between 25 ºC and 28 ºC.

By filtering only the date of the TSV (-1, 0, 1) into:

- neutral, customers who voted for "neutral" (0);
- warmer than neutral, customers who voted for " slightly warm"(+1);
- cooler than neutral, customers who voted for "slightly cool"(-1);

it is possible to look at the neutral temperature (see paragraph 3.2).

The data gathered in this way are showed in Figure 39. The neutral temperature should be the temperature at which the curve of "% warmer than neutral" and "% cooler than neutral" cross each other and the "% neutral" should be at that point the maximum recorded. This situation does not happen because of an unusual behaviour of the distribution of the votes for the operative temperature intervals below 25 ºC.
The percentage of "warmer than neutral" should proportionally decrease with the decrease of the operative temperature. The percentage of "cooler than neutral" should on the other hand increase. The behaviour is in this case inverted. The explanation could be found in the small samples in the extremities. Nevertheless, it is reasonable to assume that the neutral temperature

falls in the range between 25 ºC and 26 ºC where the distance between the curve "% warmer than neutral" and "% cooler than neutral" is minimized.

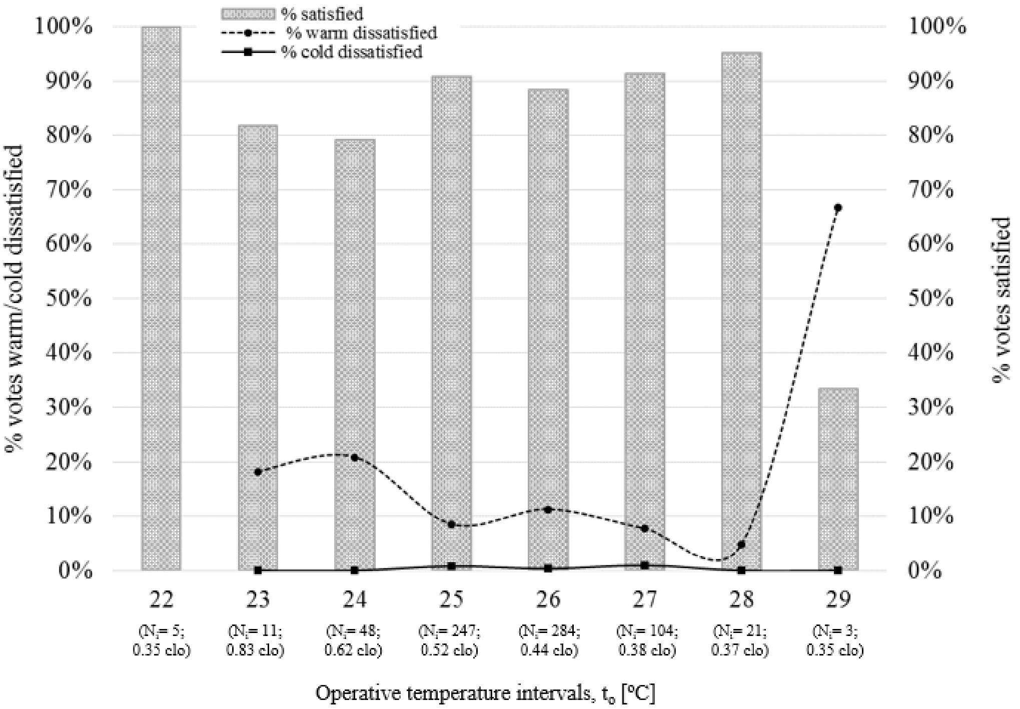


Figure 38 Distribution of satisfied, warm dissatisfied and cold dissatisfied over operative temperature intervals [ºC]

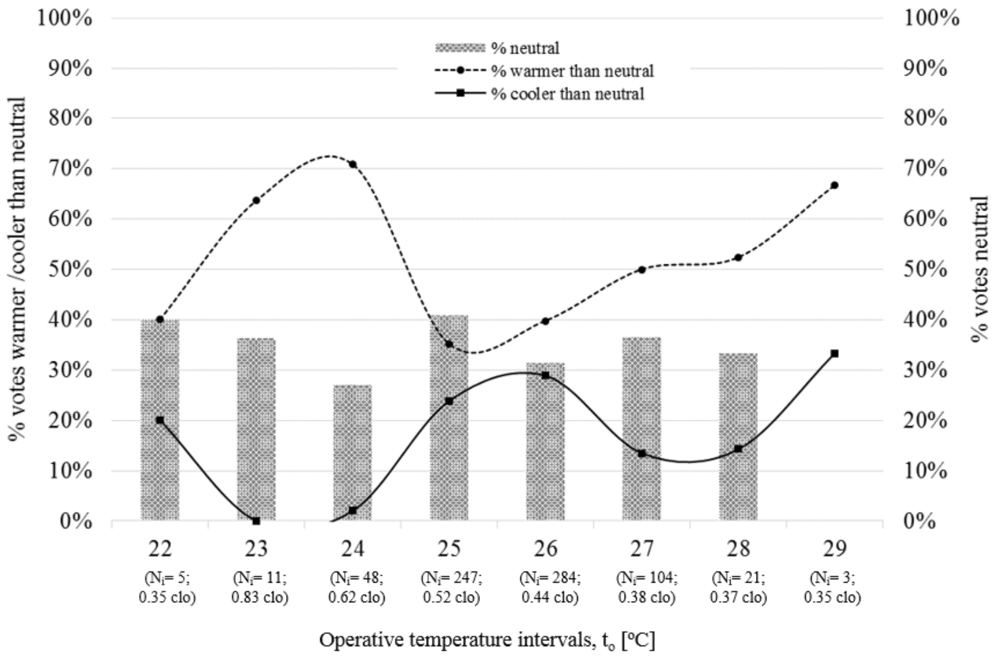
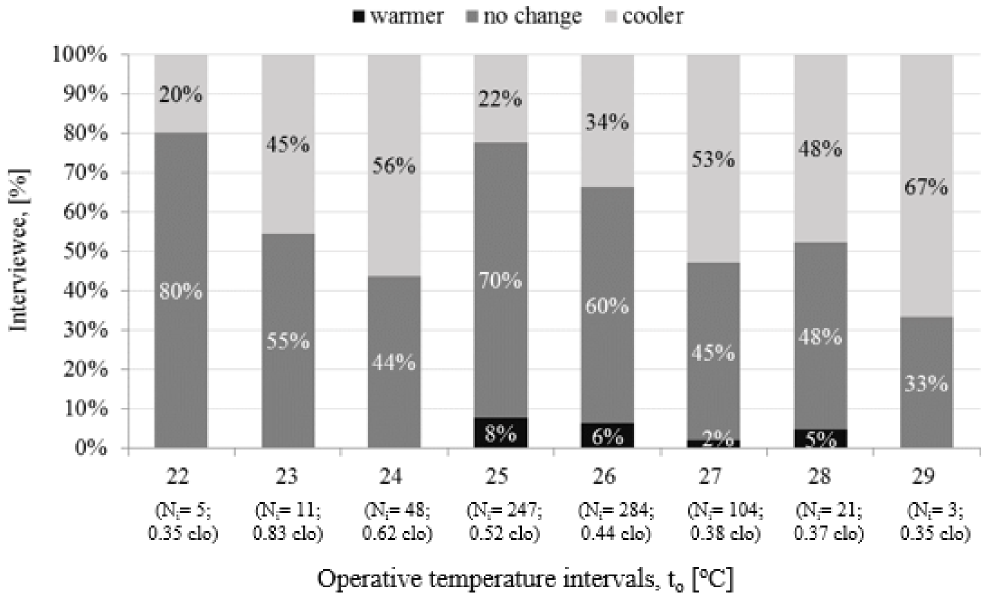


Figure 39 Distribution of customers with TSV equal to neutral, warmer than neutral and cooler than neutral over operative temperature intervals [ºC]

4.5.5.3 Customers thermal preference

The bar graph in Figure 40 reports the distribution of customers' thermal preferences.



.

Figure 40 Bar Chart of the distribution of customer's thermal preference over operative temperature intervals

For operative temperatures between 22 ºC and 24 ºC, customers' preferences are almost equally distributed between "no change" and "cooler". The higher the operative temperature experienced the higher is the percentage of people preferring to be in a cooler environment.

Again, as observed for the neutral temperature (Figure 39), a unique derivation of the preferred temperature cannot be assessed. As shown in Figure 41 indeed the curve of "% wanting to be warmer" and "% wanting to be cooler" cross in two different points. It is assumed therefore that the preferred operative temperature falls in the range between 25 ºC and 26 ºC.

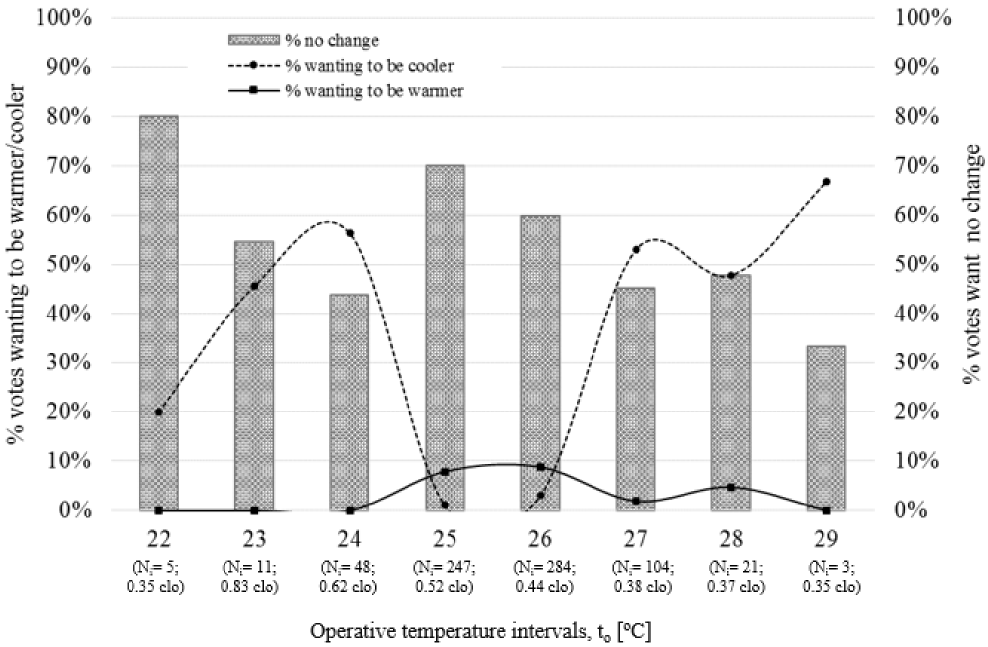


Figure 41 Distribution of the customer's thermal preference over operative temperature ranges

4.5.5.4 Customers thermal comfort

As last question the customers were asked to rate their general state of comfort using a six-point scale. The results are reported in the bar chart in Figure 42.

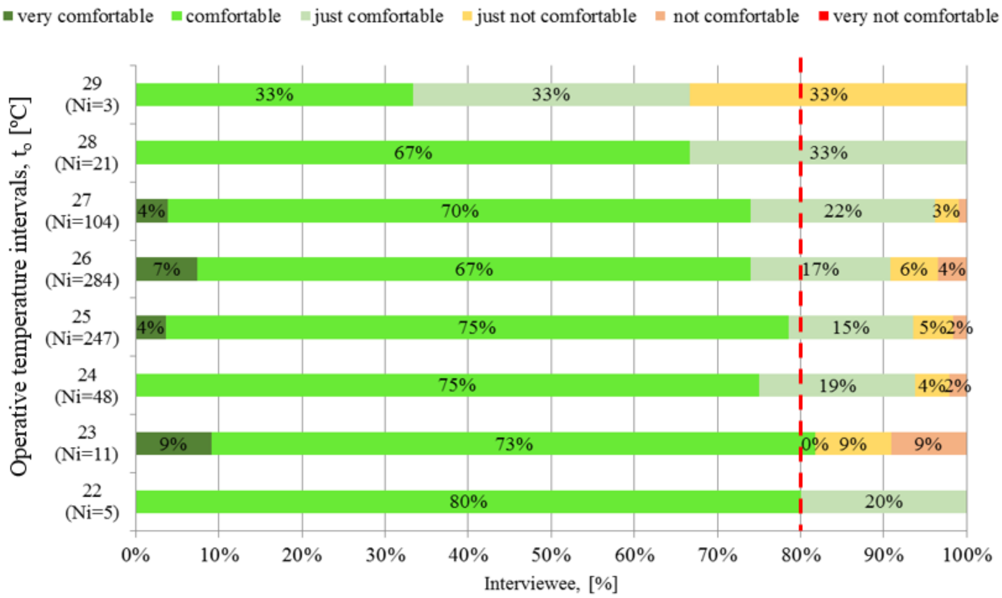


Figure 42 Bar graph distribution related to the thermal comfort questions

For the majority of the operative temperatures, people express their vote in the comfortable side of the scale. Looking at the results, an operative temperature of 28°C in summer still guarantee a comfort for at least 80% of the occupants.

The results presented in Figure 42 suggest that customers judge as comfortable a wide range of indoor operative temperatures. This result is in line with previous finding about transitional spaces acceptable temperatures presented in paragraph 3.4.

A generalization of the data is possible if the results are broaden from the sample of this study to the entire population of shopping centres users. We take advantage of inferential statistic and in particular of the Central Limit Theorem [4.13]. The application of this theorem is allowed for categorical data (as in this case) when these three assumptions are verified:

a) the sample is random;
b) the sample is independent;
c) n*p>5 and n*(1-p)>5, where "n" is the sample number and "p" is the minimum expected probability.

For the content of our study, the goal is to have for each operative temperature interval 80% of people satisfied with the thermal environment. This means that the minimum expected probability is 80% (p=0.8). To simplify the statistical analysis we have grouped the answers of interviewees into two macro categories that are: respondents stated to be in "thermal comfort condition" and those that answered to be in "not thermal comfort condition".
Thus, looking at the data, conditions a) and b) are respected because of the nature of the study (see paragraph 4.4). If we want to infer the observation to the entire population, we need to verify the operative temperature intervals that respect also condition c).

From Table 13, condition c) is verified for operative temperature intervals between 24 ºC and 27 ºC. Considering the way intervals have been created (see Table 11), we can conclude that the comfortable temperatures during summer season range between 23.5 ºC and 27.5 ºC.

Table 13 Central limit Theorem assumption check for different operative temperature interval

Operative temperature interval (°C)	Number (n)	Minimum expected probability (p)	n*p	n*(1-p)	Min(n*p, n*(1-p))>5
22	5	0.8	4	1	no
23	11	0.8	8.8	2.2	no
24	48	0.8	38.4	9.6	yes
25	247	0.8	197.6	49.4	yes
26	284	0.8	227.2	56.8	yes
27	104	0.8	83.2	20.8	yes
28	21	0.8	16.8	4.2	no
29	3	0.8	2.4	0.6	no

4.5.6 Investigation of temperature-initiated thermal overshoot

Several literature studies involving human subjects revealed the occurrence of a phenomenon named *thermal sensation overshoot*. This events consist in a variation of the thermal sensation after experiencing a temperature difference while moving from outdoor to an indoor environment, [3.10],[3.11],[4.14]. After moving from a warmer/colder environment to another environment which is respectively cooler/warmer than the previous, *thermal alliesthesia* takes effect. Thermal alliesthesia relates to the thermal pleasure sensation and overshoot generated by the restoration of a thermal stress towards neutral conditions [4.15],[4.16].

Nevertheless, attention should be paid to the initial thermal stress that generate the overshoot. The goal is assure always a temperature step between indoor and outdoor that avoids uncomfortable thermal overshoots. If reaching this goal the use of thermal sensation overshoot in summer transient condition can be used to adjust the indoor design temperature on the base of the outdoor conditions striving for energy efficient improvements with no thermal comfort penalty [4.17].

The objective is to find the optimal temperature difference between outdoor and indoor which allow to minimize the percentage of dissatisfied people. The awareness about optimal temperature can help in a better control of the indoor environment on the base of the outdoor conditions.

4.5.6.1 Effect of the permanence period on customers sensation

Before analysing the effect of temperature differences on customers' thermal sensation, the influence of permanence period is investigated.
Customers move within the shopping centre going to and from the shops placed along the common areas where, most of the time, the thermal condition are different. Therefore,

customers are constantly subjected to a thermal transient and particularly they can experience two different typologies of thermal sensation overshoot:

- a first thermal sensation overshoot due to outdoor-indoor temperature difference experienced when they first enter inside the shopping centre;
- several thermal sensation overshoots due to the temperature difference between the shops and the common areas.

In paragraph 3.3.2 the period of time need to reach thermal neutrality was discussed. A reference period of 10 minutes is assumed to be enough to reach neutrality with the environment after a temperature difference step [3.10].In relation to shopping centre we can assume that in the first 10 minutes customers are just experiencing the common areas thermal environment. If thermal sensation overshoot due to outdoor-indoor temperature occurs, the thermal sensation of customers should be influenced by the temperature difference they undergone within this timeframe. Figure 43 shows the distribution of the permanence period at the moment of the interview for the three case studies. Looking at the total sample, 34% of them were interviewed within the first 10 minutes of permanence, 27% had spent a period between 10 and 20 minutes while the majority of the customers, 40% were inside the shopping center for more than 20 minutes.

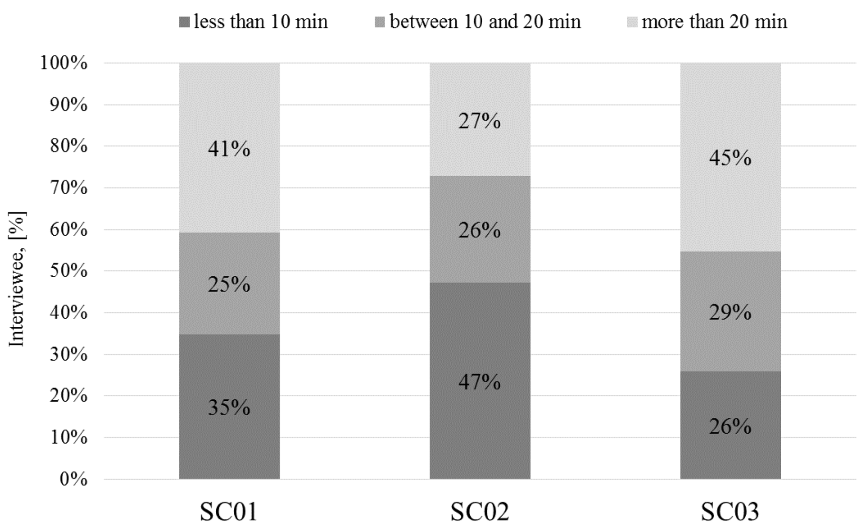


Figure 43 Permanence period within the three case studies

To verify any correlation between the environmental parameters measured and the thermal sensation, comfort, and preference of the customers, correlation statistics was used.

The Kendall non-parametric test is used since we deal with categorical data with pairwise. The Kendal correlation coefficient gives information about the strength of dependence of a dependent variable from the independent ones.

For the content of the study the dependent variables, named Y, are:

- Thermal sensation vote TSV;
- Thermal comfort vote TCV;
- Thermal preference vote TPV.

The null hypothesis (H_o) is: "*Y is independent from X*" where X can be:

- $t_{dry,out}$. outdoor air temperature (ºC);
- t_{in} : indoor air temperature (ºC);
- $t_{dry,out}$ -t_{in} : difference between outdoor and indoor air temperature (ºC);
- t_o : operative temperature (ºC);
- RH_{in} : indoor relative humidity (%);
- RH_{out} : outdoor relative humidity (%);
- V_{air} : indoor air velocity (m/s).

If data gives us confidence to reject the null hypothesis then this provides support for our experimental hypothesis. Once we have calculated the test statistic, we calculate the probability of this test statistic occurring by chance; if this probability is less than 5% (p-value <0.05/confidence level 95%) then we generally reject the null hypothesis which means that the relationship between dependent and independent variable is statistically significant.

According to the test set-up, a negative value of the correlation coefficient implies an inverse relationship between environmental parameters (X) and the dependent variable (Y).

The data were filtered for customer who have spent less than 10 minutes and more than 10 minutes. The results are shown respectively in Table 14 and Table 15.

Table 14 Correlation values among TS, TC, TP with the indoor and outdoor environmental parameters through Kendall non-parametric test (* statistical significance with 95% confidence interval, ** statistical significance with 99% confidence interval) for customers who have spent less than 10 minutes

	Environmental parameters						
	Outdoor		Indoor				
Dependent variables	$T_{dry,out}$	RH_{out}	T_{in}	RH_{in}	V_{air}	$T_{op.}$	$T_{dry,out}$ - T_{in}
Thermal sensation (TS)	NS	NS	NS	NS	NS	NS	-0.16**
Thermal comfort (TC)	NS	NS	NS	NS	NS	NS	0.11*
Thermal preference (TP)	NS	NS	-0.11*	NS	NS	-0.11*	NS

Table 15 Correlation values among TS, TC, TP with the indoor and outdoor environmental parameters through Kendall non-parametric test (* statistical significance with 95% confidence interval, ** statistical significance with 99% confidence interval) for customers who have spent more than 10 minutes

	Environmental parameters						
	Outdoor		Indoor				
Dependent variables	$T_{dry,out}$	RH_{out}	T_{in}	RH_{in}	V_{air}	$T_{op.}$	$T_{dry,out}$ - T_{in}
Thermal sensation (TS)	-0.12**	0.08*	NS	0.14**	NS	NS	-0.17**
Thermal comfort (TC)	NS	NS	NS	NS	NS	NS	NS
Thermal preference (TP)	NS	-0.08*	-0.11**	-0.11**	NS	-0.11**	0.11*

As general comment, even when the null-hypothesis can be rejected, the values of the correlation coefficient are weak. According to [3.25], only correlation coefficient ≥ 0.3 can be accepted as relevant. Therefore no strong correlations are observed. This result is not surprising considering the multi-causality that defines the state of comfort of a person. The results are however interesting because they allow to better understand the dynamics if comparing results for customers who have spent less than 10 minutes and more than 10 minutes.

