Università Politecnica delle Marche
Scuola di Dottorato di Ricerca in Scienze dell'Ingegneria
Corso di Dottorato in Ingegneria Industriale

Sviluppo di un metodo innovativo per il monitoraggio e controllo real-time del comfort in ambienti indoor basato su misure dinamiche di parametri personali

Ph.D. Dissertation of:

Andrea Calvaresi

Supervisor:

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XVI edition - new series

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Alla mia famiglia

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"*You can always do it, even when you think you cannot.*"

Ancona, Luglio 2018

Andrea Calvaresi

Abstract

The well-being of people inside buildings is one of the main aspects which should be considered in buildings design and management. The indoor environment significantly impacts both people's health and work productivity. Comfort is a very broad concept since it regards multiple aspects, such as thermal, visual, acoustic, and indoor air quality. Including in this research field, the present work aims to provide a deep investigation of comfort aspects, focusing on thermal comfort.

Thermal comfort is a complex aspect because it depends on both environmental variables and physiological variables. Considering the Fangers' model, the environmental variables can be easily monitored by using a sensors network, whereas to provide a good evaluation of the physiological variables (i.e., metabolic rate and clothing insulation) is more difficult. The personal parameters greatly affect the evaluation of the indoor thermal comfort. Therefore, this work presents new methodologies for both the real-time and dynamic estimation of those parameters to improve thermal comfort assessment. Regarding the metabolic rate parameter, the developed methodology is based on the measurements of the heart rate and others physiological parameters (e.g., breathing rate). In this perspective, a wearable multi-parametric device has been adopted to collect data. The tests have been conducted in the laboratory to find the best relationship for the estimation of the metabolic rate.

Concerning the dynamic evaluation of clothing insulation, it is derived from the external conditions (i.e., outdoor air temperature).

In addition, a virtual test bench has been developed to test the impact of the system on building management. A simulation model of a building has been used to test a PMV-based air temperature controller. The systematic error was evaluated in terms of PMV, T_{set} and energy consumptions for both the physiological parameters. Regarding the metabolic rate was obtained a variation of ±0.3, of ±3.2°C, and of ±33% for the PMV, the T_{set} and energy consumptions respectively. On the contrary for the clothing insulation parameter was obtained a variation of ±0.1, of ±1.3°C, and of ±8.5% for the PMV, the T_{set} and energy consumptions respectively. Moreover, the uncertainty of the two methodologies developed was evaluated to compare it with the systematic error. The analysis showed that by applying the methodologies proposed a decrease of the error was obtained. In particular, for the metabolic rate was obtained a variation of ±0.2, of ±2.3°C, and of ±10% for the PMV, the T_{set} and energy consumptions respectively. On the contrary, considering the clothing insulation it was obtained a variation of ±0.1, of ±0.6°C, and of ±1% for the PMV, the T_{set} and energy consumptions respectively.

Once these methodologies have been tested, they have been adopted in a real case study in which the evaluation of indoor thermal comfort was performed by using a low-cost system (i.e., Comfort Eye). It allows the real-time monitoring of indoor thermal comfort based on the Fangers' model. To reach this scope a new version of Comfort Eye system has been developed. Moreover, further validation tests have been performed in a case study in which the integration of Comfort Eye with the building management system (BMS) has been implemented.

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Chapter 1.

Introduction

The human perception and well-being are key factors during the building design and operation. Indoor air, temperature, light, sound, materials have an impact on the user health, comfort, well-being and productivity.

Studies on environmental relocations to a green building show an improvement of the occupant's perception regarding the air quality, odours, noise, lighting, thermal comfort, and ergonomics. This finding suggests that the environmental perception play an important role in self-reported health metrics [1]. In the last years, there was an increased sensitivity towards themes as health, well-being, comfort, the productivity of occupants and the building design and development is changed to obtain improvements of the quality of the indoor environment. The attention on the topic of the indoor environment depends on the time spent by humans inside buildings that is around 90% [2]. The built environment is in strong relation to the health of the user.

The term health refers to well-being, physical activity, health conditions (considering the physiological parameters and presence of health diseases), psychological conditions (i.e., stress and emotional conditions) and all the situations that involve the occupants in the environment.

Human comfort sensation is more complex than the perception of thermal, visual, acoustical or air quality environment. Comfort is a reaction to the environment that is strongly influenced by cognitive and behavioural processes.

For this reason, many studies focus on providing the evaluation of indoor microclimate conditions considering all the aspects which affect the occupants' perception. In this perspective, a weighted index which combines several variables to enhance the description of indoor comfort sensation is proposed in [3]. Moreover, new forms of questionnaires, which include all the aspects mentioned before (i.e., thermal, health, IEQ), have been developed [4].

In this work, a deeper analysis on thermal comfort was conducted. This thesis reports the development and the validation of new methodologies for the real-time assessment of the personal parameters (i.e., metabolic rate and clothing insulation) which greatly affect the indoor thermal comfort. First of all, the methodologies have been applied in a virtual test bench in which the control of the environmental conditions has been performed by means of a PMV-based approach (Predicted Mean Vote). Despite the limits of the Fangers' model, it was used because it includes the personal factors in order to estimate the indoor thermal comfort. Afterwards, the methodologies have been tested in a real-case study and a low-cost device was used for monitoring the indoor thermal comfort. It allows the assessment of thermal comfort according to the Fangers' model. Moreover, the device was integrated with a Building and Management System (BMS) that performs the management and control of the environmental conditions (shading, heating/cooling systems). Section 2 presents an overview of thermal comfort. In particular, it was discussed in terms of:

- indices and models,

- sensors,
- correlations,
- how thermal comfort is considered in the design and management phase
- limits.

Section 3 discusses about the innovative methodologies which allow the dynamic measurements of the personal parameters. Section 4 describes a virtual test bench in which the new methodologies were integrated into a virtual environment consisting of a building simulation model with technical systems that allow the control of the indoor air temperature by means of a PMV-based approach. Moreover, the uncertainty analysis was conducted and the results were discussed. Section 5 presents a description of a real case study. A demo room (in which tests are performed) and the system architecture are reported. Section 6 reports the validations and the results in terms of evaluation of physiological parameters by applying new methodologies, thermal comfort, and energy saving. Lastly, Section 7 presents the conclusions.