For the first 10 minutes of permanence within the shopping centre thermal sensation and comfort just correlate with the outdoor-indoor temperature differences. For TS the value is negative while positive for TC meaning that for high temperature difference $T_{dry,out} - T_{in}$ the TS vote goes towards the cool side of the thermal sensation scale but at the same time the level of comfort increase. This is due to the *thermal alliesthestial phenomenon* before-mentioned. The preferences seem not to be connected with temperature difference but influenced by the indoor and operative temperatures. Negative correlation coefficients suggest a preference towards cooler environment with the increase of the operative temperature which is confirmed by the data earlier presented in Figure 40 and Figure 41.
The framework seems to get more complicated after 10 minutes spent inside the shopping centre. Direct questions about customers' movements within the shopping centre were not placed. Nevertheless, it is very likely that customers are under a constant state of thermal transient because they experience different temperatures by moving from one shop to another crossing the common areas without reaching a thermal neutrality. This is proved by the fact that the thermal sensation is not correlating with either indoor or operative temperature. Indeed, the temperature recorded and used for this correlation analysis is just the one experienced during the interview in the common areas. Because of high variability of the customers' path and the complexity of a measuring campaign which would have been included also all the shops, no information about the environmental parameters experienced in the different shops are available. After 10 minutes the TS still correlates with the temperature difference $T_{dry,out} - T_{in}$ but also with the indoor relative humidity.

While in the first 10 minutes of permanence thermal comfort was influenced by the outdoor-indoor temperature difference, later on it is not correlating with any environmental parameters. This result is quite strange but it probably means that after ten minutes being inside the shopping centre, subjective parameters are more influent in the determination of the state of comfort.

Thermal preference is equally influenced by indoor temperature, relative humidity and outdoor-indoor temperature difference. For this last one, the correlation coefficient is negative meaning that there is a preference towards warmer environment with the increase of outdoor-indoor temperature difference experienced.

These results show that there is not a specific environmental parameter that correlates significantly with the way people perceive the indoor thermal environment. However, the temperature difference between outdoor and indoor is the one recording the highest correlation coefficients with the thermal sensation for both permanence periods (less than 10 minutes and more than 10 minutes).
Because thermal sensation and preference are affected by $T_{dry,out} - T_{in,}$ a further investigation was conducted. The cumulative frequency distributions for the ''want to be warmer'' and ''want to be cooler'' inclinations were plotted against the sensation of the thermal environment reported by customers for both permanence periods (Figure 44).

The point located at the intersection of the two cumulative curves corresponds to the subjects' preference in terms of sensation. As shown in Figure 44, this preference did not coincide with the thermal neutral condition, but was shifted slightly toward a negative value on the sensation scale. The optimal sensation occurred at levels of -0.33 and -0.35, respectively, for “less than 10 min” and “more than “10 min”. The values are very close meaning that no significant difference occur. The cumulative distribution on the left side of the thermal sensation scale (Figure 44) is irregular compared to the right side. This trend is probably due to the low or sometimes absent distribution of votes for that side of the scale. From the correlation analysis, we discover that for the first 10 minutes the thermal preference is influenced just by outdoor-indoor temperature difference. After this period, in addition to the outdoor-indoor temperature difference the thermal preference correlates also with the indoor parameters as indoor temperature. Nevertheless from a deeper investigation no significant difference was noticed in the optimal sensation. No matter the time spent indoor, the thermal preference of customers is slightly bias toward cool. Nevertheless, it was noticed from the analysis of the thermal preference vote over the operative temperature intervals (Figure 40) that the majority of the preference goes for “no change”.

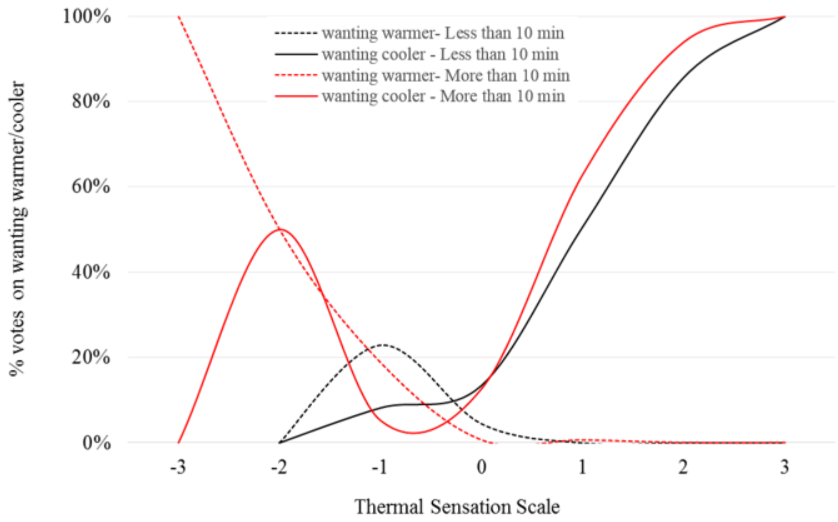


Figure 44 Percentage of preference against sensation depending on permanence period

Table 31 and Table 32 (Annex C) report the rough data of the customers’ preference which have been used for building the cumulative frequency in Figure 44. The respectively show the data for “less than 10 minute” (Table 31) and “more than 10 minutes” (Table 32).

4.5.6.2 Down-step outdoor–indoor temperature difference effect on thermal sensation

When a subject move from warmer environment to a cooler environment we refer to down-step temperature difference. In the case of shopping centre, this is basically what happen in summer season when customers from outside enter in the shopping center.

The objective is to identify the optimal temperature difference between outdoor and indoor which allow to minimize the percentage of dissatisfied people. To assure a statistical good sample for the considered temperature difference interval, because of the nature of the data collected, the analysis can be conducted just for the operative temperature intervals where the highest frequency of interview was observed. From the frequency distribution presented in Figure 31 these two intervals are 25 ºC and 26 ºC. The data related to thermal sensation were analysed according to the different outdoor-indoor temperature difference experienced. The results are presented in Figure 45 and Figure 46, for 25 ºC and 26 ºC respectively. The percentage of dissatisfied customers, mainly warm dissatisfied for all temperature difference intervals, is marginal compared to the percentage of people that are satisfied which is always over the 80% threshold.

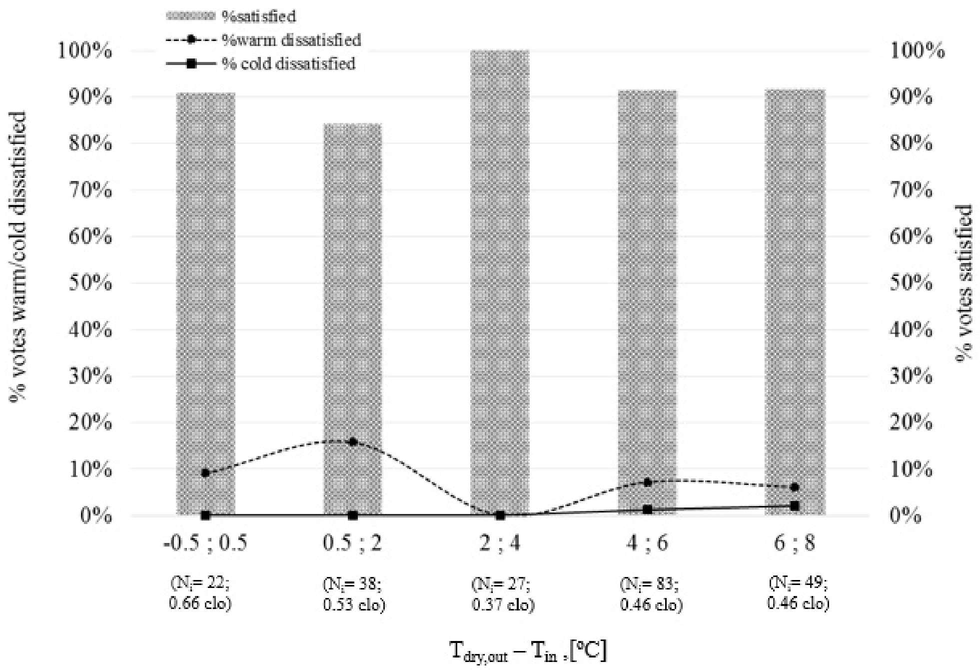


Figure 45 Effect on thermal sensation of different outdoor-indoor temperature for operative temperature equal to 25ºC

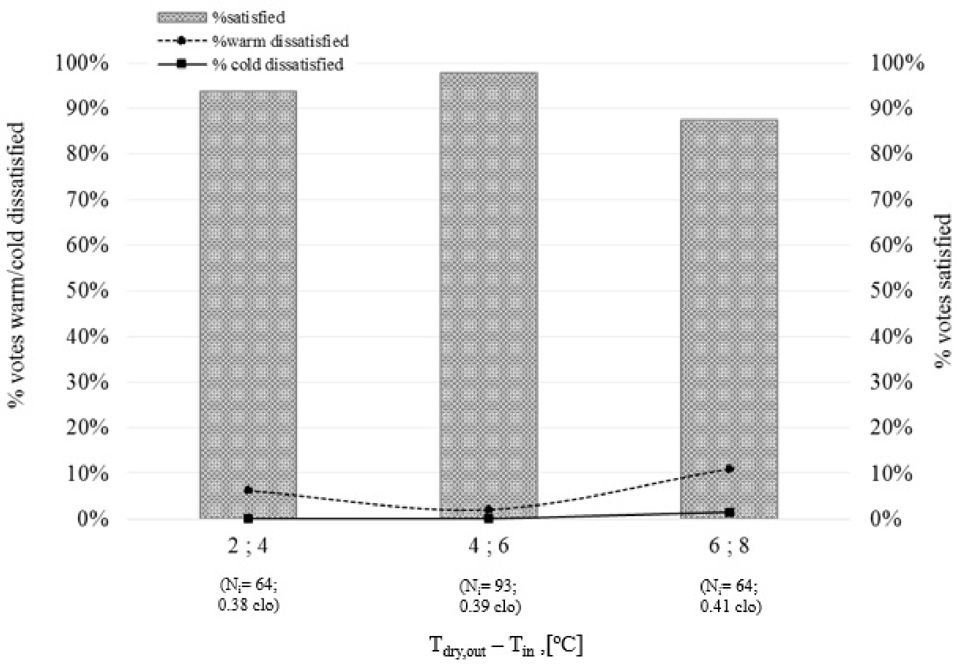


Figure 46 Effect on thermal sensation of different outdoor-indoor temperature for operative temperature equal to 26ºC

Nevertheless an optimal outdoor-indoor temperature difference can be considered the one that minimize the percentages of dissatisfied, even though are already very low. These are 2-4 ºC and 4-6 ºC respectively for 25 ºC and 26 ºC operative temperature interval (Figure 45 and Figure 46).

4.5.6.3 Down-step outdoor–indoor temperature difference effect on thermal preference

Because the objective is to find the temperature that optimize customers experience inside the centre, it is important to understand temperature difference which affects also thermal preference. Therefore the same approach of paragraph 0 was also applied to the customers' thermal preference votes. The results are shown in Figure 47 and Figure 48 respectively for 25 ºC and 26 ºC operative temperature intervals.

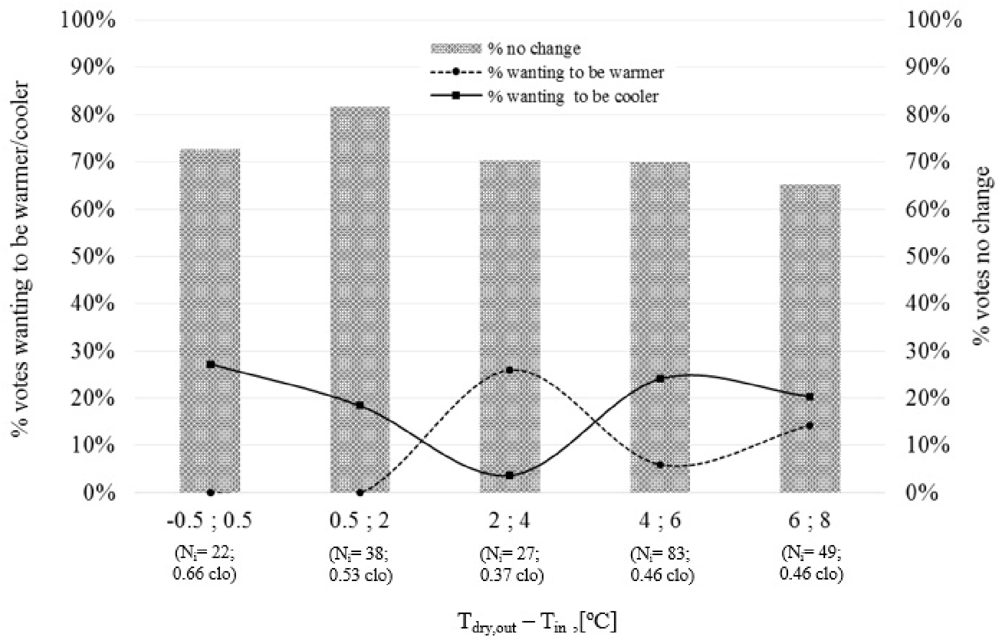


Figure 47 Effect on preference of different outdoor-indoor temperatures for operative temperature equal to 25ºC

For operative temperature in the interval of 25 ºC (Figure 47), the percentage of the customers who want to be warmer and cooler undergo to a trend inversion when the $T_{dry,out}$ - T_{in} is between 2 ºC and 4 ºC. This is probably due to the lower clothing level of the customers in that interval. It seems, however, that no specific temperature difference optimize the customers' preference.

As it can be seen in Figure 48, the temperature difference between outdoor and indoor that minimize the percentage of the customers asking for cooler environment is equal to 2-4 ºC, which is also the interval that maximizes the percentage of customers that want no change.

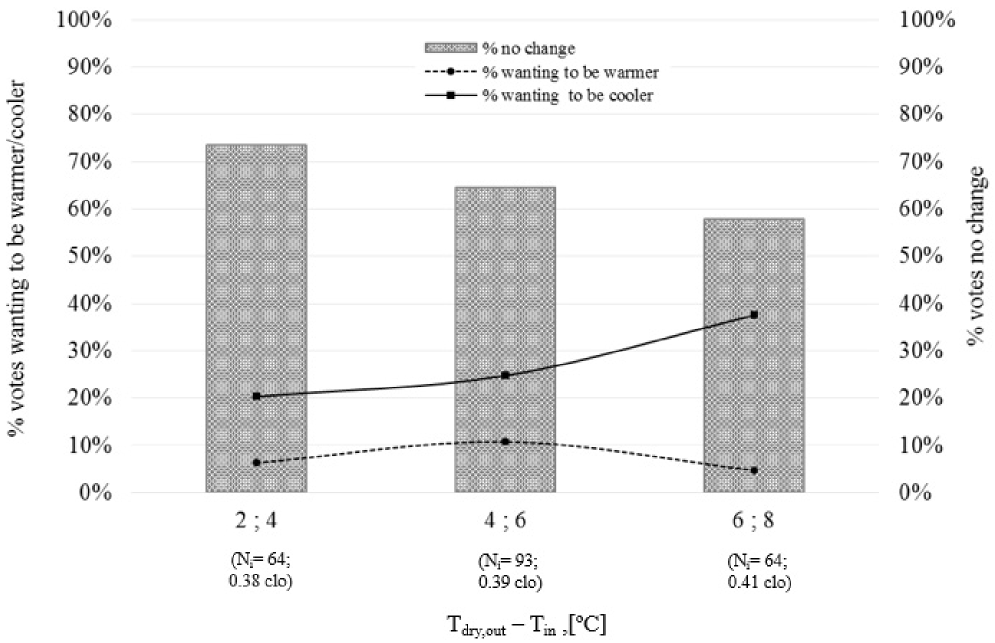


Figure 48 Effect on preference of different outdoor-indoor temperatures for operative temperature equal to 26ºC

4.5.6.4 Effect of outdoor-indoor temperature step under different seasons

In paragraph 4.5.4.2, it was highlighted that for two different days of measurements (April 5th and July 18th) customers experiencing the same operative temperature expressed different satisfaction with the thermal environment. Even though the days were in different season and in two different shopping centres, SC01 and SC03, almost the same level of environmental parameters were recorded. A summary is shown in Table 16. Average outdoor temperature are different because of the two different period of the year.

Table 16 Average values of the relevant indoor and outdoor environmental parameters the April 5th and the July 18th

	Date	Sample	Indoor			Outdoor		Clo
			t_{op} (ºC)	RH (%)	V_{air} m/s	$t_{dry,out}$ (ºC)	RH (%)	
SC01	April 5th	60	24.9	59.0	0.11	24.8	35.0	0.77
SC03	July 18th	52	25.2	41.0	0.16	28.6	38.4	0.38

One of the reason of the different customers' dissatisfaction was attributed to the higher level of clothing resistance in April. Morgan and De Dear endorsed the fact that the outdoor temperature affects the way people are dressed and therefore their clothing insulation level. In their study [4.19] they also found out that among the twenty environmental variables they tested, indoor operative temperature is the second most important variable affecting clothing insulation. They support the theory that people adjust their clothing as a function of the indoor condition they are exposed to. As example, people can lower or increase their clothing resistance by removing or adding some items depending on the condition they are experiencing. There is anyway, especially for summer season, a minimum level of clothing that cannot be overcome. For example the minimum values recorded during these two period of measurements were 0.50 clo (April 5th) and 0.23 clo (July 18th).

In Table 17 the Spearman's[14] rank coefficients are reported. They were calculated assuming the clothing level as dependent variable which might be influenced by the outdoor temperature or by the operative temperature (independent variables). In April the clothing level correlates just with the outdoor temperature. The fact that is not correlating also with the indoor operative temperature can be potentially explained in two ways:

- Customers cannot adjust their level of clothing because they are wearing a single items for the upper part of the body that cannot be removed;
- Customers that can potentially adjust their clothing level, do not do so because of psychological mechanism.

Both reasons can explain the lower percentage of satisfied people with the thermal environment compared to the day in July.

Table 17 Correlation coefficient among clothing level with the outdoor and operative temperature through Parson parametric test (* statistical significance with 95% confidence interval, ** statistical significance with 99% confidence interval)

	April 5th	July 18th
clo ~ $T_{dry,out}$	-0.32**	NS
clo ~ $T_{op.}$	NS	-0.39**

The other reason which effect could be in a way added is the temperature step experienced by the customers while entering the shopping centre. With the aim of a better understanding of this phenomenon, the effect of the temperature difference on customers' thermal sensation and preference during the day of measurements was investigated.

First of all in Figure 49 the outdoor temperature trends in SC01 on April 4th 5th 2017 and in SC03 on 17th-18th July 2017. The temperature trends are quite different and in particular the daily temperature swing is higher in the SC01 location on April. This means that, even though the customers are experiencing the same operative temperature inside the shopping centres, their thermal experiences of outdoor condition are quite different. The analysis of the thermal sensation vote over the different outdoor-indoor temperature step is reported in Figure 50.

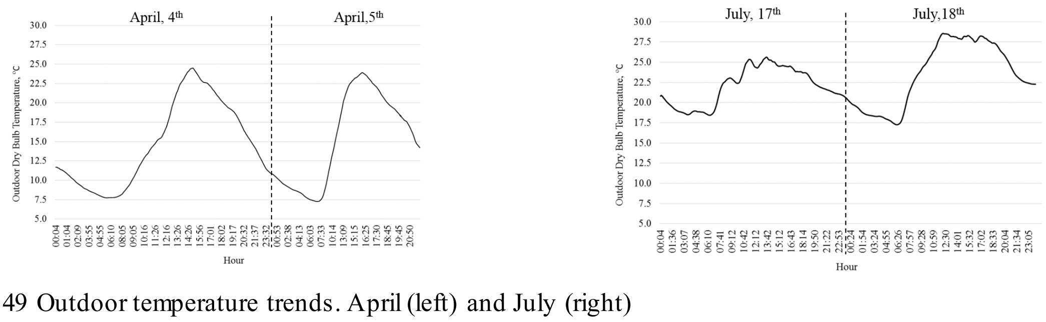


Figure 49 Outdoor temperature trends. April (left) and July (right)

[14] Both dependent (clothing level) and independent (outdoor temperature and operative temperature) are continuous variable with non-normal distribution therefore the use of Spearman's rank coefficient is justified [4.13].

For SC03 customers experience only down-step temperature differences (right side of the bar chart), meaning that they move from a warmer environment (outside) to a colder (inside the shopping centre common areas). The thermal overshoot generates an alliesthesial effect which results indeed in the highest percentage of satisfied customers.

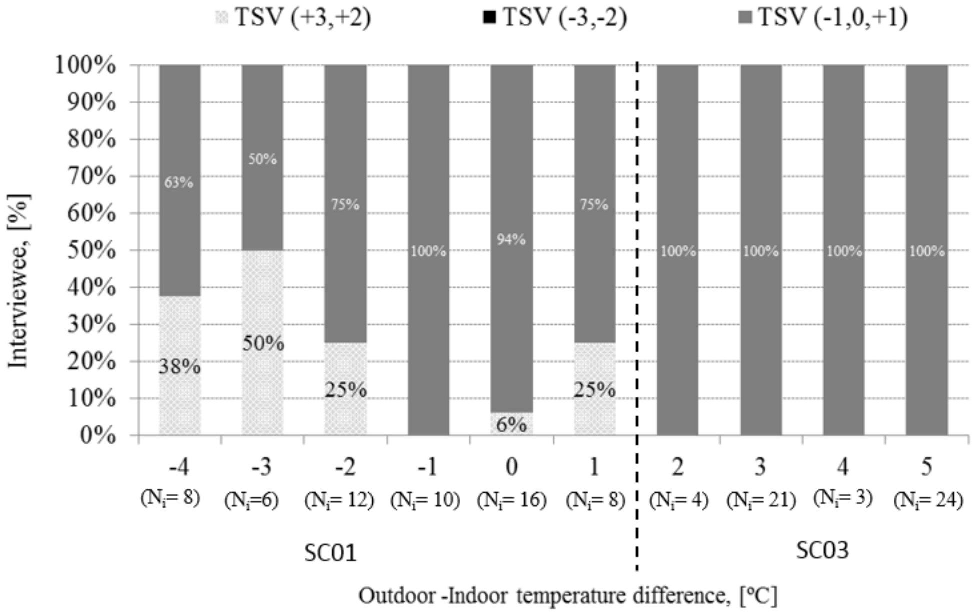


Figure 50 Bar Chart of the distribution of thermal sensation over outdoor-indoor temperature differences for SC01 and SC03 with average operative temperature close to 25 °C

What happens in SC01 is quite different. Customers experience an up-step temperature differences which create the percentage of warm dissatisfied (TSV equal to +3 and +2). People that comes from the outside were expected to find a cooler or at least the same temperature than outside, which is however not the case most of the time. The failure of this expectation creates such high percentage of dissatisfied. Most of time during the questionnaire, customers were exactly complaining about this.

Thermal sensation results find agreements with the votes related to thermal preferences shown in Figure 51. For SC01 the higher is up-step temperature difference the higher is the percentage of customers that would like to have a cooler environment. For SC03 instead the percentage of people who asked for cooler environment is lower and even some customers would prefer a warmer environment.

Based on the analysis, we can assume that high level of dissatisfaction with the thermal environment and the preferences for a cooler environment in SC01 on April are due to the still high level of clothing combined with the up-step temperature differences experienced by the customers.

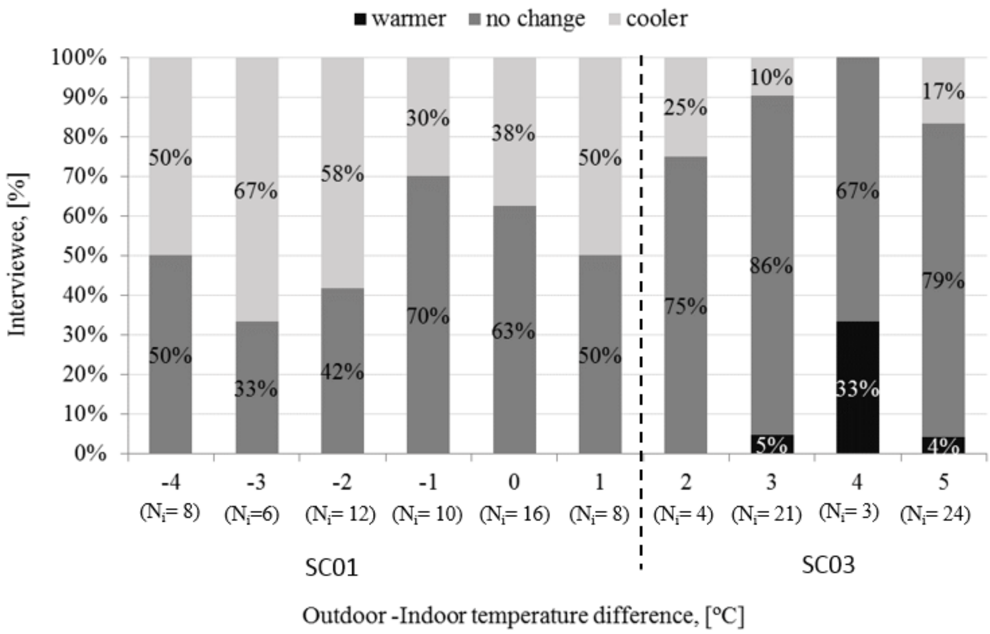


Figure 51 Bar Chart of the distribution of thermal preferences over outdoor-indoor temperature differences for SC01 and SC03 with average operative temperature close to 25 °C

4.6 Conclusion

The main results of the study can be summarized as follows:

- The steady-state model of Fanger was proved to be not accurate in the estimation of the customers' thermal sensation. It tends to overestimate discomfort, with an over-prediction error between 0.4 and 0.6 thermal sensation unit, with the increase of the operative temperature;
- The direct application of the adaptive thermal comfort model for transitional spaces is not recommended. This conclusion was reached especially for the conditions of dissatisfaction that such predicted comfort temperature can create in mid-season period. The reasons of the high level of dissatisfaction were identified in the clothing level (average value 0.77 clo) combined with the up-step temperature differences experienced by the customers;
- Shopping centres customers judge as comfortable operative temperatures that go from 23.5°C up to 27.5 °C. Neutral temperatures fall in the range between 25 ºC and 26 ºC while the preferred operative temperatures are in the range between 24.5 ºC and 26.5 °C;
- Independently from the time spent inside the shopping centre, the temperature difference between outdoor and indoor seems to have an influence on customers' thermal sensation and preference. It comes out that a comfortable environment could be guaranteed if this temperature step is restrained between 2°C and 4 °C. Nevertheless, because of the nature of the data collected during the measurements campaigns, which highest frequency was concentrated in the range of 25-26 °C of operative temperature,

the result cannot be however generalized to the whole range of outdoor temperature for the summer season;

- The study arose the necessity of a tailor-made model to assess thermal comfort in transitional spaces which correlates outdoor temperatures with indoor comfort temperatures on the basis of the direct observation of users' thermal sensation. In order to expand the database of evidence further field studies are required, gathering together a conspicuous number of data which cover all the seasons;
- To extend its reliability, the study needs to be replicated in other transitional spaces located under different climatic conditions within Europe.

4.7 Study limitation

The methodology of the field study considers both advantages and disadvantages for the research itself. Limitations arise from the lack of direct control over the environmental variables and from the difficulties to precisely asses human physiological conditions. On the other hand field studies are of great importance to study people thermal perception in a real environment under normal operation.

A first limitation of the study was that the physiological parameters of the customers were not directly measured. Therefore the metabolic activity was assumed according to the recommendation of the European standard comfort EN ISO 7730 [3.4], which suggest a value of 1.6 met for "shopping" activity.

As second limitation can be found in the scale used in the questionnaire for the evaluation of the thermal sensation. It was not continuous but discretized (7-point scale).The choice of a discrete scale was done mainly because of the paper-based questionnaire. The limitation showed up when directly comparing the PMV, a continuous value, with the actual thermal sensation of customers which is a discrete value (it varies between -3 and +3).Within the study a direct comparison was possible by categorizing the PMV (paragraph 4.5.4.1). By doing so, however a certain level of thermal sensation detail is lost.

In relation to the questionnaire, we also need to consider a bias error not quantifiable due to the spoken question with the subject in the interview. This may also affect the results as suggested by McIntyre [3.6].

As further limitation of the study it should be also considered the cultural influence of the customers interviewed. The study was conducted entirely in Italian shopping centres which means that it reflects the thermal perception of Italian customers. The results may vary if the study was conducted in another country.

4.8 Acknowledgements

The research leading to these results has received funding from the European Community's Seventh Framework Programme (FP7/2007-2013) under grant agreement n° 608678. I would like to than the project coordinator Roberto Lollini. Mover over I want to thank Baglivo Luca, Cennamo David, and Diener Valentino for the technical support in the realization of the MEMO cart, Damiano Cimino for the support in the data collection, Ulrich Filippi Oberegger for the support in the statistical data analysis. I would like also to thank with Spencer Dutton from LBNL (Lawrence Berkeley National Lab) who was as well involved in the study and with Angela Simone for the fruitful discussion related to thermal comfort measurements and interpretation of the results.

Bibliography

[4.1] P. Coleman. Shopping Environments: Evolution, Planning and Design. Oxford,UK: Elsevier. 2006

[4.2] GreenSense. Survey on Air Conditioning in Shopping malls 2016

[4.3] C.Y.Chun, A. Tamura. Thermal Environment and Human Responses in Underground Shopping Malls vs Department Stores in Japan. Building and Environment ,Vol 33, Nos 2-3, pp. 151-158, 1998

[4.4] EN ISO 7726. Ergonomics of the thermal environment.Instruments for measuring physical quantities.1998

[4.5] M.A. Humphreys. The optimum diameter for a globe thermometer for use indoors. Annals of Occupational Hygiene 1977; 20:135–40

[4.6] A. Simone,J. Babiak., M. Bullo , G. Landkilde., B.W: Olesen ., "Operative temperature control of radiant surface heating and cooling systems", In proceedings of: Clima 2007 Wellbeing Indoors. Finland, Helsinki, June 10-14 2007.

[4.7] M. Schweiker. comf. An R Package for Thermal Comfort Studies. The R Journal Vol.8/2, December 2016

[4.8] Microsoft Office Excel

[4.9] The R Project for Statistical Compunting

[4.10] F.Nicol, M.Humpreys.Derivation of the adaptive equations for thermal comfort in free-running buildings in European standards EN15251.Building and Enviroment 45 (2010) 11-17.

[4.11] M.A. Humphreys. Outdoor temperatures and comfort indoors. Building Research and Practice (J CIB) 1978; 6(2):92–105.

[4.12] Weather Underground web site

[4.13] Field A., M. J. (2012). Discovering statistic using R. London: SAGE Publications Ltd

[4.14] R. de Dear, J. Ring, P. Fanger, Thermal sensations resulting from sudden ambient temperature changes, Indoor Air 3 (1993) 181-192.

[4.15] M. Cabanac, Physiological role of pleasure, Science 173 (1971) 1103-1107.

[4.16] T. Parkinson, R. de Dear, Thermal pleasure in built environments: physiology of alliesthesia, Building Research and Information Vol.43 (2015) 288-301 Taylor &Francis

[4.17] Z. Yu,B,Yang, N. Zhu, T. Olofsson, G. Zhang. Utility of cooling overshoot for energy efficient thermal comfort in temporarily occupierd space.Building and Environment 109 (2016) 199-207

[4.18] C. Morgan, De Dear R. Weather Morgan C, De Dear R. Weather, clothing and thermal adaptation to indoor climate. Climate Research 2003;24:267-84.

[4.19] Z.Yu J. Li, B. Yang,T. Olofsson, G. Zhang. Temporarily occupied space with metabolic-rate-initiated thermal overshoot-A case study in railway station in transition season. Building and Environment 122 (2017) 184-193

5 Thermal comfort and airflow performance of a mixed-mode atrium in a warm temperate climate

5.1 Introduction

In paragraph 1, several mixed-mode ventilation scheme were presented and transitional spaces role within the ventilation strategy was investigated. In their original design intention, mixed-mode buildings are designed in such way that the HVAC system operates to maintain comfortable conditions when natural ventilation limitation shows up.

The design of a natural ventilation system is however not an easy task. The design of active systems, as mechanical ventilation and air-conditioning systems, relies on controllable energy sources. Contrarily, natural ventilation is driven by pressure difference which is extremely variable. Natural ventilation indeed relies on natural forces: wind and air temperature differences generate pressure gradients between outdoor and indoor or between different internal zones. This makes natural ventilation design very challenging [1.6]. Even for the best design practise example, the assessment of the actual performance a difficult task. The variability of climate condition outside and the indoor condition in term of internal gains play a considerable role.

In a recent work [1.7], ten typical question design practitioners have on natural ventilation were answered. The authors sustain that the rarity of natural ventilation integration in modern non-domestic building design is due to the lack of knowledge and confidence in natural ventilation system possibilities. This lack of knowledge is also generated by the lack of information about the real performance of naturally ventilated and mixed-mode buildings. As consequence, the penetration of natural ventilation solution and the energy use intensity of new non-domestic buildings was almost constant during the last decade, even in locations with a climate suitable for natural ventilation.

The authors also stressed the fact that to overcome this stationary situation, engineers and design practitioners need improved airflow simulation tools by means of reliable measurements validation.

With the aim of reducing this lack of information, the author carried out a long term measurement campaign in a central atrium of a mixed-mode multi-service building located in a warm temperate climate. The atrium has most of the transitional spaces characteristics identified in chapter 1. The objective of the measurement campaign was:

- the quantification of effect of a wind and stack-driven night ventilation over the total cooling energy consumption of a transitional space;
- the evaluation of the indoor thermal environment by means of direct thermal comfort assessment with the users of the atrium.

Thermal comfort evaluation followed the same methodological approach used for shopping center which was already presented in chapter 4.

In the following paragraphs the case study, the methodology followed and the results about the characterization of the thermal environment and thermal comfort assessment are presented and discussed.

5.2 Case study

The building is located in the warm temperate climate of Seixal [1.18], in the south bay area of Lisbon, Portugal. Some of its features have been already presented in paragraph 1.3.2 being one of the case studies of the database of mixed-mode ventilated transitional spaces [1.10].

It is a multi-service building consisting of two main blocks with 3-floors connected by a central atrium. Each block is equipped with both single and open space offices. On its north –west orientation the building faces an auditorium which is physically separated from the main building. The ground floor is occupied by the atrium and a cafeteria. In the basement there are a parking, the technical room and an archive. The two offices blocks face North and South orientation.

The central atrium (volume ≈ 16244 m^3) is a transitional space for temporary users and people working in the adjacent offices as well as a working area for internal employees. The space is conditioned by means of a radiative floor system, which is supported, during mid-season and summer, by a night-time ventilative cooling strategy. The nighttime ventilative cooling strategy involves different openings located at different oriented façades.

Wind and stack-driven ventilation runs during night circulating airflows from West to East side of the atrium through top hung openings located at different heights. The strategy was designed considering the prevailing wind direction of the site. At night, it usually comes from the ocean, namely from North-West orientation. In Figure 52 the exterior and the interior view of the atrium while in Figure 53 the ventilation strategy is reported.

Figure 52 Building view from the outside (left), an internal view of the central atrium (right)

On the inlet side (West façade) there are two rows of windows consisting of 8 openable modules each (see Figure 53). On the outlet side (East façade) there is one row of 12 windows but just 5 of them can be operated. All the windows can have two positions, totally closed or opened with 25° opening angle. No modulation is applied. Windows features are reported in Table 18.

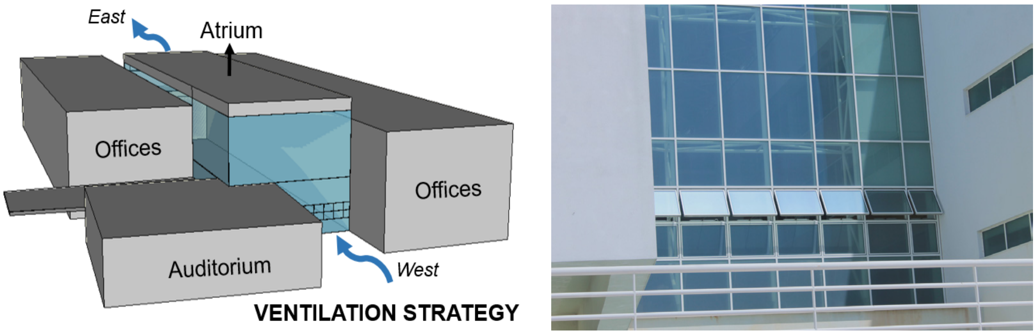


Figure 53 A 3D sketch of Seixal city Hall showing the night ventilation strategy (left) and an outdoor view of the second row of inlet windows on west side (right)

Table 18 Features of the windows used in the ventilation strategy

Façade Orientation	**Dimension**	**Typology**	**Maximum opening angle**	**Number of Module**	**Reference height of the middle plane from the ground**
West	130 cm x 95 cm	Top hung tilted	25°	14 (7 mod/row)	2.12 m (first row) 3.1 m (second row)
	85 cm x 95 cm	Top hung tilted	25°	2 (1 mod/row)	2.12 m (first row) 3.1 m (second row)
Est	124 x 145 cm	Top-hung tilted	25°	5	13.8 m

The windows are equipped with electric actuators which are connected to the general Building Management System (BMS) of the building. The control strategy is manual which means that the technical engineer of the building, based on outdoor and indoor climatic conditions, decides between two different modes, mode A and mode B (Table 19).

When mode A is selected, on inlet side (west façade) only the second row of windows is opened while on outlet side (east façade) 3 windows are operated. In mode B, all openable windows on both inlet and outlet are operated. When night ventilation is applied, the windows are kept opened for all night starting from closing hours (8 p.m.) until the morning next day (8 a.m.). The ventilation strategy was tested by the technical engineer also during working hours. Because of complains about draught from the people working in the atrium, he decided to operate the windows only at night.

The building is also equipped with two rows of nine windows located in the upper part of the atrium, on opposite orientation (North-South). Operated between April and October these windows in the upper part of the building allow during daytime to exhaust the warm exhaust air that stack under the ceiling with fresh one coming from the outside. Nevertheless, for the content of this study just the openings located on west and east orientation are considered in the performance assessment.

Table 19 Control modes for windows operations

Mode	Inlet Openings	Outlet Openings	Total Effective Opening Area [m^2][5.1]	Total Effective Opening Area/ Floor Area
A	Second row	3 modules	9.7	1%
B	First & Second row	5 modules	18.7	2%

5.3 Methodology

The aim of the study is to assess the performance of the large mixed-mode atrium. The advantage of using natural ventilation at night is expected to affect the thermal performance of the atrium resulting in a reduced cooling demand while maintaining comfortable conditions.

In order to assess the performance, a long-term monitoring campaign was set up. During a period of four weeks, the atrium was therefore operated under three different modes which features are described in Table 20.

In a reference scenario, *mode RFC*, the atrium was operated just with the radiant cooling floor during daytime. Under *mode NV & RFC natural ventilation* operates at night from 8 p.m. till 8 a.m. and the cooling radiant floor is activated during day when needed. The cooling set-point is equal to 24 ºC which means that the system switch automatically on when the indoor temperatures are higher than this threshold. The last *mode* named *NV* consists in recirculating outside fresh air at night. The cooling system is intentionally switched off during the day in order to prove if natural night ventilation could be alone enough to maintain comfortable conditions within the atrium during the day.

Table 20 Operation modes tested during the long-term measurments

Mode	Description
RFC	Operation of just the radiant cooling floor during the day with cooling set-point equal to 24 ºC
NV & RFC	Operation of natural ventilation at night under mode A (Table 19). During the day the radiant cooling floor is activated if the indoor temperature is higher than 24 ºC.
NV	Operation of natural ventilation at night only. The radiant cooling floor is intentionally switched off.

We assessed indoor thermal comfort during the long-term measurements campaign by applying the same methodology presented in chapter 4. 15 guests and 15 workers of the atrium were interviewed under modes *NV* and *NV & RFC* to check if any differences occur in the way their perceive the thermal environment. The data collected though the questionnaires were cross checked with the environmental variables recorded by MEMO (Figure 24).

Before the long term measurements set-up, a first experiment to calculate a correlation coefficient between the air velocity at inlet and the bulk airflow at night was performed. This coefficient will help to quantify the bulk airflow under *mode NV* and *NV & RFC* during the long term measurement campaign. In paragraph 2 the methodology of this experiment is presented while in paragraph 5.3.1.1 the set-up of the long term measurement is discussed. For the methodology of the thermal comfort assessment we refer to chapter 4.

5.3.1 Correlation coefficient and bulk airflow measurement

Full-scale measurements of airflow in buildings are commonly performed by using tracer gas technique. This technique is based on the injection of gas into the space where concentration response is then measured. Carbone dioxide was used as tracer and two different tracer gas methods were tested. The first method, *Constant release method*, consists in a continuous release of a traceable gas into the space with a constant flow during the entire measuring period. When stabilized indoor conditions are reached the bulk airflow is calculated by solving the mass balance described in equation (5) [5.2]

$$F\left(\frac{m^3}{s}\right) = \frac{CO_{2,released}\,\left(\frac{mg}{s}\right)}{[CO_{2,outlet}]-[CO_{2,inlet}]\,\left(\frac{mg}{m^3}\right)} \quad (5)$$

Where

F is the bulk air flow m^3/s;

$co_{2,released}$ is the CO_2 released during the experiment, mg/s;

$co_{2,outlet}$ is the CO_2 concentration measured at outlet windows, mg/m^3;

$co_{2,inlet}$ is the CO_2 concentration measured at inlet which we assume equal the outdoor concentration, mg/m^3.