Chapter 2.

State of the Art

The control and monitoring of indoor conditions represent an important task with the aim of ensuring suitable working and living spaces for people. Especially in industrialized countries, several rules and standards have been released to provide technicians with suitable design tools, effective indexes and parameters for checking the indoor microclimate.
Comfort is a very wide concept which depends on many factors such as the indoor air quality, acoustic comfort, visual comfort and thermal comfort. All these aspects together should be considered to allow having a complete description of the comfort sensation and to optimize the management of the monitoring systems. Moreover, in recent years, the psychological aspect was investigated. It was observed that having the personal control of environmental conditions provides a better thermal sensation and thermal comfort [5]. Therefore, it is important for the occupants to have the opportunity to control the environment in order to adjust the indoor conditions. Same results about the psychological aspect were reported in [6].
In particular, this thesis is focused on the thermal comfort and personal parameters which have a significant influence on it. Thus, in the following pages, a deeper investigation of these aspects is presented.

2.1. Thermal comfort

The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) defined thermal comfort as ‘‘the condition of the mind in which satisfaction is expressed with the thermal environment’’ [2]. Therefore, according to the above definition, comfort is a subjective sensation.
Thermal comfort is one of the most important factors that play a fundamental role in the well-being of the occupants. In the next paragraphs, this aspect will be deeper investigated. Moreover, the models, the sensors, the design phase and management phase of the buildings, and the correlation with other aspects of comfort and actual limits are presented.

2.1.1 The comfort models

Thermal comfort has been studied from the early 1920s when the first attempt of “comfort zone” definition was done by the ASHRAE. During the successive decades, the balance between the human body and the surrounding environment has been deeply investigated to determine mathematical models that express the overall interaction (body heat production and exchange, influencing factors, etc.). Some mathematical models have been developed to express the body heat exchange in function of the above variables [7]. Basing on them and observations in controlled and real environments, comfort models have been determined, providing different indexes that can be used to set the boundaries for thermal design. Among the number of modelling approaches, two of them showed the higher accuracy and applicability up to now: the Fangers' model and adaptive model. The former is applicable in mechanically conditioned buildings, while the latter is generally used in buildings that are not mechanically conditioned, or which are equipped with natural ventilation.

2.1.1.1 The Fangers' Model

The Fangers' model aims to predict the mean thermal sensation of a group of people in the same environment [8]. It is based on the classic steady-state model that refers to the heat balance model of the human body. The PMV (Predicted Mean Vote) index is a function of the air temperature (t_a [$°C$]), mean radiant temperature (t_r [$°C$]), water vapour partial pressure p_a $[Pa]$, which, in turn, is a function of the measurement of relative humidity (RH [%]), air velocity (v_a [$\frac{m}{s}$]), clothing insulation (I_{cl} [m^2K/W]) and metabolic rate (M [$\frac{W}{m^2}$]) and represents the thermal sensation for the occupants:

$$PMV = f(t_a, t_r, v_a, p_a, I_{cl}, M) \qquad (1)$$

In addition, the Fangers' model provides the PPD index (Predicted Percentage Dissatisfied) that evaluates the percentage of people that expressed thermal discomfort.
In Figure 1 the relationship PMV-PPD is reported:

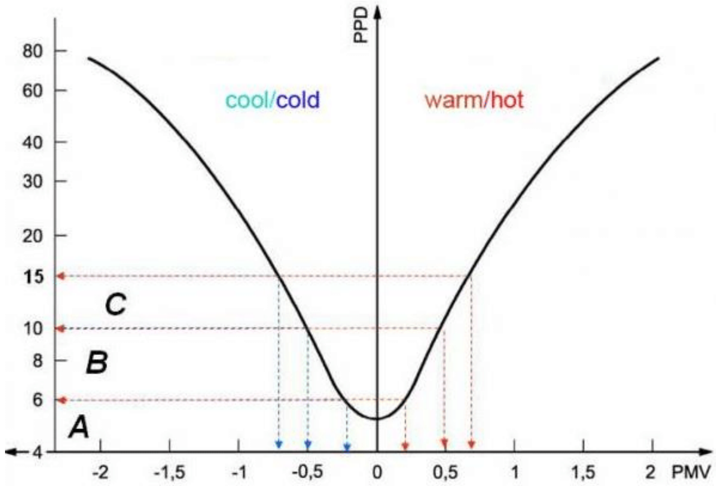


Figure 1 *The relationship between PMV-PPD* [9]

The assessment of thermal comfort is usually supported by the questionnaires which compare the values obtained from the model, with those obtained from the real sensations perceived by the occupants.
In most cases, it was observed that the PMV model underestimate the real thermal sensation of the people as reported in [10]. It is known that the PMV index is not able to consider psychological and behavioural adaptations. Thus, there is a lot of interest in thermal comfort research to develop the adaptive models.
In [11] the authors proposed a theoretical adaptive model for the PMV which considers factors such as culture, climate, social. This model includes a coefficient which describes adaptive factors that affect thermal comfort sensation. This adaptive model allows extending the applicability of the PMV model to the free-running buildings.
In addition, Fanger and Toftum proposed an extension of the PMV model for non-air-conditioned buildings in a warm climate that includes an expectancy factor as explained in [12].

2.1.1.2 Adaptive approach

As mentioned above the other model for thermal comfort is the adaptive one. The adaptive approach for thermal comfort derives from statistical studies conducted in real buildings and has its main focus on naturally ventilated buildings. It has been observed that people are more tolerant than what the Fangers' model suggests. Adaptive approach proposes a linear correlation between comfort temperature for the occupants of the building and outdoor air temperature.
In the adaptive comfort model, the occupant of a building is no longer simply a passive subject, as it appears in the PMV model, but people are considered as active agents that interact at all levels with the environment in which it stays. This model is based on the ability of the occupants to adapt to environmental conditions, acting on the variables that affect them.
It is possible to summarize the adjustments in three categories: behavioural adaptation, physiological adaptation, and psychological adaptation. Behavioural adjustments are directly related to the thermal balance of the human body.
Humphreys was the pioneer who found the relationship between the comfort temperature and the outdoor air temperature [13]. The adaptive model generally uses the monthly mean outdoor temperature as the index for outdoor temperature [14].

$$T_{comf} = a \cdot T_{a,out} + b \qquad (2)$$

Where T_{comf} is indoor comfort temperature [°C], $T_{a,out}$ is the monthly mean outdoor temperature [°C] and both a, b are constants.
Several researchers developed adaptive comfort models for naturally ventilated residential buildings related to the specific geographical area as reported in [15][16][17]. Indraganti investigates the importance of behavioural adaptation for the occupants of buildings [18].
In the previous work, a thermal comfort field survey was conducted, which included information on the use of building controls. The results have been shown that several designs

and nonthermal factors, such as operation and maintenance of controls, noise, and occupant's attitude, age, and tenure impacted the occupant's adaptive behaviour and thermal comfort significantly.
As reported before, adaptive models are usually used in naturally ventilated buildings but recently, some studies have been carried out in air-conditioned buildings with the aim to extend the applicability of this model [19].

2.1.2. Sensors for thermal comfort

To provide thermal comfort assessment adopting the PMV model more physical quantities have to be measured. The standard procedure for the assessment of thermal comfort adopts microclimate stations which are equipped with sensors that are able to measure physical variables. In the regulation [20], the sensors necessary to measures environmental variables are reported. The microclimate stations are costly and they do not provide a real-time assessment for thermal comfort. In the last decades, with the growth and the improvement of technologies, many sensors and devices have been developed. The trend in research is to provide low-cost sensors with good performance as presented in [21]. Small dimensions of low-cost sensors and new paradigms of communication allow creating wireless sensors networks (WSN) that have the capability of real-time monitoring and therefore they can provide dynamic scenario about indoor thermal environment conditions [22][23][24]. WSN with respect to the microclimate station allows to develop measurement nodes and collect data from multiple points of the environment in order to provide a better description of indoor environmental conditions.
Furthermore, providing real-time assessment of comfort sensation is essential to adjust environmental variables for improvements in thermal sensation. In the following study, the authors present a device for real-time monitoring of indoor thermal comfort [25]. In addition, the Internet of Things technologies (IoT) [26] and wearable sensors are used to collect data in order to obtain comfort prediction [27]. Wearable devices are designed for monitoring health status and physical activities. Moreover, these sensors can capture some factors that can affect thermal comfort such as activity level, ambient temperature, and sweat secretion.
There are many commercial solutions involving the use of integrated sensors for thermal comfort assessment. In [28] Nest Thermostat has been presented. It is a smart device designed to control a central air conditioning unit based on heuristics and learned behaviour. It is able to connect to the user's home or office network and interfaces with the Nest Cloud, thereby allowing for remote control of the unit. In [29] the authors have been demonstrated that using cheap and simple sensing technology (PIR) to evaluate occupancy and sleep patterns in a home, can provide a 28% of energy saving on average. The basic idea is to control the HVAC equipment based on a setback schedule: the house is conditioned to a set-point temperature when the occupants are typically active and floats to a more energy-efficient set-back temperature when the occupants are typically away or asleep. Lastly, in [30] a "Smart Lamp", useful to optimize the indoor thermal comfort and energy savings, was developed. The results showed how the application of the Smart Lamp effectively reduced the energy consumption, optimizing the thermal comfort.

2.1.3. Applications and advancements

The design of buildings from the thermal comfort point of view concerns two main aspects: the design phase and the management phase. In this perspective, an efficient building is one in which there are both good comfort levels and an optimal management of the systems that can guarantee comfort conditions. The building design and the building management are very complex aspects to consider simultaneously. For this reason, often a compromise is needed. The goal is to maximize comfort by reducing energy consumption.

2.1.3.1 Thermal comfort and building design

Computer simulations for buildings design is a very useful approach to optimize indoor environments conditions for thermal comfort. Computational Fluid Dynamic (CFD) is the main technique applied for the thermal comfort studies and for building energy modelling in different climate zones. In recent years, the focus of these applications is studying the airflow in a room and the air quality, since they can provide detailed information on the performance of mechanical or natural ventilation strategies [31].

Furthermore, in the design phase, a great importance is given to building energy simulations (BES) essential to achieve a good level of thermal comfort. In [32] the results of CFD and BES methods are compared and it is reported that a combination of this techniques can improve the accuracy of simulations.

The Standard [33] provides a description of input parameters for design and assessment of energy performance of buildings. For the design of buildings and dimensioning of room conditioning systems, the thermal comfort criteria (minimum room temperature in winter, maximum room temperature in summer) shall be used as input for heating load [34] and cooling load [35] calculations. This will guarantee that a minimum-maximum room temperature can be obtained at design outdoor conditions and design internal loads. Criteria for the thermal environment shall be based on the thermal comfort indices PMV-PPD with assumed typical levels of activity and thermal insulation for clothing (winter and summer) as described in detail in [36]. Based on the selected criteria (comfort category) a corresponding temperature interval is established. The values for dimensioning of cooling systems are the upper values of the comfort range and values for dimensioning of the heating system are the lower comfort values of the range

The criteria for the thermal environment in buildings without mechanical cooling may be specified using the same method mentioned above for mechanically heating/cooling ventilated buildings, or differently from those with mechanical cooling during the warm season due to the different expectations of the building occupants and their adaptation to warmer conditions. The level of adaptation and expectation is strongly related to outdoor climatic conditions. In summer, most naturally ventilated buildings are free-running so there is no mechanical cooling system to dimension and the criteria for the categories are based on indoor temperature. Summer temperatures are mainly used to design for the provision of passive thermal controls (e.g., solar shading, the thermal capacity of the building, design, orientation, and the opening of windows, etc) to avoid overheating of the building.

2.1.3.2 Thermal comfort and building management

The Heating, Ventilation and Air Conditioning (HVAC) system is the principal element for building management. Improving their efficiency means improving energy consumption. The aim of this aspect is to achieve a good comfort level, energy saving, and air quality control. The energy efficiency of the buildings, that is a fundamental aspect of intelligent control, is becoming the trend for the future generation of edifices. As reported in [37] and in [38] it is possible to classify the control strategies in two main categories:

1) conventional controls;
2) intelligent controls.