After reaching stabilized indoor conditions the release of the CO_2 is stopped and a natural decay of its concentration begins. By knowing the CO_2 concentration at multiple point during the decay it is possible to calculate the airflow through the equation (6) [5.3]

$$F\left(\frac{m^3}{s}\right) = \frac{\left(\sum_{j=1}^{n} t_j\right) * \sum_{j=1}^{n} ln\left[c(t_j) - c_{bg}\right] - n * \sum_{j=1}^{n} \ln\left[c(t_j) - c_{bg}\right]}{n * \sum_{j=1}^{n} t_j^2 - \left(\sum_{j=1}^{n} t_j\right)^2} * \frac{V_{atrium}}{3600} \quad (6)$$

Where

C_{bg} is the CO_2 background concentration equal to the initial value of CO_2 at the beginning of the decay, mg/m^3 ;

tj is the j-th elapsed time from the decay process starting;

C(tj) is the measured gas concentration at time (tj), mg/m^3;

n the total number of measured elapsed time points (n=35);

V_{atrium} is the total volume of the atrium, m^3.

The bulk air flow rate is evaluated using both methods and then the average value is used to calculate the correlation constant k between airflow and inlet air velocity through equation (7).

$$k = \frac{\bar{F}}{v_{air\_in}} \quad (7)$$

Where

$\bar{F}$ is the average value of the two bulk airflow calculated with equation (5) and (6), m^3;

v_{air_in} is the average value of the air velocity measured at inlet opening, m/s.

5.3.1.1 Experimental set-up

The experiment was conducted under control mode A (see Table 19). Figure 54 shows the measurement setup.

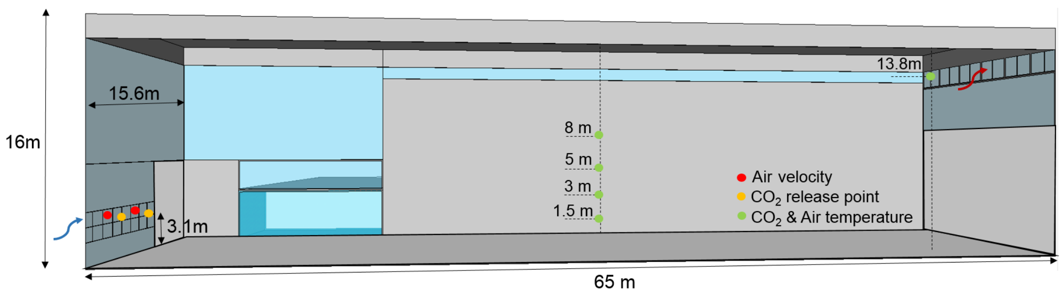


Figure 54 Location of the sensors used for the experiment and CO_2 release point location

The CO_2 injection took place at 3.1 m from ground, close to the inlet in two different positions. The air velocity of the air entering the atrium is monitored at the same level. A central row of CO_2 and air temperature sensors is used to track the development of the condition (air temperature and CO_2 concentration) inside the atrium as well at the outlet level. Sensors characteristics are collected in Table 21.

Table 21 Specification of the measurement equipment used for indoor

Sensor	Measurement	Specification	
E+E elektronik EE65	Air velocity (indoor)	Range	0 to 10 m/s
		Accuracy	± 0.2 m/s + 3%
CO2 Meter (K-33 ELG)	Carbon dioxide (indoor)	Range	0-10000 ppm
		Accuracy	± 30 ppm + 3%
	Temperature (indoor)	Range	-40 to + 60°C
		Accuracy	±0.4 °C at 25 °C

Natural ventilation relies on natural forces. For this reason information about the actual climatic conditions of the building site are important for the assessment of the ventilation performance. Therefore a dedicated weather station was positioned close to the building in an open free area at 5 m above ground level as indicated by the red star in Figure 55.

Figure 55 Location of the installation of the weather station marked with the red asterisk

It consists of a wind speed and direction sensor, a pyranometer for measuring the global and diffuse radiation and a temperature and humidity sensor. The data were acquired every 5 minutes. The sensors specifications are collected in Table 22.

Table 22 Specification of the measurement equipment used for the weather station

Sensor	Measurement	Specification	
Wind Monitor 05103 Campbell Scientific	Wind speed(outdoor)	Range	0-100 m/s
		Accuracy	± 0.3 m/s or 1% reading
	Wind Direction(outdoor)	Range	0 to 360 °
		Accuracy	±3 °
Pyranometer SPN1 Delta-T Devices	Solar radiation (global and diffuse)	Range	1 to 2000 W/m^2
		Accuracy	±5% ±10 W/m2
HOBO (U12-013)	Temperature (outdoor)	Range	−20.0 to 70.0 ◦C
		Accuracy	±0.35 ◦C from 0 to 50.0 ◦C

The experiment was performed at the end of May 2017, after public opening hours, once the building was not occupied. Starting from 6:30 p.m. CO_2 was released in the atrium for two hours and a half before reaching stabilized conditions at around 9:15 p.m. During this time the CO_2 release rate was monitored assuring to be constant. Once the stability was reached the release of CO_2 was stopped and a natural decay process started for about 45 minutes. The experiment was concluded at 22:00 p.m..

5.3.2 Long term measurement campaign

The long term measurement campaign lasted one month in July 2017. In Figure 56 the measurement set-up is reported.

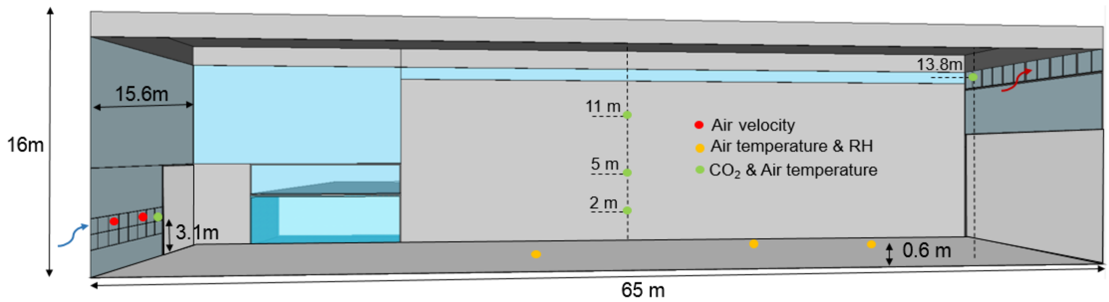


Figure 56 Location of the sensors used during the long-term measurements campaign

The configuration is similar to the one used for the bulk airflow experiment (see paragraph 5.3.1.1). A center line of sensors at different positions from the ground (2m, 5m and 11m) measures CO_2 concentration and air temperature. Then, within the usually occupied area three HOBO sensors were positioned at 0.6 m from the ground recording air temperature and relative humidity. Air velocity is tracked at inlet opening while CO_2 concentration and air temperature are also monitored at inlet level and outlet level. In order to quantify the cooling demand of the radiative floor system, the supply and return water temperatures were also monitored by using two thermocouples positioned in direct contact with the water flow inside the pipes. The sensors characteristics are collected in Table 23. Acquisition time step was set to 5 minutes. The same weather station described in paragraph 5.3.1.1 was used for the long term measurements.

5.4 Results and discussion

In this section the results of the whole study are presented and discussed. The results are presented in the following order:

- Determination of the correlation constant k ;
- Comparisons in term of energy consumption, thermal and airflow characteristics of the modes during the long term measurements;

- Thermal comfort assessment.

Table 23 Specification of the measurement equipment used for the long term monitoring

Sensor	Measurement	Specification	
E+E elektronik EE65	Air velocity (indoor)	Range	0 to 10 m/s
		Accuracy	± 0.2 m/s + 3%
CO2 Meter (K-33 ELG)	Carbon dioxide (indoor)	Range	0-10000 ppm
		Accuracy	± 30 ppm + 3%
	Temperature(indoor)	Range	-40 to + 60°C
		Accuracy	±0.4 °C at 25 °C
HOBO (U12-013)	Temperature (indoor)	Range	−20.0 to 70.0 ◦C
		Accuracy	±0.35 ◦C from 0 to 50.0 ◦C
	Relative Humidity	Range	5% - 95% RH
		Accuracy	±2.5% from 10% to 90% RH
HOBO (U12-013)	Temperature (inlet /outlet)	Range	−20.0 to 70.0 ◦C
		Accuracy	±0.35 ◦C from 0 to 50.0 ◦C
TEL AIR 7001	CO2 concentration (inlet/outlet)	Range	0 -2500 ppm
		Accuracy	±50 ppm or 5% of reading
ONSET TMC6-HE sensor probe	Water temperature radiant floor (Supply and Return)	Range	-40° to 100°C
		Accuracy	±0.25°C from 0° to 50°C

5.4.1 Determination of the correlation constant *k*

As already discussed in the introduction, pressure differences drive the circulation of airflow within building. The pressure difference can be either generated by wind or by the thermal stratification inside the building, named buoyancy. The pressure force due to wind is expressed in equation (8) while the one produced by buoyancy in equation (9).The combined effect can be calculated with equation (10).

$$\Delta P_{,w} = \frac{1}{2}\Delta C_p \rho W_s^2 \quad (8)$$

Where

ΔC_p is the pressure coefficient difference, Pa;

ρ is the air density, kg/m^3;

W_s is the wind speed recorded by the weather station, m/s.

$$\Delta P_{,b} = \rho g (H_{out} - H_{in}) \left(\frac{T_{out} - T_{outlet}}{T_{outlet} + 273.15}\right) \quad (9)$$

Where

ρ is the air density, kg/m^3;

g is the gravitation acceleration m^2/s;

H_{out} is the reference height of the outlet openings, m;

H_{in} is the reference height of the inlet openings, m;

T_{out} is the outdoor temperature, ºC;

T_{outlet} is the air temperature measured at outlet openings, ºC.

$$\Delta P_{,tot} = \sqrt{\Delta P_{,w}^2 + \Delta P_{,b}^2} \quad (10)$$

Where
$\Delta P_{,w}$ is the pressure difference due to wind, Pa;
$\Delta P_{,b}$ is the pressure difference produced by buoyancy, Pa.

The pressure coefficient difference, ΔC_p, used in equation (8), is the difference between the average pressure coefficient at inlet and the one at outlet calculated according to equation (11)

$$C_p = \frac{P_{local}}{\frac{1}{2}\rho U_{ref}^2} \tag{11}$$

Where

P_{local} is the local wind driven static pressure, Pa;
ρ is the air density, kg/m^3;
U_{ref} is the reference value of wind speed equal to 10m/s at 10m from the ground, m.

By means of a CFD simulation model I estimated the local pressure, P_{local}, generated by the wind at inlet and outlet level for eight different wind orientations. The simulation was run with the commercial CFD code Ansys Fluent 15 [5.4] and the pressure coefficient out coming from the simulation are collected in Table 24.

The pressure coefficient is the ratio of the local wind driven static pressure and the incoming wind pressure express by equation (11).

Table 24 Pressure coefficient at inlet, outlet and difference

	N	NE	E	SE	S	SW	W	NW
Cp_{in}	-0.73	-0.27	-0.18	-0.54	0.00	0.46	0.97	0.31
Cp_{out}	-0.64	0.07	0.19	0.33	-0.58	-0.72	-0.42	-0.82
ΔC_p	-0.09	-0.35	-0.37	-0.86	0.58	1.18	1.39	1.13

At each time step, depending on the wind direction I calculate the $\Delta P_{,w}$ by using the associated ΔC_p..The analysis of the pressure trend during the experiment, even if was conducted afterwards, was essential to understand the airflow physic within the atrium during the whole experiment. It was also crucial to verify the goodness of the experiment.

The graph in Figure 57 shows the distribution of the monitored wind direction, and wind speed and the pressure generated by wind during the experiment according to the pressure distributions predicted by the CFD analysis. The prevailing wind direction was from north and north-west orientation. We also observed a progressive decrease of the wind speed along the duration of the experiment.

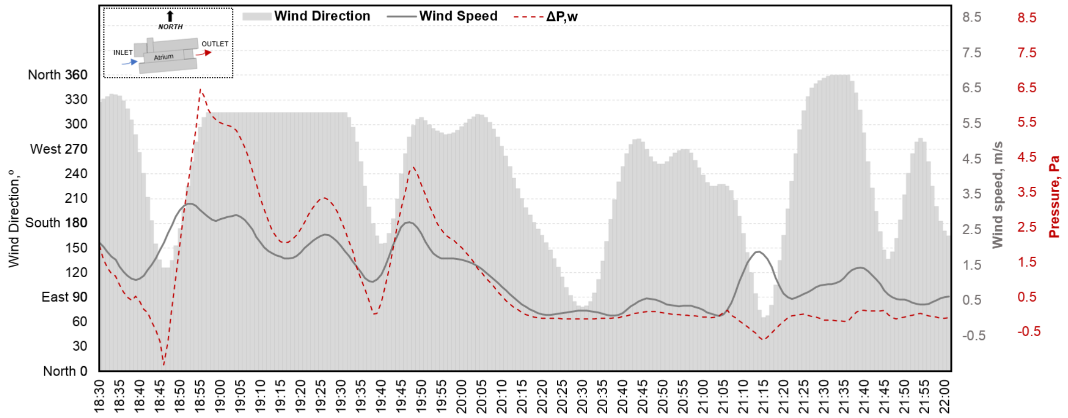


Figure 57 Wind distribution, wind speed and pressure generated by the wind during the experiment

While the pressure due to wind decreased with time, the difference between indoor and outdoor temperature increased resulting in an increase of buoyancy pressure (Figure 58).

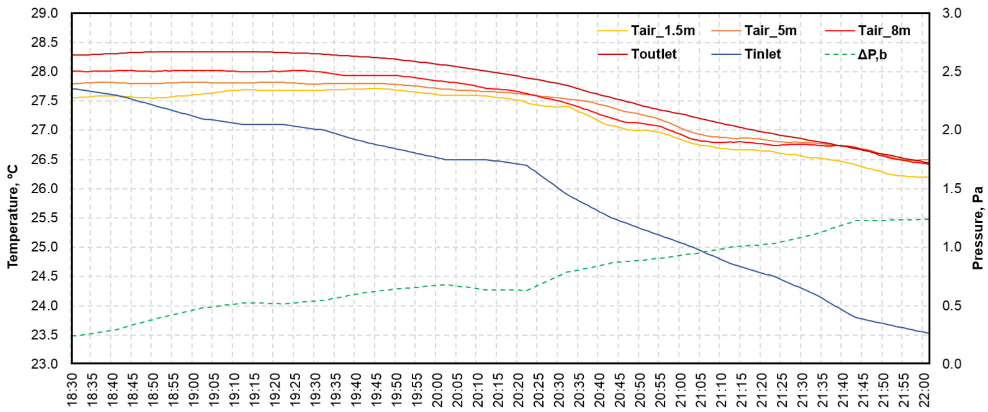


Figure 58 Temperature distribution during the experiment and buoyancy pressure

For the first half of the experiment the main driving force is the wind pressure which is very variable and unstable as shown in Figure 59. In the second half, the airflow is mainly driven by the buoyancy resulting in more stabilized conditions.

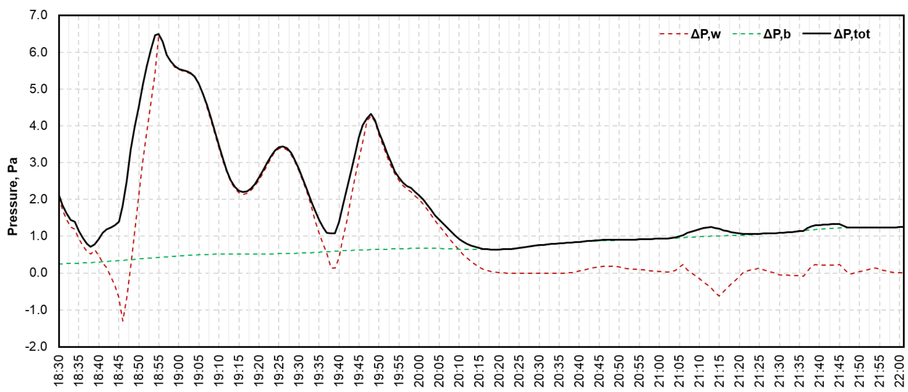


Figure 59 Physics of the pressure during the experiment

With reference to the CO_2 concentration variation, three different phases during the experiment can be identified as showed in Figure 60.

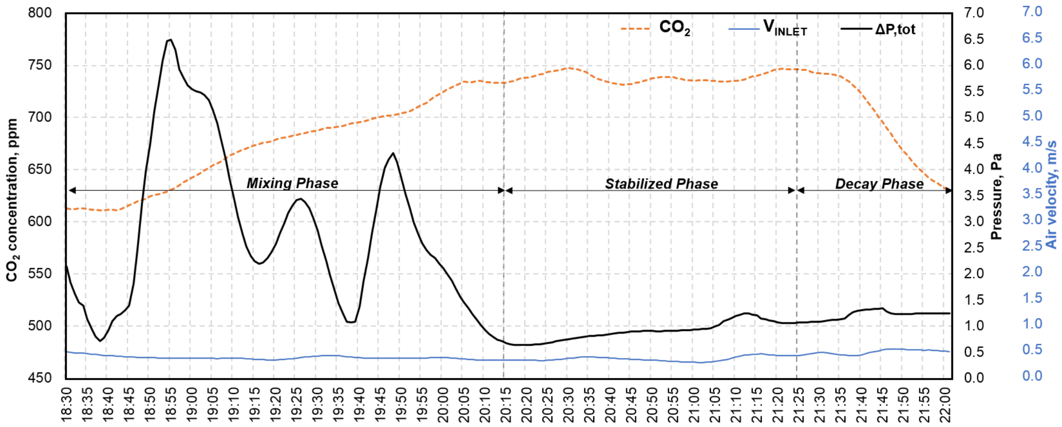


Figure 60 Phase of the experiment on the bases of CO_2 distribution

The first phase is the *mixing phase,* where the total pressure conditions are unstable and the CO_2 concentration progressively increases. This phase lasts for around one hour and half till a stable concentration of CO_2 is reached. At this point we enter in the second phase, named *stabilized phase*, where we can observe a stable conditions for both the CO_2 concentration and the total pressure for around one hour inside the atrium. The stabilized conditions allow us to calculate the average airflow. Considering a total CO_2 release of 1720 mg/s and a CO_2 concentration difference between inlet and outlet of around 330 ppm (600 mg/m^3), the airflow, calculated through equation (5) is equal to 2.9 m^3/s.

For both calculations the $CO_{2,inlet}$ and the C_{bg} are assumed to be equal to 400 ppm, measured value of the outdoor CO_2 concentration.

The last phase, named *decay phase,* starts when the CO_2 release is stopped and the CO_2 indoor concentration begins its natural decay. During this last phase we also observe stabilized condition of total pressure .The decay time was about 35 minutes. After this period the initial conditions inside the atrium were reached again. The airflow calculated during the decay, through (6), it is equal to 2.7 m^3/s. The error between the two methods is 6%. For the calculation of the constant correlation k we use the average of the two airflow values which is equal to 2.8 m^3/s.

Considering an average air velocity at inlet of 0.40 m/s for the stabilized phase, the correlation constant k, calculated though equation (7), is equal to 6.93.

This constant in going to be used to assess the bulk airflow at night under modes *NV* and *NV & RFC* during the long term measurements, just by tracking the air velocity at inlet.

5.4.2 Analysis of the atrium energy and thermal performances

Outdoor condition may deeply differ within the timeframe of a month and it is common that temperatures, solar radiation and relative humidity daily distribution do not follow the same trends. Therefore a first analysis to identify which days in term of outdoor conditions are comparable is essential. Assuring an equality in outdoor conditions allow us to derive more robust consideration about the energy and thermal performance of the atrium.

For each day of measurement the number of hour is which the outdoor temperatures were above the cooling set-point threshold (24ºC) was calculated through equation (12).

$$CDH = \sum |T_{out} - 24ºC| \quad (12)$$

The parameter *CDH,* which can be associate to a cooling degree hour parameters, helps to understand for which days the outdoor climatic conditions are more extreme, resulting in a higher cooling demand.

Solar gains play an important role in the energy balance of a building. Especially for big space as atria with large glazed façade, the level of solar gains to be offset in order to maintain comfortable level in the indoor spaces is not negligible. An approximation of the level of solar gain is done by multiplying the average valued of the direct solar radiation[15] during the occupied hours (8 a.m.-7p.m.) with the g-value of the glazing façade system which is equal to 0.41.

CDH and *Solar gains* for each measurement day are presented in Figure 61. In the graph, the different operation modes are marked with boxes with different colours. The days identified with the star are the one in which the direct thermal comfort assessment with guests and workers took place. As expected, it is challenging to have days that can be directly compared. Nevertheless, some information about the reduced cooling demand because of the operation of the night ventilation can be retrieved. This estimation is indeed possible by comparing 25th and 26th July (mode *NV & RFC*) with 27th and 28th (mode *RFC*). For these days the level of the solar gains and the CDH trend are quite the same.