Conventional control referred to the on/off switching control such as PI (proportional–integral) or PID (proportional–integral–derivative). Limits of conventional strategies are given by their focus on energy saving and not on comfort factors. Furthermore, the wrong choice of gain's factor for the PID controller could make the systems unstable. For this reason, designers have preferred optimal adaptive and predictive controls.

On the other hand, the intelligent controls use algorithms to provide better environmental control conditions to minimize the energy consumption. Artificial neural networks and fuzzy logic controls are widely adopted. The synergy of the neural network's technology with fuzzy logic has started to be applied in buildings.

In [39] two artificial neural network (ANN)-based predictive and adaptive models were developed and employed in an algorithm. Results show that the model's combination can be used to provide better management and more comfortable and energy efficient indoor thermal environment.

In [40] an approach based on a combined neuro-fuzzy model for dynamic and automatic regulation of indoor temperature is proposed. The results show that the efficient dynamical regulation of the on/off times of the HVAC system and of its inlet air speed achieves a more efficient use of energy rather than simple on-off devices.

Finally, in [41] an application of a combined neuro-fuzzy model for indoor temperature dynamic and automatic regulation is described. The authors have demonstrated the effectiveness of the hybrid neuro-fuzzy approach and the importance of efficiently designing the temperature forecast model.

2.1.4 Limits

Many models for the assessment of thermal comfort have been recently developed and new technologies too. An aspect that it is not possible to avoid when discussing comfort is the interaction that people have with the environment. The interactions between people and the environment are crucial aspect so it is fundamental to take into account the feedback of the subject to give a good thermal comfort assessment. Researchers have shown that thermal comfort depends not only on the environmental variables described in the Fangers' model or in the adaptive models but also from the other parameters such as indoor air quality variables, psychological effects on thermal comfort sensation as explained in the previous sections. For this reason, it is necessary to be able to integrate more variables in the models that can provide a better description of comfort sensation. In the last decades, many studies have been carried out in order to enlarge the application domain of Fangers' model and also the accuracy of input parameters [42]. The validity of the modified models that have been found is often related only to the limited conditions in which they are studied. More studies reported that Fangers' model underestimate the indoor thermal comfort whereas the PMV index has a good correlation both thermal sensation vote (TSV) and humidity as explained in [43]. The adaptive models are recently enlarged adopted for the purpose of optimized indoor thermal comfort conditions, many models are developed depending on climate regions. Moreover, differently, from the Fangers' model, adaptive models do not consider the personal parameters (i.e. metabolic rate and clothing insulation) in the assessment of thermal comfort. In addition, the adaptive models have a limited range of applicability. They can be applied for metabolic rates lower than 1.3 met and usually they differ according to the plant type. Moreover, the adaptive models do not take into account the other dimensions of comfort.

2.1.5 Thermal comfort correlations

In this section, the possible correlations between thermal comfort and personal parameters (i.e., metabolic rate) are discussed.

2.1.5.1 Metabolic rate and blood pressure

Usually, the assessment of indoor thermal comfort is provided by post-processing techniques. To have a real-time monitoring of thermal comfort conditions, it is necessary considering the real-time measurements of physiological parameters (e.g., metabolic rate and clothing insulation). The common approach is to consider the metabolic rate as a constant. Nowadays with the development of wearable devices, such as smartwatches equipped with low-cost sensors, the measurements of metabolic rate are now easily estimable by means of the measure of heart rate.

Metabolic rate is a variable that plays a key role in the Fangers' model. In [44] the methods which allow an evaluation of the metabolic rate are reported. These approaches are characterized by considerable uncertainty.

People have different metabolic rates that can fluctuate due to their activity level and to environmental conditions. Slight change of activity level induces greatly different in thermal sensation. So, the allowable fluctuation of metabolic rate in order to have the neutral sensation of comfort depends on environmental conditions. In [45] the authors have investigated the factors which act on the allowable fluctuations range of metabolic rate and they have reported that the air temperature is the most significant factor that affects the fluctuation of the metabolic rate within the thermal comfort zone, the next is the relative humidity and the air velocity.

In recent studies, the continuous monitoring of the metabolic rate by means of heart rate measurements has been tested. Moreover, the sensitivity analysis of the PMV model was studied [46][47]. The continuous monitoring of metabolic rate can improve the estimation of comfort conditions and in the future, provide a personalized comfort model.
However, there are many works that are trying to find new correlations between different parameters in order to enhance the assessment of the PMV.
In [48] the authors have investigated the relationship between the mean blood pressure (MAP) and the activity level because blood pressure is a variable that significantly affects the metabolic rate. It is observed a strong correlation between them and the following expression for the activity level was reported:

$$Activity\ level = 0.1092 \cdot e^{(MAP \cdot 0.0296)} \quad (3)$$

Thus, considering this new formulation for the activity level, the authors have found a modified model which performs the evaluation of the PMV index based on the measures of the blood pressure. The results have shown that in air-conditioned buildings, the PMV model overestimated the thermal sensation up to 54% as compared to the actual vote, whereas the overestimation of the modified model (depending on mean blood pressure) was found to be 22% only. The expression (3) describes a further way to estimate the activity and consequently to evaluate the PMV index. Anyhow, it is difficult to apply since it is not possible to have a real-time and continuous measurement of the pressure.

2.1.5.2 Evaluation of clothing insulation parameter

According to the Fangers' theory, a further personal parameter which widely affects the assessment of indoor thermal comfort is represented by the clothing insulation. It is defined as the heat resistance of clothing. There are various factors which influence the selection of clothing type. the factors which influence the selection of clothing can be divided broadly into four major groups, i.e. social factor, economic factor, environmental factor and physical factor. All these factors play significant roles in the selection of clothing of a person. The social factors include the place where a person lives (urban or rural area), cultural background of the person, gender, occupation, occasion, social status, etc. Depending on the place where a person lives, the clothing pattern changes. In an urban area, due to close cultural interactions between the various sections of people, the clothing pattern becomes more cosmopolitan in nature. But on the other hand, the rural clothing is more influenced by the regional factors. Similarly, clothing is also influenced by cultural background and upbringing of a person. The upbringing influences the taste of a person toward the clothing significantly. In some cases, a person selects his clothing depending on the occupational requirement. The environmental factors include climatic conditions (too cold, too hot, raining, chilled wind, etc.), protection from the extreme environment, unusual places (space or underwater), etc. Depending on the environmental conditions the clothing needs changes. The last and very important factor is the physical conditions of a person, which include age, the condition of health of a person, body structure, the physiological response of body, activity level, etc. The clothing pattern

changes with the age of the person due to the psychological and physiological changes with time [49].
Commonly the clothing insulation is measured with the help of human subjects or on thermal manikins because they reproduce correctly the way the clothes are used. However, the thermal manikin represents the most common tool used to measure the thermal insulation because of the simplicity and repeatability of the experiments [50]. In the aforementioned work, the authors found that the dynamic thermal insulation values are always lower than the corresponding static ones. The effects of body motion and air movement greatly affect the evaluation of clothing insulation [51]. This phenomenon is usually called "Pumping Effect". Thus, this should be taking into the account for the thermal comfort model [51]. To estimate the effect of body motion and wind on clothing insulation, a movable thermal manikin may be used in simulated wind conditions, or heat balance experiments with human participants can be performed. In addition, the body posture, the activity level, the air velocity, the accumulation of sweat, the compression, thickness, the number of layers and the fit of the clothing may change the thermal insulation significantly. As reported in [52], to maintain thermal comfort the clothing flexibility was a very valid approach. As clothing flexibility increased, a higher cooling set-point and a lower heating set-point could be adopted without affecting thermal comfort but realising significant energy savings.
Generally, in the Standard, thermal comfort ranges are usually calculated for clothing insulation equal to 0.5 clo and 1 clo. If other information is not available, thermal comfort evaluations for the cooling season are performed with a clothing insulation equal to 0.5 clo, and for the heating season with a clothing insulation equal to 1 clo [53].
Moreover, the selection of the clothing insulation for thermal comfort calculations affects the design (sizing and analysis) of HVAC systems (Heating, ventilation, and air conditioning), the energy evaluation and the operation of buildings. A model that is able to predict how building occupants change their clothing would greatly improve HVAC system operation. Previous attempts to develop a dynamic clothing model demonstrated that the ability to more accurately predict variations in clothing leads to improved thermal comfort [52], smaller HVAC size and lower energy consumption [54].
Furthermore, in recent years, the correlation between clothing insulation and external conditions has been investigated. In particular, dynamic models which perform an evaluation of clothing level based on the measure of the external temperature have been developed [55]. According to this approach, in this work, a further analysis has been conducted and a relationship for dynamic evaluation of clothing insulation has been obtained.

2.2 Impact of Comfort on the occupant's productivity and well-being

"Health is a status of the absence of disease". Following this direction, the building design and development can play a fundamental role to avoid and decrease the cause of disease for occupants. Moreover, the environmental building construction can improve a healthy and active lifestyle of the user and decrease the incidence of pathologies introducing ICT systems and assistive technologies. In particular, comfort is more than a physiological reaction to environmental stimuli but it can provide a subjective reaction to the environment. Comfort

can maintain the homeostasis that is a reaction to the environment indicating the absence of environmental stressor and which is strongly related to health.
Discussing the health status of the occupant, it is possible to identify 3 pillars:

- Well-being aspect
- Physiologic aspect
- Psychologic aspect

Well-being
Following the indications of the Centres for Disease Control and Prevention (CDC), there is a single definition of well-being: "Well-being includes the presence of positive emotions and moods (e.g., contentment, happiness), the absence of negative emotions (e.g., depression, anxiety), satisfaction with life, fulfilment and positive functioning". Different and multiple studies showed the impact of a healthy environment in the well-being of occupants. A lot of aspects can improve when the Indoor Environmental Quality (IEQ) is considered during the building design and development. In particular, the user satisfaction, behaviour, work productivity and comfort [56] [57] [58].

Physiologic aspect
The physiological aspect of the user is more correlated to a health condition. For this reason, during the building design, the health of the subject is one of the first aspects to be considered, e.g. the environmental air quality is connected to the respiration diseases [59] [60] and environment with an inadequate ventilation can promote health problems. Lots of studies have found reductions in health diseases and improved health conditions in the home, school and office settings in green buildings as a result of IEQ improvements [1]. Lighting, acoustic and thermal comfort have also an impact on the user health [61]. During the building design and developed, the attention has to be on the user health condition, to improve the positive feedbacks of the user related to the environment. In fact, interventions that promote health can also enhance indoor environmental quality (IEQ) and provide an opportunity to improve the health status of the user [62].

Psychologic aspect
During the building design and development is fundamental to consider the psychological aspect of the user. The psychological mechanism of the adaption to indoor and outdoor is known in the thermal history [63]. The personal variables and parameters are modified to take account of the adaptive changes. For this reason, the psychologic aspect can give a better prediction of the comfort vote measured in comfort surveys [64]. The psychological adaptation can't be observed directly and it can depend to:

- Physiological parameters/status
- Indoor environment
- Outdoor environment
- Personal physical factors
- Environmental controls

- Thermal expectation [65]

Since the people spend more than 90% of their life indoors it is important to understand the indoor office environment and the effect it has on occupant productivity. An office environment has a high level of influence on its occupants' productivity [66] [67]. Many studies on sustainable buildings report that green design strategies and technologies improve the indoor workplace environment. such strategies/technologies enable the creation of an environment which favours occupants' comfort and performance in both newly built and retrofitted buildings [68].