The thermal performances of the atrium under the three different modes can be examined by comparing the days 14th (mode NV) 26th (mode NV & RFC) and the 28th (mode RFC). In Figure 62 the wind speed and direction rose chart of the data recorded during the measurements campaign period is presented. As expected the prevailing wind direction is from North and North-West. The wind speed highest frequency is between 3 m/s and 4 m/s. In Annex C the wind speed and direction rose chart for each hour of the night from 8 p.m. till 7 a.m., period in which night ventilation is operated, are collected.

[15] The direct solar radiation is calculate as difference between the global and the diffuse solar radiation. Both parameters were recorded by the dedicated weather station (see Table 22).

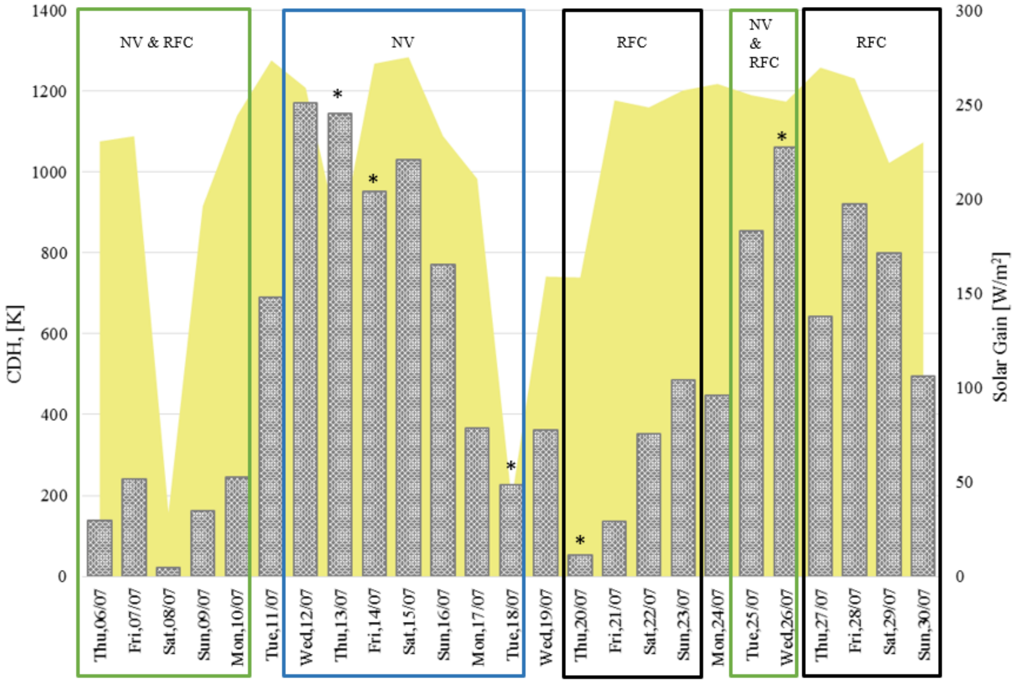


Figure 61 *CDH* and Solar Gains for all the days of the measurements campaign. Days identified with the star are the one in which the direct thermal comfort assessment with guests and workers took place.

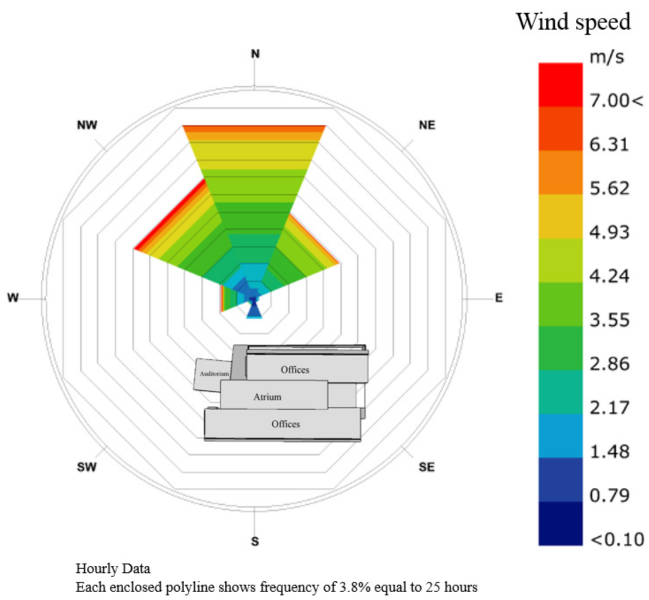


Figure 62 Wind rose based on the data recorded by the weather station installed close to the building in the period between July 4th and July 31th 2017

5.4.2.1 Comparison between NV & RFC and RFC

By comparing the cooling demand of the atrium under mode *NV & RFC* with the reference mode *RFC* is possible to estimate the effect of night ventilation in term of cooling demand reduction. As observed in paragraph 5.4.2, two consecutive comparable days under mode *NV & RFC* and mode *RFC* are respectively 25th - 26th July and 27th-28th July. Even though the outdoor conditions are quite similar, a more accurate comparison between the cooling demands under the different modes is possible by normalizing the data over the external climate conditions.

The cooling demand was estimated thanks to the monitoring of supply and return water temperature of the dedicated radiant cooling floor of the atrium. The cooling demand was calculated according to equation (13)

$$Q_{cool} = \dot{m}_w * Cp_w * \sum_{h_i}^{h_j} (T_{w,r} - T_{w,s}) \quad (13)$$

where:
$\dot{m}_w$ is the water flow of the radiant cooling floor which is equal to 7.2 kg/s [m^3/h][16];
Cp_w is the specific heat of the water which is equal to 4.186 [kJ/kg K];
$T_{w,r}$ is the return water temperature [ºC];
$T_{w,s}$ is the supply water temperature [ºC];
h_i is 8 a.m.;
h_j is 7 p.m.

In order to be able to compare the energy consumption during different days and cooling modes, the daily cooling demand (kWh) was normalized over the cooling degree hour, as shown in equation (14)

$$Q_{cool,n1} = \frac{Q_{cool}}{CDH} \quad (14)$$

where:
Q_{cool} is the cooling demand, kWh;
CDH is calculate according to equation (12).

The results are presented in Figure 63. The outdoor maximum temperature is different just in July 27th being 2.5 ºC lower than the other three days of measurements when maximum outdoor temperature is around 34.5 ºC. When night ventilation is operated (mode *NV & RFC*) the normalized cooling demand is reduced by 43%. The values are calculated as average values over the two days of measurements under mode *NV & RFC*

[16] The value was recovered from the technical information gave from the energy facility manager of Seixal city Hall

and under *mode RFC*. The absolute values of the cooling demand, normalized and not, are shown in Table 25.

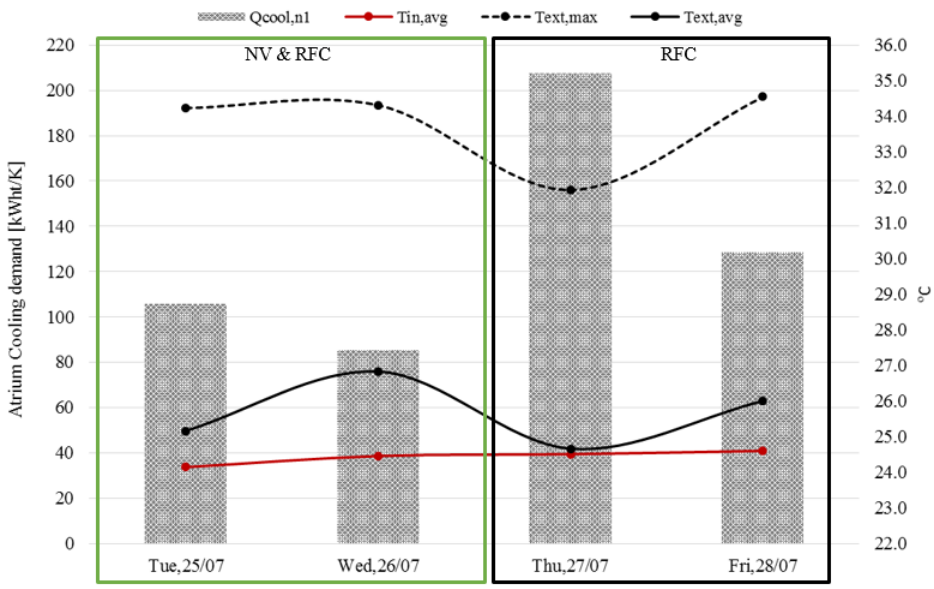


Figure 63 Comparison of the normalized cooling demand (N1and N2) between mode *NV & RFC* and *RFC*. The graph also show the average indoor and outdoor temperature during occupied hours (8 a.m.-7 p.m.) and the maximum outdoor temperature recorded for the four measurements days

Table 25 Comparison in term of normalized cooling demand between mode NV & RFC and RFC

Mode	Q_{cool} [kWht]	$Q_{cool,n1}$ [kWht/K]
RFC	315	96
NV & RFC	438	168
saved	123	72
% saved	28%	43%

The reduced cooling demand is related just to one day measurements; therefore considering the whole summer season the potential energy saving are promising. In the following paragraph 5.4.2.1 and 5.4.2.2 the thermal performance of the atrium operated under the three modes are analyzed. In particular, the thermal performance of the environment under mode NV are examined and compared with the other modes. By doing so we want to investigate if the cooling system can be avoided or restrained to extreme outdoor conditions. This achievements could result in reduction of operation costs of the building without compromising users' thermal comfort, which is also tested by the direct thermal comfort assessment presented in paragraph 5.4.3.

5.4.2.2 Comparison between NV and NV & RFC

As already discussed in 5.4.2 , a robust comparison between the different modes would be possible if the outdoor climatic conditions are almost the same. The selected days for comparison of thermal performance are the 14th (mode NV), the 26th (mode NV & RFC) and the 28th (mode RFC). In Figure 64 the indoor and outdoor temperature trends for the three days are shown. The values showed are the mean values recorded by the three sensors located in the occupied area at 0.6 m from the ground (see Figure 56).

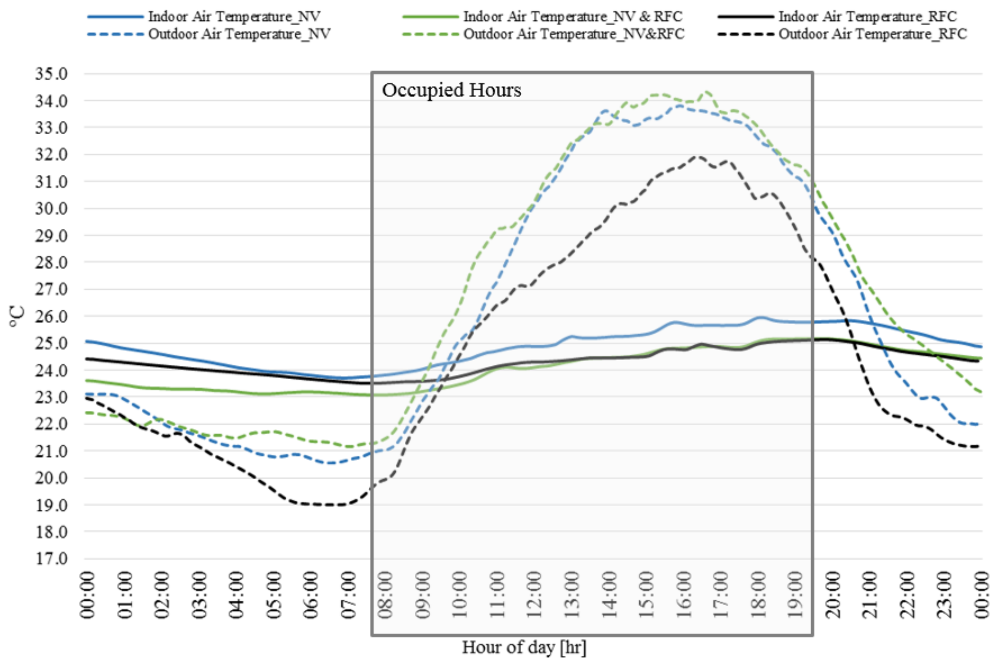


Figure 64 Indoor and Outdoor temperature trends during the three different modes (NV-14th July, NV & RFC-26th July, RFC-28th July)

The trend and the values of the outdoor temperatures recorded under mode *NV* and *NV & RFC* are quite the same. The outdoor condition under mode *RFC* slightly differ in the maximum and minimum peak of temperature reached which are on average 2K lower compared to the other modes. During occupied hours, under mode *NV*, although the outdoor temperature are unfavourable in comparison with other modes, the indoor temperature in the occupied area is just 1K higher compared to mode *NV & RFC* and mode *RFC*. The decrease in temperature at night operated by night ventilation at occupied level is about 1K. This values is observed by comparing the indoor air temperature trend of *NV & RFC* mode with the one of *RFC* between 12 p.m. and 6 a.m.

When looking at the temperatures recorded at the different height of the atrium, the effectiveness of the natural displacement ventilation at night is more evident. Figure 65 reports the temperature trends at 2m, 5m and 11m and outlet together with average CO_2 concentration. A decrease of about 5 ºC is observed at 11m and outlet level between 8 p.m. and 7 a.m.. At this time the solar gains probably starts to influence the thermal balance of the building and consequently the temperature inside the atrium. At that time indeed the indoor temperature start raising at all the measurements height.

A decrease of the indoor temperature of around 4 K is also observed when night ventilation is not operated as Figure 66 displays. Nevertheless the outdoor temperatures in the night between 27th and 28th are lower and have a different behaviour compared with the one of the night between 13th and 14th (mode *NV*) therefore we can assume that the decrease in indoor temperature is influenced by the infiltration which makes also the level of CO2 decreasing.

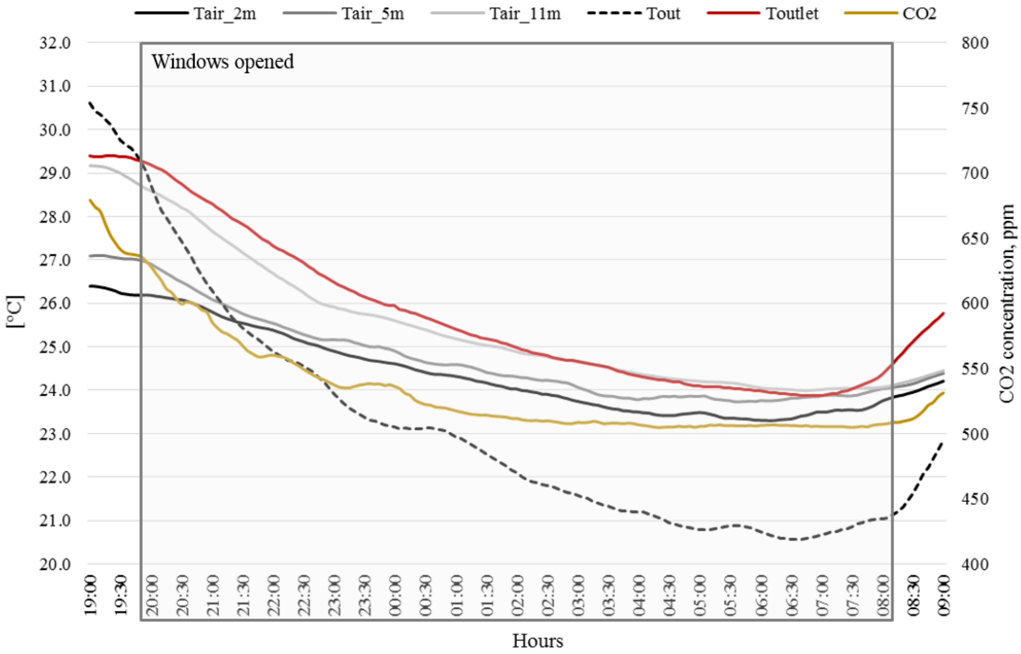


Figure 65 Temperatures and CO_2 trend during night under NV mode (night between 13th and 14th July)

In paragraph 5.4.1, the results of the tracer gas experiment for the calculation of bulk airflow and the correlation coefficient *k* were presented. This coefficient is now used to estimate the bulk airflow at night during mode *NV* and *NV & RFC* by multiplying the coefficient for the air velocity values recorded at inlet level (see 5.4.1).The values are plotted for both mode *NV* and mode *NV & RFC* respectively in Figure 67 and Figure 68. By elaborating the environmental data recorded during the measurement campaign the total pressure difference that drives the circulation of the airflow was also calculated. The methodology was presented in paragraph 5.4.1. In Figure 66 the total pressure rise along the night up to 2 Pa, when the morning after the windows are closed. During the night between 25th and 26th the pressure difference is more unstable with higher peaks in the first three hour of operation. It became more stable during the rest of the night. The mean, minimum and maximum values of the bulk airflow and the total pressure difference for the two nights of measurements are reported in Table 26.The values are similar to the one calculated during the tracer gas experiment, meaning that the conditions in which the correlation constant was derived were not far away from the real conditions in which the building is usually operated.

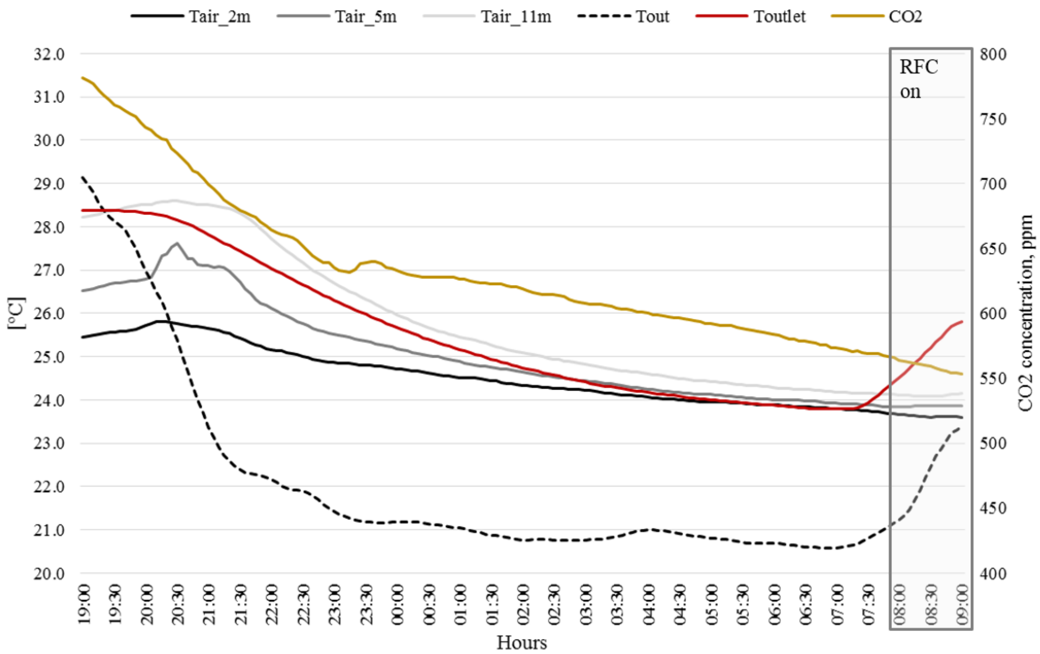


Figure 66 Temperatures and CO_2 trend during night under RFC mode (night between 27th and 28th July)

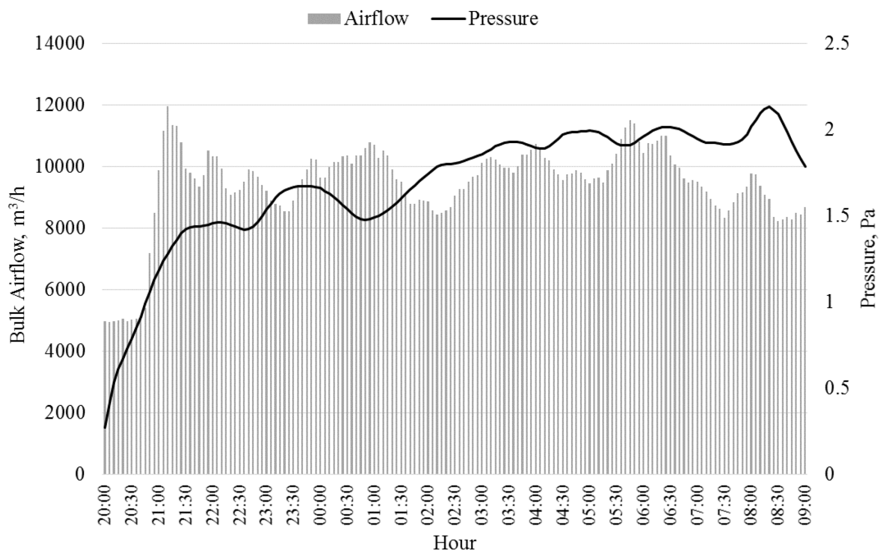


Figure 67 Bulk airflow and pressure (NV mode) during the night between 13th and 14th of July

Table 26 Bulk airflow and pressure during the mode NV and NV &RFC

Mode		Bulk Airflow [m^3/h]	Pressure [Pa]
NV	Mean	9449	1.66
	Min	4941	0.27
	Max	11952	2.02
NV & RFC	Mean	9550	1.11
	Min	4824	0.74
	Max	13672	2.23

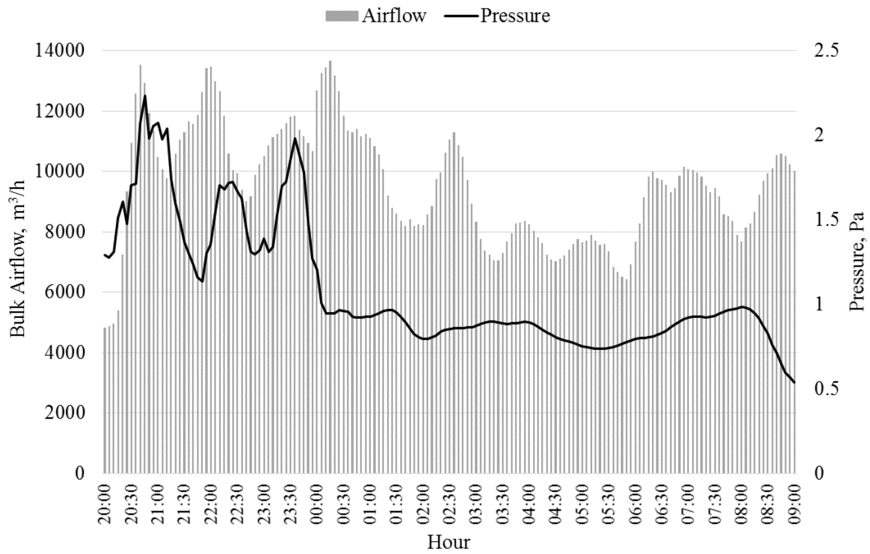


Figure 68 Bulk airflow and pressure (NV & RFC mode) during the night between 25th and 26th of July

5.4.3 Thermal comfort assessment

The central atrium of Seixal City Hall has all the characteristics of transitional spaces described in chapter 1. There are two main typologies of users:

- Temporary users that we are going to call *guests,* which represent citizens and external people that occasionally go to the City Hall to handle different bureaucratic activities. Workers usually based in the lateral row of offices also fall within this category. They pass by the atrium to go to the cafeteria or to attend meeting in the meeting rooms based at the atrium level. For the scope of the study, we however decided to interview only external guests;
- Internal employees based in the office spaces in the atrium, which we are going to call *workers.* Differently from *guest* they daily experience the thermal environment.