The indoor environment influences the health and well-being of the occupants. Healthy buildings lead to more flourishing and happy inhabitants [69][70]. The built environment industry should deliver a built environment which is conducive to its occupants and promotes their health and well-being. Efficient and conducive workplaces help to reduce employee absenteeism, reduce staff turnover, and increase occupant productivity and satisfaction, thus increasing the perceived health and well-being of their occupants [71]. All this evidence highlights the impact of indoor environmental quality on employee productivity and emphasises the importance of understanding Indoor Environment Quality (IEQ) and its effects on occupants' productivity. In the case of office environments, performance/productivity can be measured using different criteria such as individual performance, team performance and organisational performance [72][73]. Considering the physical factors many of them affect the occupant productivity. Research studies in the field of the indoor environment focusing on occupant comfort and productivity used different methods of data collection to highlight the occupants’ discomfort and its relationship to productivity. As reported in [74] the assessment of the occupant productivity depends on three main aspects: indirect assessment, subjective assessment and physical parameters’ measurement. The indirect assessment include measuring absenteeism in employees, the number of hours worked each week, the number of grievances filed and employee turnover [73]. The subjective assessment can be monitored using a survey (interviews and questionnaire) while the physical parameters can be acquired adopting several kinds of devices and sensors.

Focusing on the indoor temperature parameters, many studies report how this variable affects several human responses including thermal comfort and the indoor air quality. Consequently, it impacts on the performance at work. The indoor air temperature parameter can be controlled with different accuracy depending on the building and its HVAC system. In [75] the authors report the results of multiple studies. The outcomes are consistently and show an average relationship of 2% decrement in work performance per degree °C when the temperature is above 25 °C. Moreover, similar studies were conducted for the indoor air quality aspect. In fact, in [76] the authors confirm that good air quality improves the performance of work. A positive correlation between the air quality, as it is perceived by occupants, and the performance indicates that performance will increase on average by 1.5% when the proportion dissatisfied with the air quality is decreased by 10% in the range of air quality levels causing 25-70% to be dissatisfied. The results imply that doubling the outdoor air supply rate at constant pollution load, or a two-fold decrease of pollution load at constant ventilation rate, can increase overall performance by 1.9%.

Furthermore, in [74] eight physical factors which influence the indoor environmental quality and occupant productivity were discussed. Thus, monitoring the comfort conditions is a very important aspect since allows to improve the work performance, well-being and the management of comfort causing a reduction in terms of energy consumption.

Chapter 3.

Development of innovative methodologies for thermal comfort evaluation

Thermal comfort is probably the most important aspect of Indoor Environmental Quality (IEQ). It has a direct impact on the energy consumption of any building as any sense of discomfort of occupants leads to the tweaking of controls to non-optimal levels.
This thesis is focused on this key aspect of IEQ.
Thermal comfort is generally measured by sensors compliant with mathematical models that express the overall interaction between the human body and the environment (body heat production and exchange, influencing factors, etc.). The most used is based on the Fanger comfort theory which enumerates six factors to determine the heat balance and provides a formula to calculate the PMV index. Four of the six are environmental parameters: relative humidity, air temperature, mean radiant temperature, and air velocity. The remaining two are personal factors: the metabolic rate and clothing insulation. The PMV measurement requires thus the capability of sensing not only environmental parameters but also factors related to occupants' characteristics. Concerning the environmental quantities, the microclimate station is the most used device for short-term monitoring. In recent years, the monitoring of IEQ has been enhanced adopting several kinds of sensors which are able to both communicate between them and continuous monitoring of different environmental variables.
The communication protocol such as the Internet of Things (IoT) technology allows the creation of wireless sensors network. A multitude of sensors is connected wirelessly to develop distributed networks. The wireless sensor networks (WSNs) is one of the most essential technologies utilized in IoT-based smart home automation in order to have a smart environment [77] [78].
As previously said, according to the Fangers' comfort theory, the personal factors are represented by the metabolic rate and the clothing insulation. The general approach is to consider subjective parameters (that greatly affect thermal comfort) as constant by using values from Standard, according to the typical end-use of the building. This assumption usually does not reflect the real conditions and leads to incorrect evaluations.
In the perspective of improving these estimations, in this work, new methodologies were developed in order to have a dynamic evaluation of metabolic rate and clothing insulation. In the following paragraphs, the description of the new methods for the estimation of the personal factors is reported.

3.1 Real-time measurements of metabolic rate

In this Section, a deeper investigation on metabolic rate parameter (*M*) has been carried out. The goal is to provide an innovative methodology for dynamic and real-time evaluation of *M* to enhance the assessment of thermal comfort.

3.1.1 Impact of metabolic rate for thermal comfort assessment

Metabolic rate is defined as the amount of daily energy that a person consumes while at rest in an environment that is temperate and neutral, and while in a post-absorptive state. The chemical and physical reactions that occur in an organism are reversible and depend on changes in the energy status.

As reported in the state of the art, metabolic rate is one of the most essential parameters that affect indoor thermal comfort. In [79] a sensitivity analysis of the PMV index was performed in order to investigate the PMV variation related to the metabolic rate. PMV was computed at a given thermohygrometric condition for different values of M together with its variations $dPMV = {}^{\partial PMV}/_{\partial M} \cdot dM$, where dM=±0.1 met according to the accuracies required in ISO 7730 [36]. The authors report that for low metabolic rate (<1met) the sensitivity of PMV becomes higher (Figure 2) and the subject tends to feel a colder sensation (i.e., PMV decreases).

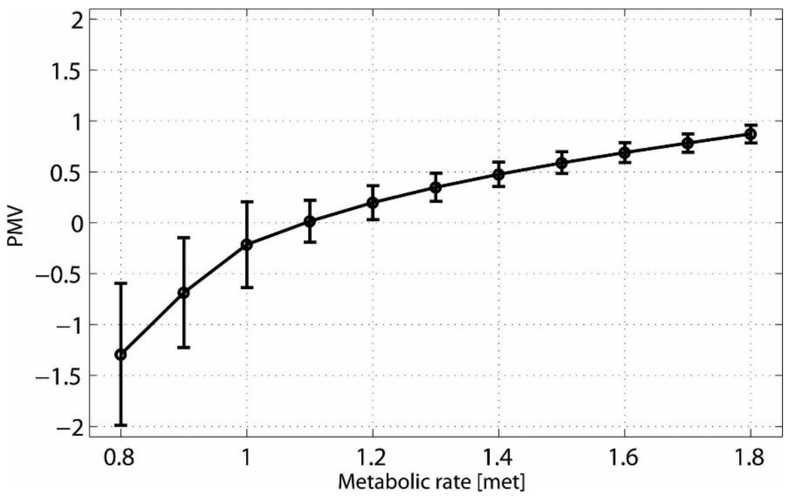


Figure 2 *PMV as a function of the metabolic rate with variation intervals associated to dM=±0.1 met*

For this reason, it is important to have a good evaluation of this quantity to obtain an accurate estimation of indoor thermal comfort [80]. Small variations of this physiological parameter can induce widely different thermal sensation.
Generally, the assessment of indoor thermal comfort is performed assuming a constant value of *M*. This approximation often leads to a discrepancy between users' comfort sensation and the comfort values evaluated by the Fangers' model.
In fact, the metabolic rate changes continuously according to the physical activity performed by the subject.
According to the Standard [44], there are several methodologies based on the statistical analyses or measurements of indirect parameters that can be used for the assessment of *M*. Among these, a methodology based on the continuous monitoring of the subject's heart rate (*HR*) should be able to provide an estimation of *M* with an accuracy of ±10% [44]. The relationship between *HR* and *M* can be derived by recording the heart rate at different stages of the defined muscular load during an experiment in a neutral climatic environment. In the following, the equation which allows the estimation of metabolic rate by means of the continues measurements of *HR* is reported:

$$M(t) = \frac{1}{RM} \cdot (HR(t) - HR_0) + M_0 \qquad (4)$$

Where M is the metabolic rate [Wm^{-2}], M_0 is the metabolic rate at rest [Wm^{-2}], RM is the increase in the heart rate per unit for metabolic rate and HR_0 is the heart rate at rest. In [47] a simplified version of the equation (4) which is based on a first order polynomial curve relating the metabolic rate and the continuous deviation between HR and HR_0 was used. The results show that by applying this method, the different activities can be identified, considering the real perception of the subject in a room.

3.1.2 New methodology for dynamic assessment of the metabolic rate

In this thesis, a new methodology which uses continuous measurements of the heart rate and others physiological parameters (i.e., *BR*, posture, acceleration module) has been developed. In [81], an investigation about the features of the ECG (electrocardiogram) signal was discussed in order to correlate them with the characteristics of different physiological signals acquired by several kinds of sensors.
Nowadays, the monitoring of users' health status is possible by means of smart sensing devices at low-cost and with high measuring capabilities. The wearable devices can acquire multiple physiological and physical waveforms and they are equipped with onboard algorithms to process the signals and extract the required quantities. In [82] the authors have performed a characterization of a commercial wearable monitoring device for the continuous acquisition of physiological quantities.
In this thesis, a first approach is presented to provide a real-time estimation of metabolic rate through continuous measurements of the heart rate. This methodology was integrated into

the thermal comfort monitoring system and a wearable device was adopted to measure the physiological parameters.
In [83] a new kind of indicator (i.e., *IN5*) was found in order to identify the activity performed by the user. It represents the area of an irregular polygon and it derives from a combination of multiple parameters acquired with the BioHarness 3.0 device (BH3).
The BH3 sensor is shown in Figure 3:

Figure 3 *BioHarness 3.0 multi-parametric device*

In Table 1, the characteristics of the BH3 device are reported:

Table 1 *Characteristics of BioHarness 3.0*

Sensor module size	27mm x 7mm
Sensor module Weight	18g
Strap Fabric	Washable conductive smart fabric
Operating temperature	-30°C to 60°C
Humidity	0% to 95% relative humidity (non-condensing)
Battery	4.2V Li-Ion rechargeable
Runtime	12 to 18 hours
Charging time	3 hours
IP rating	IP-55
Wireless	Up to 2 miles
GPS Accuracy	Within 5 meters

Table 2 shows the embedded sensors on the BH3 device:

Table 2 *Embedded sensors on BioHarness 3.0 device*

Heart Rate	0 to 240 bpm (±1 bpm)
Breathing Rate	0 to 120 bpm (±1 bpm)
Activity	(±) 16g in each axis (Vertical/Lateral/Sagittal)
Estimated Core Body Skin Temperature	33°C to 41°C
Posture	±180

The BioHarness 3.0 is a multivariable physiological device for the real-time monitoring of five parameters: Heart Rate [bpm] (*HR*), Breathing Rate [bpm] (*BR*), Acceleration [g], Activity level [VMU - Vector Magnitude Unit] and Posture [°].
Specific information about the validity and reliability of the BioHarness 3.0 device are discussed in [84] and [85], through dedicated laboratory tests. The good performance of such equipment makes possible to apply it in several fields of applications, e.g. the continuous monitoring of sportsmen's functional state in the conditions of natural activity [86].
Other recent researchers underline the potentials of using this tool in outpatient settings [87], [88], [89], emergency department triage [90], or as a support tool in the prevention of abnormal events, e.g. fall detection [91], [92].
Differently, from the other wearable devices, the BH3 sensor is able to acquire and store both raw physiological waveforms (e.g., ECG and Breathing rate) and the computed quantities after a dedicated processing (*HR*, *BR*).
The aim of this work is to provide dynamic measurements of metabolic rate which are obtained by combinations of multiple parameters measured by using the BioHarness 3.0 device.
Based on the approach described in [83], different indicators (i.e., *IN5*, *IN4*, *IN3*) which depend on the number of the parameters considered (i.e., the ones measured by the same device) were found. Combinations of 5, 4, and 3 parameters were evaluated. The single indicator can be expressed by relationships reported below:

$$IN\,5 = \frac{1}{2} \cdot ((HR_n \cdot BR_n \cdot sen(a_1)) + (BR_n \cdot POS_n \cdot sen(a_1)) + (POS_n \cdot ACT_n \cdot sen(a_1)) + (ACT_n \cdot ACC_n \cdot sen(a_1)) + (ACC_n \cdot HR_n \cdot sen(a_1))) \quad (5)$$

$$IN\,4 = \frac{1}{2} \cdot ((HR_n \cdot BR_n sen(a_2)) + (BR_n \cdot ACT_n sen(a_2)) + (ACT_n \cdot ACC_n sen(a_2)) + (ACC_n \cdot HR_n sen(a_2))) \quad (6)$$

$$IN\,3 = \frac{1}{2} \cdot ((HR_n \cdot ACT_n sen(a_3)) + (ACT_n \cdot ACC_n sen(a_3)) + (ACC_n \cdot HR_n sen(a_3))) \quad (7)$$