The main difference between these two building users is the permanence period within the space. While the *workers* spend inside the atrium around eight hour per day, the *guests* spend in general few hours inside the building. While waiting to be served they usually relax on the couch and sofa in the middle of the waiting area showed in Figure 69.

Guests are the one who experience thermal transient. It occurs when coming from the outside, they enter inside the building. After ten minutes however, as seen in the study of Chen et al.[3.10], their thermal sensation should be stabilized as well as the one of the workers that are inside the atrium since longer.

Our question is if there is any differences between *guests* and *workers* in the way they perceive the indoor environment under the different operation modes. To answer to this question a thermal comfort assessment campaign was set up. The methodology adopted is the same presented in paragraph 4.2. The questionnaire was translated into Portuguese language. The full version is available in the Annex D.

Figure 69 Interior view of the central atrium of Seixal City Hall

The five days of measurements are highlighted with a star in Figure 60. Each day 15 *workers* and 15 *guests* were interviewed between 9 a.m. and 12 a.m. about their state of comfort inside the atrium. Because of the very different outdoor climatic conditions met during the campaign it is possible just to compare the results of the days 14th (mode *NV*) and 26th (mode *NV & RFC*) which have almost comparable outdoor conditions. The days before have almost the same trend. This mean that we are comparing the thermal sensation of participant that have experienced similar outdoor conditions (see Figure 60).

From the study we want to understand if night ventilation only (mode *NV*) is enough to assure a comfortable environment during days of full summer. This is possible by directly comparing users' thermal acceptability, sensation and preference under the two modes (*NV* and *NV & RFC).*

Table 27 reports the statistics of the sample. Table 28 reports the indoor and outdoor environmental characteristics during the measurements days. The clothing level is reported too.

Table 27 Statistics of the sample of thermal comfort assessment in Seixal City Hall

	NV		**NV & RFC**	
	Female	**Male**	**Female**	**Male**
Number of guests	8	7	7	8
less than 30 years old	1	0	0	0
between 31-50 years old	7	2	6	4
more than 50 years old	0	5	1	4
Number of workers	9	6	10	5
less than 30 years old	1	0	1	0
between 31-50 years old	4	2	5	2
more than 50 years old	4	4	4	3

Table 28 Environmental characteristics (indoor and outdoor) and clothing level under modes NV and NV & RFC during the thermal comfort assessment

		Indoor				**Outdoor**		**Clothing**
		T_o (°C)	V_{air} (m/s)	RH (%)	CO_2 (ppm)	$T_{dry,out.}$ (°C)	RH (%)	Clo
NV	Mean	25.0	0.10	58	813	25.8	59	0.59
	SD	0.2	0.08	1	32	1.6	5	0.13
	Min	24.7	0.01	57	744	23.7	47	0.38
	Max	25.4	0.44	59	870	29.3	66	0.82
NV & RFC	Mean	24.1	0.11	60	780	26.4	52	0.60
	SD	0.2	0.09	1	38	1.6	5	0.11
	Min	23.8	0.05	59	705	23.7	44	0.37
	Max	24.5	0.51	61	833	29.3	60	0.82

The mean operative temperature for mode *NV* is 1 K higher than in mode *NV & RFC* which is the only parameter slightly differing. The other parameters are almost comparable. Also the average clothing level is the same and equal to 0.6 clo. Because all of the interviewee were seated, the insulation of the chair was also considered. This is why the value is higher is compared to the average clothing values recorded during the study in shopping centre (Table 10).

For the calculation of the PMV, the activity level considered is different between *workers* and *guests*. Referring to EN ISO 7730 [3.4] for *workers* 1.2 met which refers to office activities was used while for the *guests* 1.0 met was used which refer to relaxed activities. For the scope of this thermal comfort assessment, the reference measurements point for global thermal comfort of the mobile cart MEMO (Figure 24) was lowered at 0.6 m, reference position for seated people [3.4].

With the same methodology presented in the paragraph 4.5.4.1, the PMV values were calculated for each interview and compared with the actual thermal sensation vote, expressed through the questionnaire. The comparison between the two values is shown in Table 29.

Table 29 Comparison between thermal sensation prediction (PMV) and actual (TSV)

User type	**Mode**	N_i	**mean Bias**	**sd Bias**	**se Bias**
guests	NV	15	-0.33	0.49	0.13
guests	NV & RFC	15	-0.53	0.52	0.13
workers	NV	15	-0.13	0.83	0.21
workers	NV & RFC	15	-0.07	0.46	0.12

The comparison is between both mode *NV* and *NV & RFC* and between *guests* and *workers*. The values of the mean Bias are negative meaning that the actual thermal sensation of customers is towards cool compared to the prediction. For the case of *workers* the mean Bias is lower compared to the *guests*. The reason can be related to the fact that workers do not experience any thermal transition due to temperature difference, while this happens for the *guests* when entering inside the atrium. Fanger's model indeed does not correlate with the outdoor condition or either takes into account the temperature differences experienced by people since it is based on steady-state conditions.

From the analysis of the thermal acceptability (Figure 70) and thermal sensation votes (Figure 71), no substantial differences between *guest* and *workers* under the two different modes are observed. Under *NV* mode, for both guests and workers two over fifteen (13%) have a thermal sensation toward warm (+3,+2).

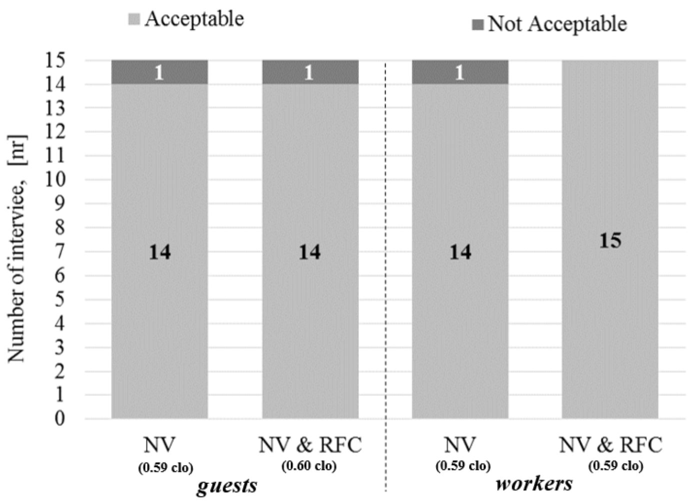


Figure 70 Distribution of thermal acceptability between guests and workers under mode NV and NV & RFC

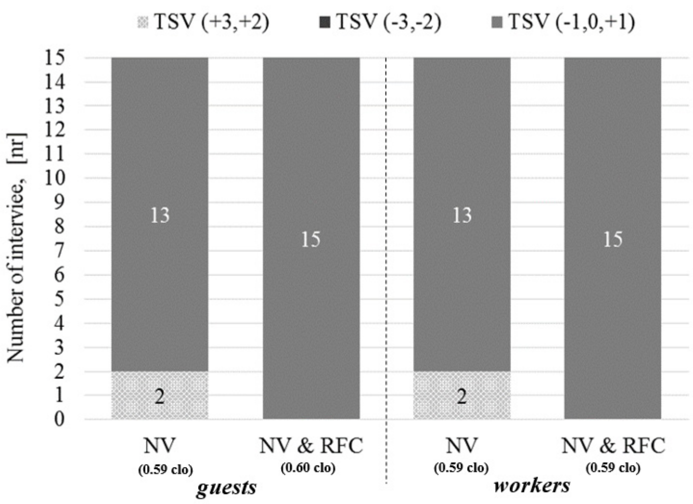


Figure 71 Distribution of thermal sensation votes between guests and workers under mode NV and NV & RFC

The distribtuion of the thermal preference vote (Figure 72) slighlty differ between guests and workers. In both modes there is always one worker asking for a warmer environment.

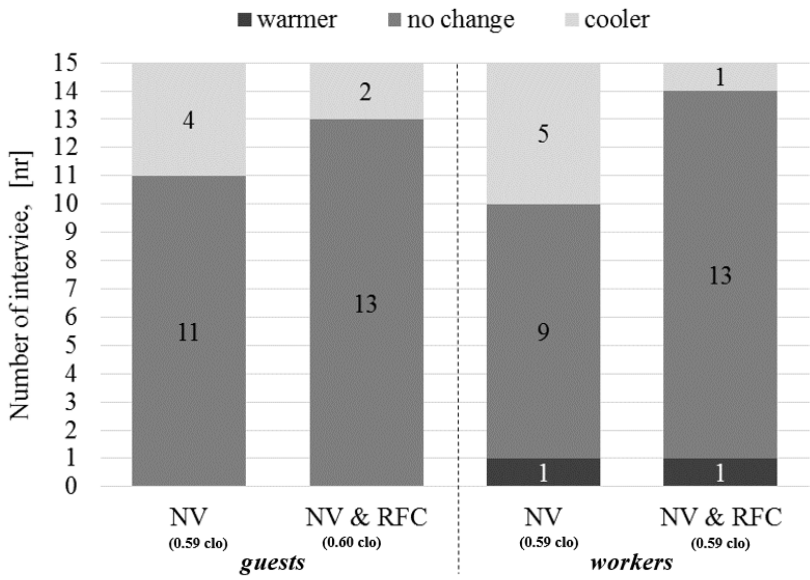


Figure 72 Distribution of thermal preferences between guests and workers under mode NV and NV & RFC

The distribution of thermal comfort votes shown in Figure 73 reveals that for both workers and guests the 80% threshold is reached under the two different modes. For the guest under *NV* mode the achieviement of the theshold is however very tight (exactly 80%).

Figure 73 Distribution of thermal comfort votes between guests and workers under mode NV and NV & RFC

Under the light of the direct interview with both *guests* and *workers*, no substantial differences have been underlined. The thermal conditions guaranteed through *NV* mode are accepted and judged comfortable from both *guests* and *workers* as well as the one provided by *NV & RFC* mode. Thefore it is reasonable to think that the atrium can be operated just letting the night ventilation working resulting in a significant reduction of the cooling consumption.

5.5 Conclusion

The main findings related to this thermal comfort and airflow performance assessment of a mixed-mode atrium located in a warm-temperate climate are:

- The realization of tracer gas technique in big volumes is difficult and challenging. Nevertheless, stabilized condition can be reached. The analysis of the pressure differences that drive natural ventilation, even though realized in the post-processing data phase, is essential to understand whether the experiments are successful or not;
- The derivation of the correlation coefficient between the bulk airflow and the air velocity measured at inlet level turned to be a good method to characterize windows when no information about windows opening are available;
- The operation of the night ventilation allow to save around 43% of the daily cooling demand (72 kWht/K) if compared to a fully active cooling operation of the atrium;
- Direct thermal comfort assessment of the atrium users (both guests and workers) revealed no substantial differences in the way the thermal environment is perceived when operated under different modes. It seems therefore reasonable to suggest that by recirculating fresh air from the outside at night, it is enough to maintain comfortable conditions inside the atrium in the following day.

Further analysis, which consists in validated thermal and airflow model for the atrium will help us to better understand the physics and performance of the atrium. Analysis for the optimization of the controls and modulation of opening area also during the day can be afterword performed. The validated model can also help in understand and quantify the fully potential of the atrium. Because of the difficulties in the derivation of the bulk airflow for such large volume, the whole experiment was conducted considering just part of the potentiality in term of night ventilation, in fact only part of the available openings were operated (mode A). The full potentiality (mode B, Table 19) can be investigated by means of a building energy simulation model of the atrium validated using the collected measured data.

5.6 Acknowledgements

The research was conducted in collaboration with Professor Guilherme Carrilho da Graça at the Department of Engenharia Geográfica, Geofisica e Energia of the University of Lisbon. I am very thankful for this opportunity. It has been a very intense period and I want to express my gratitude for his support, the fruitful discussions and all the new skills I gained during this period.

I want to thank as well with Nuno Mateus for his precious support and help during all the work.

I would like also to thanks with the facility managers of Seixal City Hall Gonçalo Vila and Vera Rodriguez and with the security manager Mr. Grilo for their availability and support for the field study.

I would also to thanks with all the workers of Seixal City Hall involved in the thermal comfort study for their patience in participating in the study.

Bibliography

[5.1] B.M. Jones, M.J.Cook, S.D.Fitzgerald. A review of ventilation opening area methodology. Energy and Buildings 118(2016) 249-258

[5.2] Mateus, N. M., Nunes Simões, G., Lúcio, C., & Carrilho da Graça, G. (2016). Comparison of measured and simulated performance of natural displacement ventilation systems for classroms. Energy and Buildings, 133, 185-196.

[5.3] Cui S., Cohen M., Stabat P., & Marchio D. (2015). CO2 tracer gas concentration decay method for measuring air change rate. Building and Environment, 84, 162-169

[5.4] Ansys, F. (2017). *Release 18.0.Theory Guide.* Ansys Inc.

6 Conclusion

Transitional spaces are widely employed in non-residential architecture. Their use may range from areas to sit and relax or as a passage way to walk about, stop shopping or dash to catch a train, and other activities. They do not accommodate the main activity of the building but nonetheless they are operated as an extension of the interior environment. As a consequence their design look for the same level of comfort of indoor spaces.

With the aim of a deeper understanding of these peculiar building zones, this PhD dissertation focused on three aspects related to transitional spaces which are:

- the mixed-mode ventilation design;
- the thermal comfort requirements;
- the actual thermal performance of mixed-mode operated transitional spaces.

Within non-residential buildings, shopping centers have shown a great potential for the conversion from fully mechanical into mixed-mode operation. Shopping centres common areas have indeed some characteristics (both architectural and technical) that makes the conversion very feasible. The conversion becomes also very cost effective when the investment costs are restrained to the connection of the windows and skylight actuators to the BMS, which is most of the time already present in complex buildings as shopping centres. The conversion from fully mechanical into mixed-mode operation falls, in reality, into a retrofit action of the common areas. When approaching a retrofit action, synergies with other retrofit solutions, e.g. the level of internal gains, cannot be overlooked. The investigation of the potential synergies between retrofit solutions is indeed suggested as the first step of a design procedure proposed for the retrofit into mixed-mode operation of the shopping centre common areas.

The conversion from fully mechanical into mixed-mode operation is further encouraged by the findings related to thermal comfort in shopping centers common areas. The field study allowed to identify wider range of indoor thermal comfort conditions for summer period. This range could suite with the more relaxed ranges of indoor temperature that passive system can assure. Shopping centers customers' judge as comfortable operative temperatures that go from 23.5°C up to 27.5 °C while the actual recommended design criteria for department stores (EN 7730) refer to a narrow range. The recommended comfort temperature are also completely disjointed from the high variability of outdoor condition within a season. Contrarily the study proved that outdoor condition cannot be disregarded. The way customers perceive the thermal environment is indeed influenced by the indoor-outdoor temperature difference they experience. In particular, it was observed that customers were dissatisfied with the thermal environment, preferring a cooler one, when they were experiencing an up-step temperature difference wearing a typical spring-like clothing ensemble. The two thermal comfort models, PMV-PPD model and adaptive model, resulted to be not accurate to estimate customers' thermal sensation. Therefore the necessity of a tailor-made model to assess thermal comfort in transitional spaces is disclosed. The model could correlate indoor comfort temperatures with outdoor temperatures on the basis of the direct observation of users' thermal sensation. In order to expand the database of evidence, further field studies are required, gathering together a conspicuous number of data which will cover all the seasons.

The study highlighted how customers are inclined to accept less stringent environmental conditions, compared to the one predicted by the PMV-PPD model. This finding unlock important energy use implication. If shopping centre HVAC systems are operated in a more flexible way and natural ventilation potential is exploited, the final goal of achieving more energy efficient buildings without sacrificing users' comfort seems closer. The ability of providing comfortable indoor conditions by natural ventilation was proved by the thermal comfort performance assessment of a mixed-mode operated atrium.

Daytime indoor thermal conditions guaranteed by just operating night-time ventilation were judged comfortable by the atrium users as well as the ones provided by a mixed-mode operation of the atrium. Users' state of comfort was independent from the way the space was conditioned. It is therefore reasonable to think that when climatic and occupancy conditions allow for it, indoor comfort condition of transitional spaces can be potentially guaranteed by passive solution only, as ventilative cooling. This reflect in a consistent reduction of the operation costs for cooling. These results are restrained to a warm-temperate climate. But even in situations/locations where air conditioning is unavoidable, the wider range of indoor thermal comfort conditions would mean less cooling demand and hence less electricity consumption for the air conditioning systems.

In the perspective of the reduction of building energy consumption without compromising thermal comfort, the results of this thesis boost the interest towards building operated under mixed-mode. The potentialities of transitional spaces expressed in the thesis need to be taken into account in non-residential building design.

The nature of the results for shopping centers transitional spaces can be then extended to all non-residential building that have transitional spaces with similar features.

In relation to the mixed-mode operated atrium, an energy model validation of thermal and airflow performance over the measured data is foreseen. A validated model is a powerful tool that can be then used to assess the mixed-mode solution in different climates. It can be as well used to identify better control strategies that can further reduce the energy consumption of the building optimizing thermal comfort.

Publication List

2017

M. Avantaggiato, W. Pasut, ecc **D6.5: IEQ assessment**, CommONEnergy FP7 project, (FP7-2013 grant agreement no 608678). 2017

M. Avantaggiato. **Database of mixed-mode ventilated transitional spaces**. 10.5281/zenodo.1011229.

A. Belleri, M. Avantaggiato, T. Psomas, P. Heiselberg, **Evaluation tool of climate potential for ventilative cooling, International Journal of Ventilation**, Pages 1-13, 25 October 2017 https://doi.org/10.1080/14733315.2017.1388627

A. Belleri, M. Avantaggiato, R. Lollini, **Ventilative cooling in shopping centers' retrofit: the Mercado del Val case study**, Energy Procedia, Volume 111, March 2017, Pages 669-677 https://doi.org/10.1016/j.egypro.2017.03.229

M. Avantaggiato, A. Belleri, M.De Carli, R. Lollini. **Mixed-mode ventilative cooling opportunity for an existing shopping mall retrofit.** 38th AIVC Conference-7th TightVent- 5rd venticool, 2017,pp 816-826, 13-14th September Nottingham, United Kingdom

M. Avantaggiato, N. Mateus, A. Belleri, W. Pasut, G.C. Da Graca. **Bulk airflow measurements in a large naturally ventilated atrium in a mild climate.** 38th AIVC Conference-7th TightVent- 5rd venticool, 2017, pp 211-219, 13-14th September Nottingham, United Kingdom

M. Avantaggiato, G. Barchi, A. Belleri, C. Dipasquale, R. Lollini, W. Pasut, M. Haase, A. Toleikyte, F. Lam Nang, M. Rozanska, F. Manesis, K. Grabowiecki, A. De Ferrari, A. Ampenberger, F. Visconti, P. D'Agaro, G. Cortella, O. Saro, I. Mangialenti, S. Mangili, M. Martinelli, S. Papantoniou ,J. Gantner.**Guidelines on how to approach the energy-efficient retrofitting of shopping mall**, CommONEnergy FP7 project, (FP7-2013 grant agreement no 608678). 2017

A. Belleri, M. Avantaggiato, **D3.3: Ventilative cooling**, CommONEnergy FP7 project, (FP7-2013 grant agreement no 608678). 2017

M.V. Cambronero Vàzquez, A Belleri, M. Avantaggiato, C. Dipasquale, J.A. Guiterrez., M. Haase, K.S. Skeie .**D5.1-Systemic solution-sets**; CommONEnergy project (FP7-2013 grant agreement no 608678). 2017

2016

A. Belleri, M. Avantaggiato**, Ventilative Cooling in Shopping Malls Retrofit**, REHVA Journal, January 2016, 53, pp 21-25

M. Avantaggiato, A. Belleri, **Progettare il retrofit dei centri commerciali con il ventilative cooling**, Casa&Clima,61, pp 54-60, Giugno 2016

M.Avantaggiato, A. Belleri, W.Pasut, S. Dutton, R. Lollini, **Assessment of thermal comfort in shopping center transitional spaces, Indoor Air 2016**, The 14th international conference of Indoor Air Quality and Climate, Ghent, Belgium July 3-8 2016, Volume 1, pp 2594-2603

2015

M. Avantaggiato, A. Belleri, M. De Carli, R. Lollini, **Ventilative cooling strategies to reduce cooling and ventilation needs in shopping centres**, 36th AIVC Conference-5th TightVent- 3rd venticool, 2015, 23-24th Madrid, Spain, pp 633-644

Linee Guida sul Comfort, TIS Innovation Park-Cluster Edilizia, October 2015

Annex A

EURAC research

CommONEnergy

Study related to the shopping centre users´ indoor thermal comfort perception

With this questionnaire, we would like to have information about your comfort inside the shopping centre. In particular, we want to know your satisfaction about the ambient temperature that you are experience in this moment. The results will help us to identify possible change on the heating-cooling systems´ set-points with a possible contribution on reducing the shopping centre energy consumption. Euracresearch will use the collected data only for scientific purpose. Your involvement is voluntary and the data will use in an anonymous and confidential way. Thanks for collaboration.

European Accademy of Bozen, Viale Druso 1, 39100 Bolzano, is responsible for the data processing available at the following e-mail address: marta.avantaggiato@eurac.edu. Marta Avantaggiato and Annamaria Belleri are responsible for the data analysis.

Before starting the questionnaire, we need to know:

1. Did you drink some water, coffee, tea or alcoholic drink in the last 20 minutes?

2. Did you eat something in the last 20 minutes?

3. Health condition: were you sick in the previous 7 days?

4. What activity were you been doing 30 minutes ago?

Some questions about you...

age?		
less than 30 years old	31 – 50 years old	more than 50 years old

gender?	

How long have you been inside the shopping centre?		
less than 10 min	between 10 and 20 min	more than 20 min

How long have you been walking inside this zone?			
less than 5 min	between 5 and 10 min	between 10 and 20 min	more than 20 min

How do you evaluate the indoor air quality?			
very satisfied	quite satisfied	quite unsatisfied	very unsatisfied

How do you evaluate the thermal environment in this moment?	
Acceptable	Not acceptable

For the whole body, rate your current thermal sensation

- Hot
- Warm
- Slightly Warm
- Neutral
- Slightly cool
- Cool
- Cold

In this moment you prefer to be...?

- Cooler
- No change
- Warmer

Please evaluate the thermal environment

very not comfortable	not comfortable	just not comfortable	just comfortable	comfortable	very comfortable

What are you wearing?

Annex B

EURAC research CommONEnergy

Studio relativo alla percezione del comfort termico degli utenti all'interno del centro commerciale

Con questo questionario vorremmo avere informazioni riguardo il tuo stato di benessere all'interno del centro commerciale e in particolare il tuo grado di soddisfazione riguardo la temperatura dell'ambiente in cui ti trovi in questo momento. I risultati del questionario ci serviranno a identificare possibili modifiche ai parametri di controllo dei sistemi di riscaldamento e raffrescamento contribuendo ad una possibile diminuzione dei consumi energetici del centro commerciale. I dati raccolti saranno utilizzati da EURAC (Accademia Europea di Bolzano) al solo fine scientifico per un progetto di ricerca riguardo il comfort termico all'interno dei centri commerciali. La partecipazione al questionario è volontaria e i dati saranno trattati in maniera anonima e confidenziale. Ti ringraziamo in anticipo per la disponibilità.

Ai sensi dell'articolo 13 del D. Lgs. n. 196/2003 La informiamo che i Suoi dati sono trattati a fini scientifici. I dati verranno trattati con modalità informatizzate e cartacee e non sono soggetti a comunicazione e diffusione. Il conferimento dei dati è facoltativo; tuttavia il mancato conferimento degli stessi comporta l'impossibilità di essere sottoposti al questionario. Lei può in ogni momento esercitare le facoltà previste dall'art. 7 del D. Lgs. 196/2003 contattando il titolare del trattamento, l'Accademia Europea Bolzano, Viale Druso 1, 39100 Bolzano, al seguente indirizzo e-mail: marta.avantaggiato@eurac.edu. I responsabili del trattamento dei dati sono: Marta Avantaggiato e Annamaria Belleri.

Prima di cominciare col questionario, vorremmo sapere:

1. Hai bevuto acqua, tè, caffè o bevande alcoliche negli ultimi 20 minuti?

2. Hai mangiato negli ultimi 20 minuti?

3. Hai avuto l'influenza o il raffreddore negli ultimi 7 giorni?

4. Quale attività stavi svolgendo circa 30 minuti fa?

Alcune domande su di te...

età?		
meno di 30 anni	31 – 50 anni	più di 50 anni

sesso?	

Da quanto tempo sei all'interno del centro commerciale?		
meno di 10 minuti	dai 10 ai 20 minuti	più di 20 minuti

Da quanto tempo stai camminando in questo ambiente?			
meno di 5 minuti	dai 5 ai 10 minuti	dai 10 ai 20 minuti	più di 20 minuti

Quanto è soddisfatto della qualità dell'aria dell'ambiente in cui si trova in questo momento?			
molto soddisfatto	abbastanza soddisfatto	piuttosto insoddisfatto	molto insoddisfatto

Dal punto di vista termico: come valuta l'ambiente in cui si trova?	
Accettabile	Non accettabile

Come ti senti in questo momento? Sono/Ho...

- ○ Molto accaldato
- ○ Caldo
- ○ Leggermente caldo
- ○ Né caldo né freddo (neutrale)
- ○ Leggermente fresco
- ○ Freddo
- ○ Molto freddo

In questo momento preferiresti avere (un ambiente) ...?

- ○ Più freddo
- ○ Nessun cambiamento
- ○ Più caldo

Valuti l'ambiente in cui si trova...					
altamente non confortevole	non confotevole	appena non confortevole	appena confortevole	confortevole	molto confortevole

Cosa stai indossando in questo momento?

Annex C

Table 30 Tabulation of the data plot in Figure 35

	SC01			SC02			SC03					
Day	04-Apr	05-Apr	06-Apr	10-Jun	21-Jun	22-Jun	13-Jul	14-Jul	15-Jul	18-Jul	19-Jul	20-Jul
N_i	18	60	25	101	94	86	55	75	73	52	54	31
clo	0.78	0.77	0.78	0.50	0.48	0.42	0.36	0.38	0.38	0.38	0.37	0.40
t_{rm}	17.3	17.9	18.3	21	19.5	20.4	26.2	25.9	25.9	25	24.4	24.4
t_{comf}	24.5	24.7	24.8	25.7	25.2	25.5	27.4	27.4	27.4	27.1	26.9	26.9
t_o	24.3	24.6	25.2	25.5	25	25.7	26.6	27.2	25.8	25.2	25.8	25.6
% satisfied	67%	52%	84%	78%	89%	90%	95%	89%	96%	100%	96%	97%

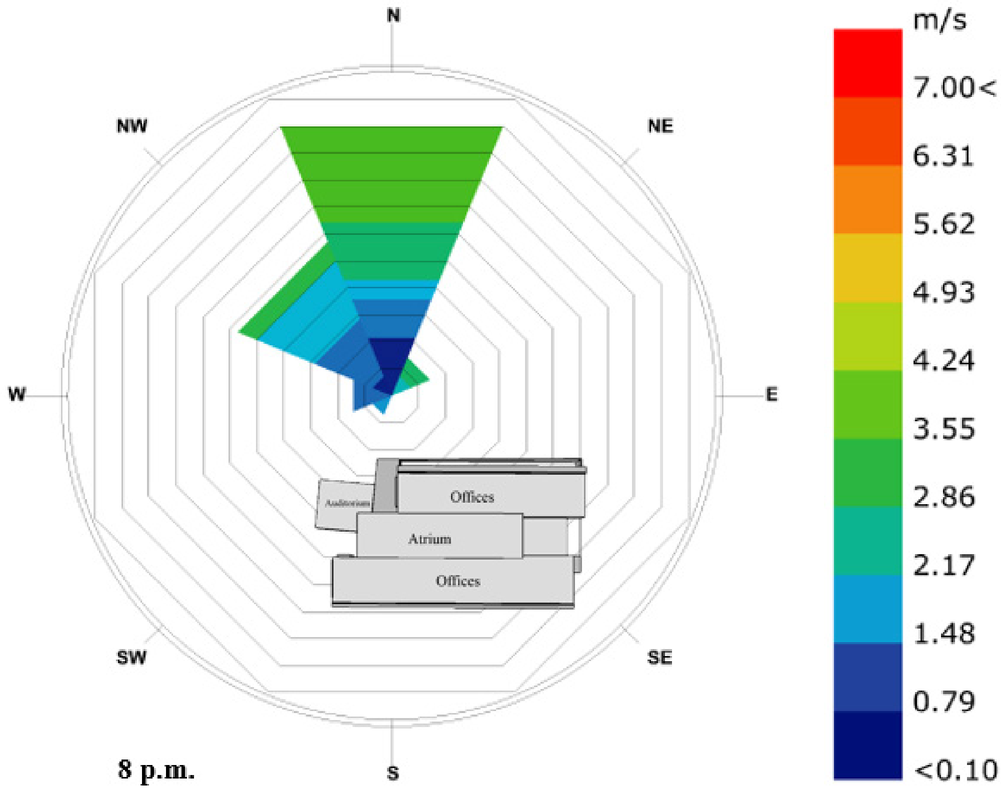
Table 31 Distribution of preference over thermal sensation for customers with "less than 10 minutes" permanence period

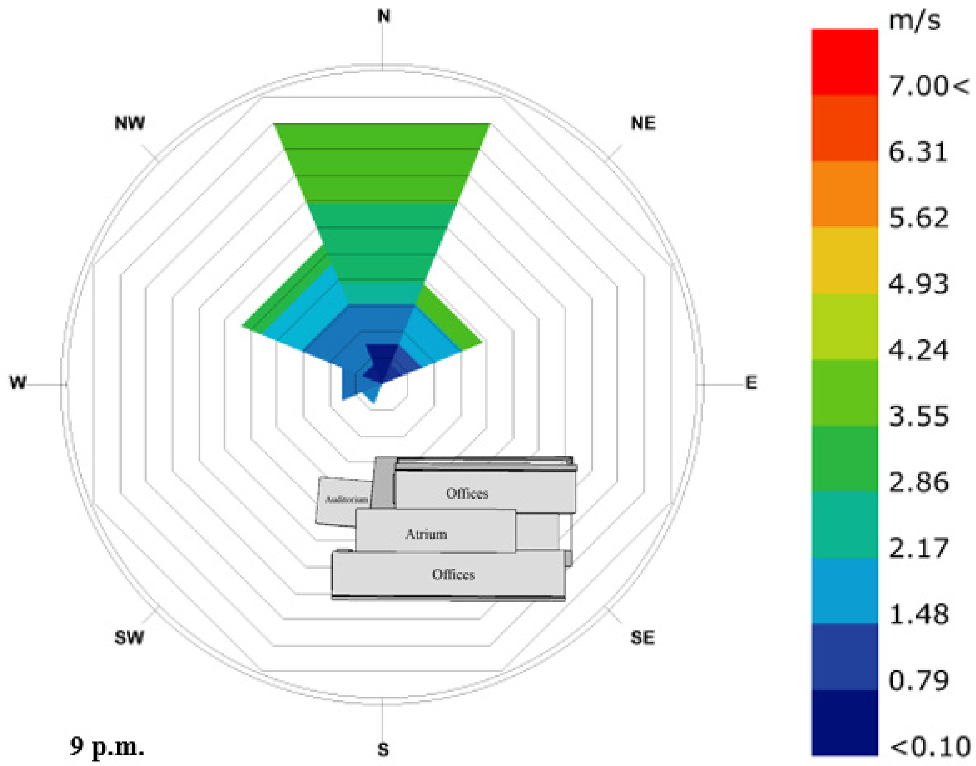
TSV	N_i	wanting warmer	wanting cooler	no change	% wanting warmer	% wanting cooler
-3	0	0	0	0	-	-
-2	1	0	0	1	0%	0%
-1	61	14	5	42	23%	8%
0	89	4	12	73	4%	13%
1	71	0	36	35	0%	51%
2	21	0	18	3	0%	86%
3	1	0	1	0	0%	100%

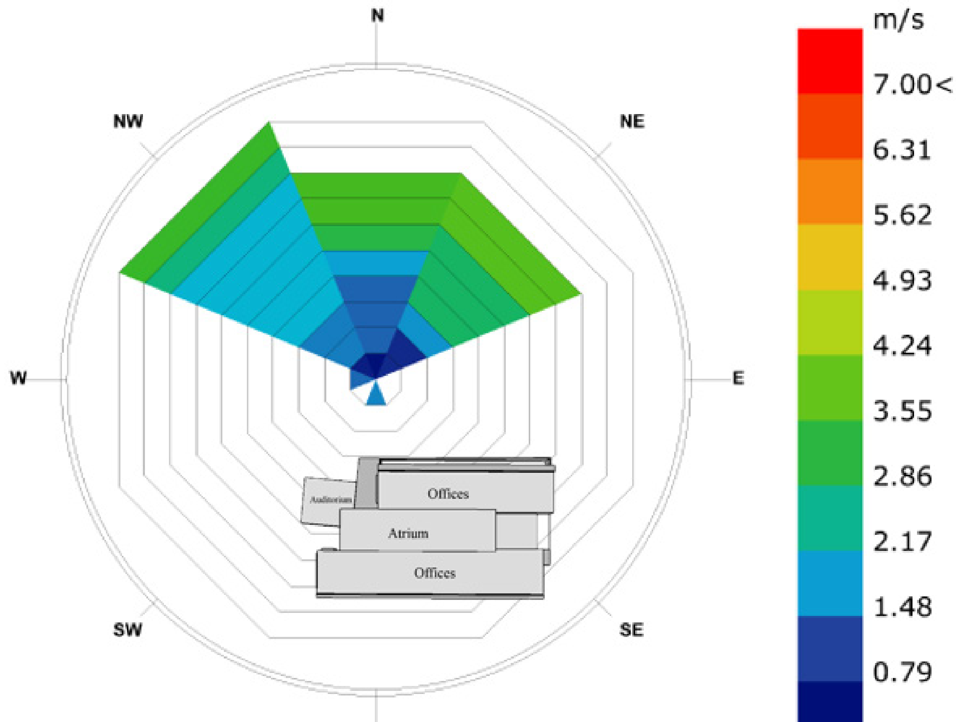
Table 32 Distribution of preference over thermal sensation for customers with "more than 10 minutes" permanence period

TSV	N_i	wanting warmer	wanting cooler	no change	% wanting warmer	% wanting cooler
-3	1	1	0	0	100%	0%
-2	2	1	1	0	50%	50%
-1	96	18	5	73	19%	5%
0	165	1	21	143	1%	13%
1	162	1	102	59	1%	63%
2	50	0	47	3	0%	94%
3	4	0	4	0	0%	100%

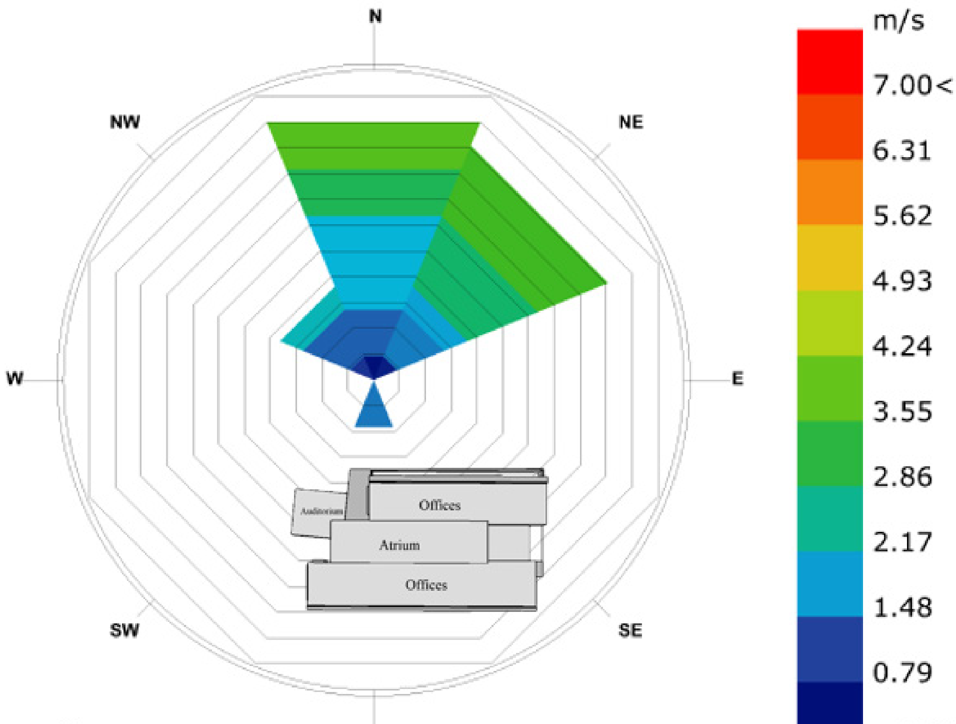
Annex D


N
NW
NE
W
E
SW
SE
S
Offices
Auditorium
Atrium
Offices
8 p.m.
m/s
7.00<
6.31
5.62
4.93
4.24
3.55
2.86
2.17
1.48
0.79
<0.10

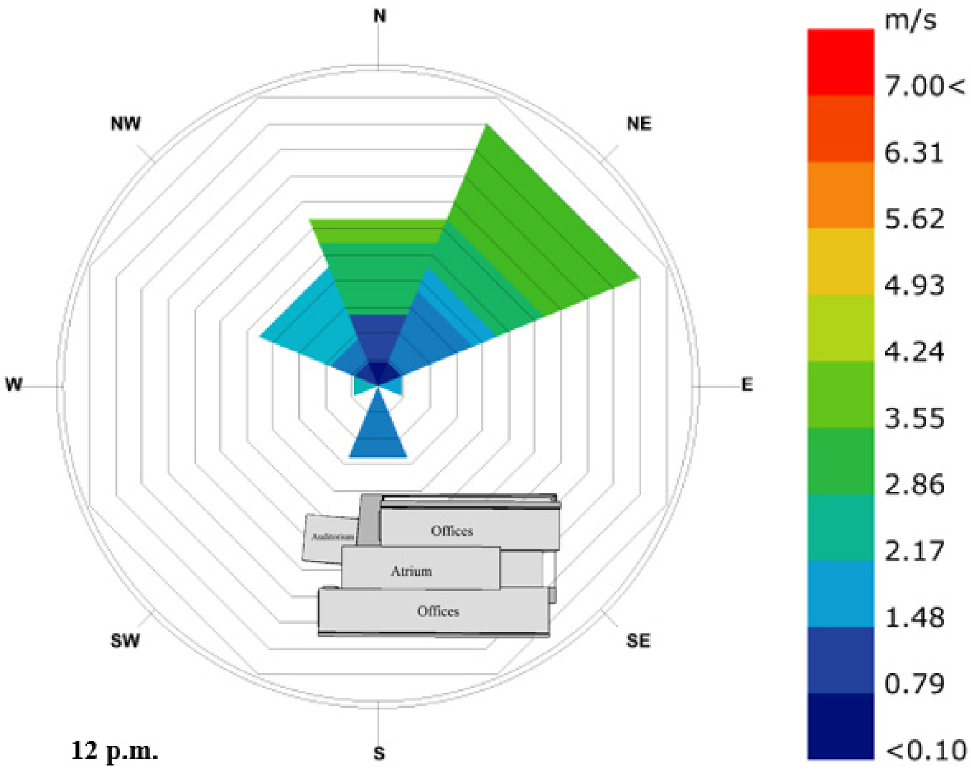

N
NW
NE
W
E
SW
SE
S
Offices
Auditorium
Atrium
Offices
9 p.m.
m/s
7.00<
6.31
5.62
4.93
4.24
3.55
2.86
2.17
1.48
0.79
<0.10

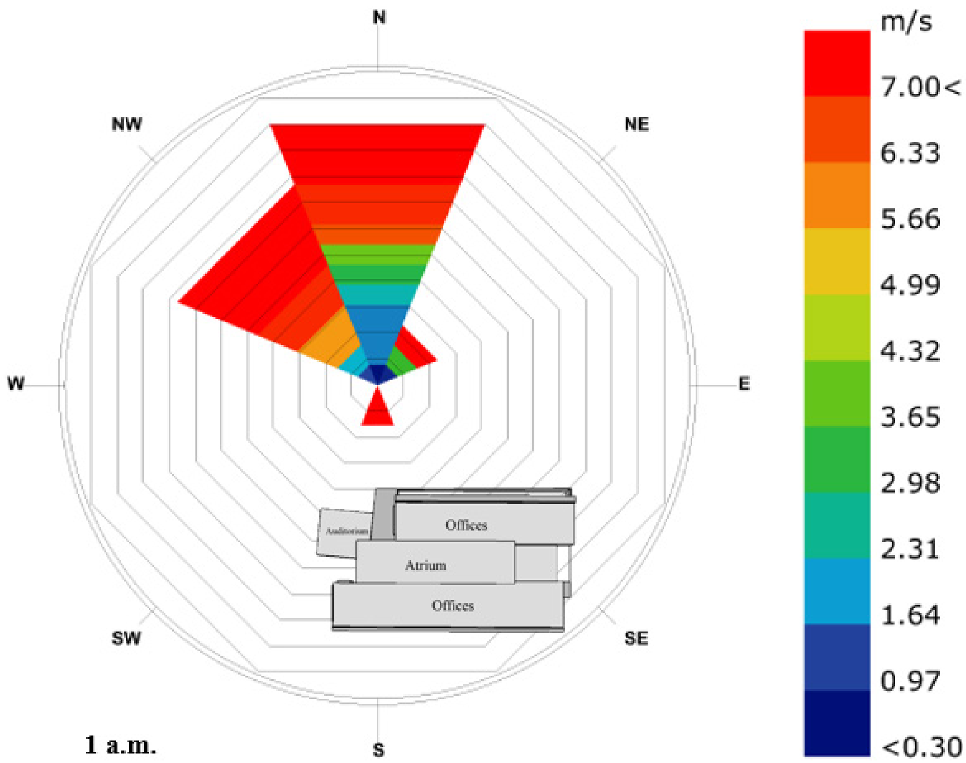

N
NW
NE
W
E
SW
SE
S
Auditorium
Offices
Atrium
Offices
m/s
7.00<
6.31
5.62
4.93
4.24
3.55
2.86
2.17
1.48
0.79
<0.10

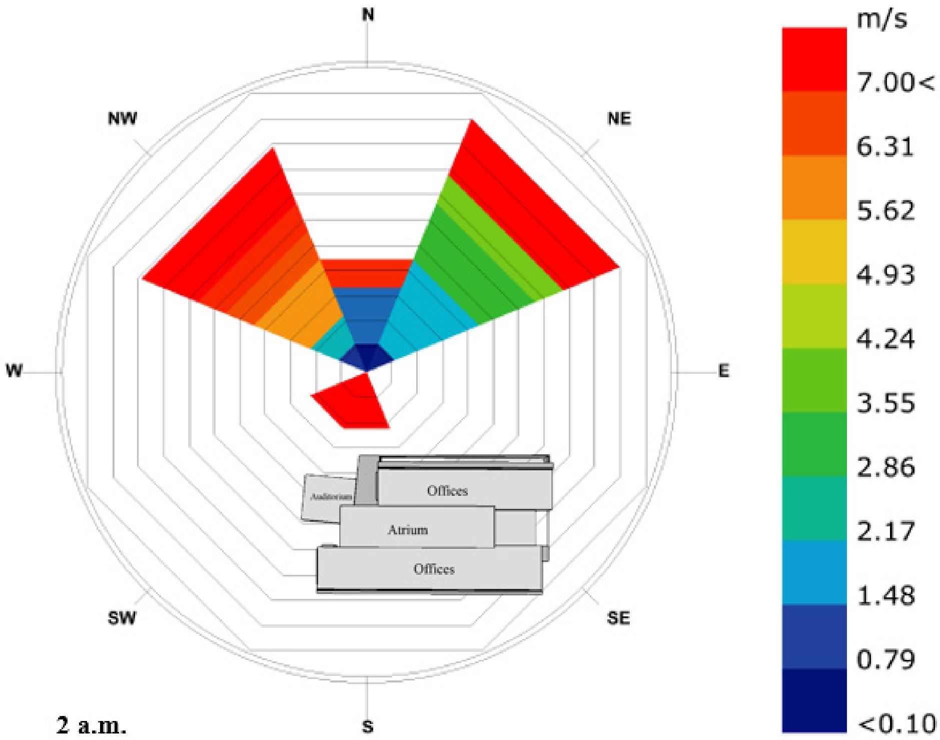
10 p.m.

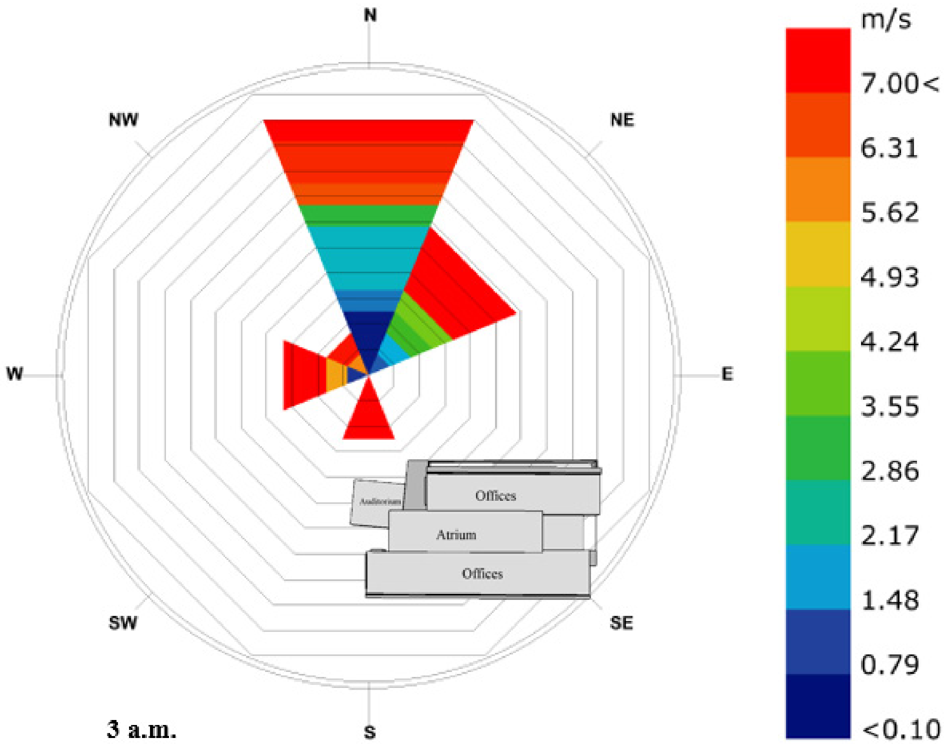

N
NW
NE
W
E
SW
SE
S
Auditorium
Offices
Atrium
Offices
m/s
7.00<
6.31
5.62
4.93
4.24
3.55
2.86
2.17
1.48
0.79
<0.10

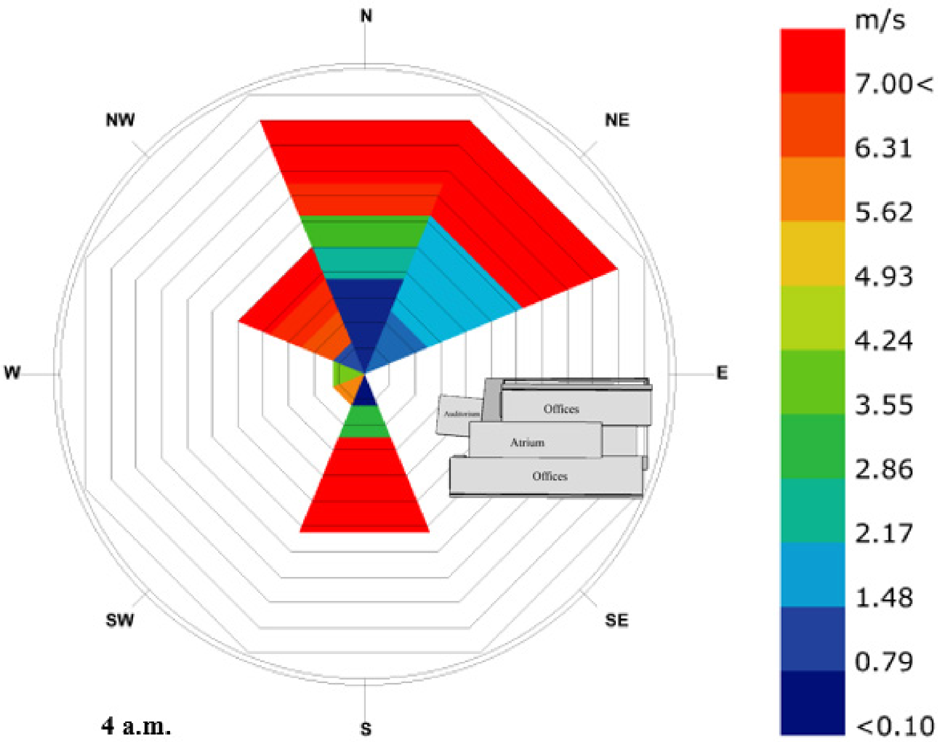
11 p.m.

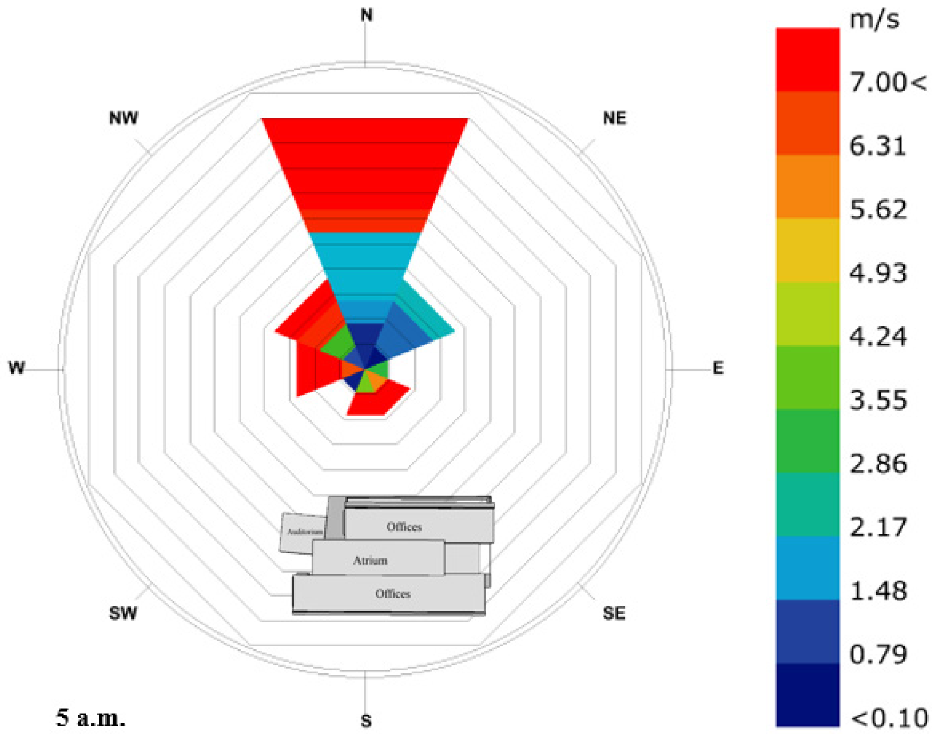

N
NE
E
SE
S
SW
W
NW
Auditorium
Offices
Atrium
Offices
12 p.m.
m/s
7.00<
6.31
5.62
4.93
4.24
3.55
2.86
2.17
1.48
0.79
<0.10

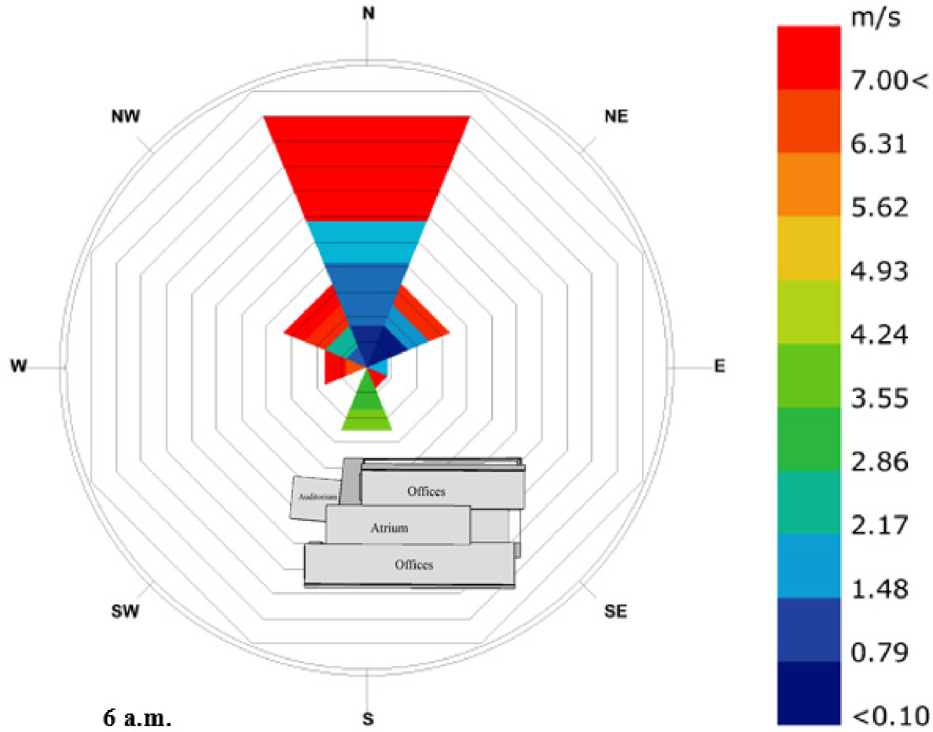

N
NE
E
SE
S
SW
W
NW
Auditorium
Offices
Atrium
Offices
1 a.m.
m/s
7.00<
6.33
5.66
4.99
4.32
3.65
2.98
2.31
1.64
0.97
<0.30

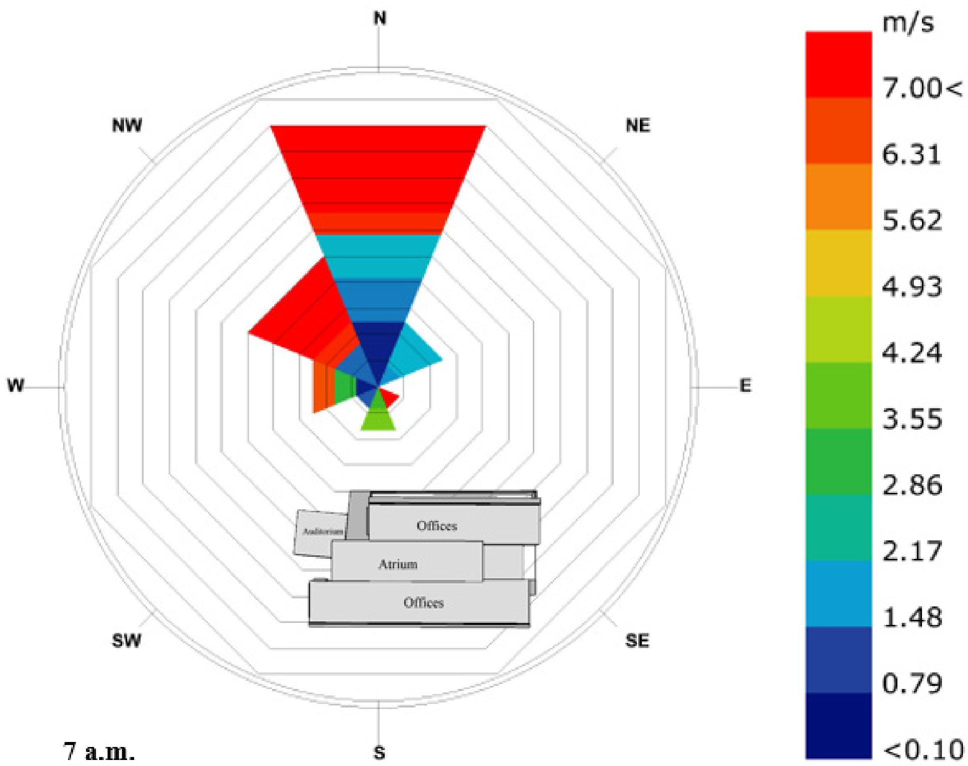

N
NW
NE
W
E
SW
SE
S
Offices
Atrium
Offices
2 a.m.
m/s
7.00<
6.31
5.62
4.93
4.24
3.55
2.86
2.17
1.48
0.79
<0.10


N
NW
NE
W
E
SW
SE
S
Offices
Atrium
Offices
3 a.m.
m/s
7.00<
6.31
5.62
4.93
4.24
3.55
2.86
2.17
1.48
0.79
<0.10


N
NE
E
SE
S
SW
W
NW
Offices
Atrium
Offices
m/s
7.00<
6.31
5.62
4.93
4.24
3.55
2.86
2.17
1.48
0.79
<0.10
4 a.m.


N
NE
E
SE
S
SW
W
NW
Offices
Atrium
Offices
m/s
7.00<
6.31
5.62
4.93
4.24
3.55
2.86
2.17
1.48
0.79
<0.10
5 a.m.


N
NE
E
SE
S
SW
W
NW
Offices
Atrium
Offices
m/s
7.00<
6.31
5.62
4.93
4.24
3.55
2.86
2.17
1.48
0.79
<0.10
6 a.m.


N
NE
E
SE
S
SW
W
NW
Offices
Atrium
Offices
m/s
7.00<
6.31
5.62
4.93
4.24
3.55
2.86
2.17
1.48
0.79
<0.10
7 a.m.

Annex E

EURAC research

Ciências ULisboa

Estudo de perceção do conforto térmico dos utilizadores da Câmara Municipal do Seixal

Através deste questionário, gostaríamos de obter informações sobre a sua sensação de conforto térmico no interior da Câmara Municipal do Seixal. Em particular, gostaríamos de saber o seu grau de satisfação relativamente à temperatura ambiente que está a experienciar neste momento. Os resultados obtidos ajudar-nos-ão a identificar possíveis mudanças no sistema de ar condicionado do edifício e uma eventual contribuição para a redução do consumo de energia do edifício.
A equipa de investigadores da Eurac e da Faculdade de Ciências da Universidade de Lisboa utilizarão os dados recolhidos apenas para fins científicos. A sua contribuição neste estudo é voluntária e os dados recolhidos serão usados de forma anónima e confidencial. Obrigado pela sua colaboração.

European Accademy of Bozen, Viale Druso 1, 39100 Bolzano, é responsável pelo processamento de dados, disponível no seguinte endereço de e-mail: marta.avantaggiato@eurac.edu. Marta Avantaggiato é a responsável pela análise dos dados.

Antes de iniciar o questionário, gostaríamos de saber:

1. Condições de saúde: Esteve doente nos últimos 7 dias?

2. Comeu alguma coisa nos últimos 20 minutos?

3. Bebeu água, café, chá ou alguma bebida alcoólica nos últimos 20 minutos?

4. Que atividade estava a fazer há 30 minutos?

Algumas perguntas sobre si...

Idade?		
Menos de 30 anos	31 – 50 anos	Mais de 50 anos

Género?	

Há quanto tempo está dentro do edifício?		
Menos de 10 minutos	Entre 10 e 20 minutos	Mais de 20 minutos

Qual a sua opinião sobre a qualidade do ar interior?			
Muito satisfeito	Satisfeito	Insatisfeito	Muito insatisfeito

Como avalia o ambiente térmico neste momento?	
Aceitável	Não Aceitável

Como é que se sente neste momento?
○ Com muito calor
○ Com calor
○ Ligeiramente com calor
○ Nem frio nem quente (neutro)
○ Ligeiramente com frio
○ Com frio
○ Com muito frio

Neste momento, preferia estar num ambiente...
○ Mais frio
○ Igual
○ Mais quente

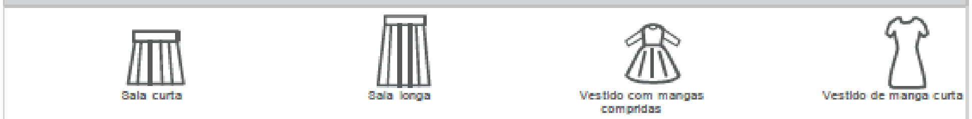
Avalie o ambiente térmico					
Muito desconfortável	Desconfortável	Ligeiramente desconfortável	Ligeiramente confortável	Confortável	Muito confortável

O que tem vestido neste momento?

Casaco, colete

T-shirt, pullover, camisa

Vestido e saia



Calções e fato

Meias e sapatos

Acessórios