Where HR is the heart rate [bmp], BR is the breathing rate [bpm], POS is the posture of the subject [°], ACT is the activity level [expressed as VMU – Vector Magnitude Units], ACC is the acceleration module [g]. Subscript "n" indicates that values were normalized. The normalization was calculated for the following range value: 40÷240 bpm for HR, 4÷100 bpm for BR, -90°÷90° for posture, 0÷4 for activity level and 0÷6 g for acceleration module. The angles a_1, a_2, a_3 are 72°, 90° and 120° respectively.
In [83], the authors selected different tasks according to the standard values of M and they developed a methodology which allows identifying the subjects' activities based on the combination of the parameters acquired simultaneously by the BH3 sensor.
Thus, a specific test was conducted to identify the most accurate calibration curve for the dynamic evaluation of metabolic rate. Ten young and healthy individuals recruited among university students were involved (5 females and 5 males, age: 21±1 years, weight: 61±13 kg, height: 1.71±0.09 m, BMI: 20.95±2.72 kg/m^2). Within the conducted tests, the subjects were asked to perform 4 different kinds of activity. Standard ISO 7730 reports that the PMV model returns an estimate of indoor thermal comfort which can be considered reliable for metabolic rate values that not exceeding 4 met. The standard values that were chosen to perform tests are reported in Table 3.

***Table 3** Standard value of metabolic rate*

Number of Activity	Activity	Metabolic Rate [met]
1	Sedentary activity	1.2
2	slow walk on the flat	2.5
3	go down the stairs	3.5
4	Climbing stairs	4

Each subject completed the activity profiles in 20 minutes and the tests were carried out following a well-defined order (i.e., ascending profile of metabolic rate per activity, then descending profile of metabolic rate activity). The acquisition of the physiological signals of interest was performed on-board by the BH3 device and the quantities computed (e.g., heart-rate, breathing rate, acceleration module, etc.) were directly stored inside the device.
The data were post-processed and Figure 4 and Figure 5, show an example of the time-domain variation of each signal acquired during the tests:

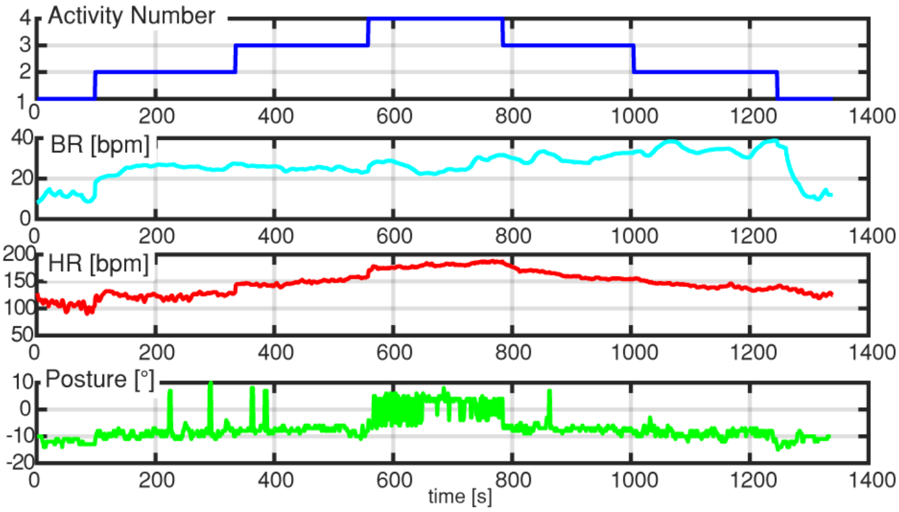


Figure 4 *Trend of standard-based metabolic rate (activity number), breathing rate, heart rate and posture parameters during the tasks*

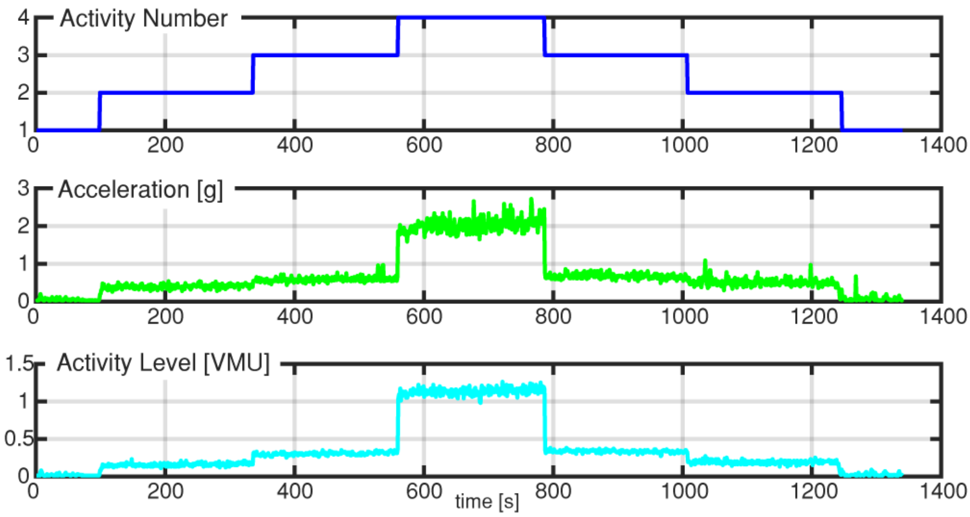


Figure 5 *Trend of the standard-based metabolic rate (activity number), acceleration and activity level during the tasks*

First of all, the variability of the *HR*, *BR*, posture, acceleration and activity parameter was investigated. In Figure 5, it is possible to observe that both the acceleration and activity signals follow the reference profile with a good approximation. Conversely, the heart rate,

the breathing rate and the posture deviate from the standard (Figure 4). This is probably caused by the fact that an increase in metabolic activity is correlated with an increase in physiological parameters, but they take a longer time to become stable. The same considerations are valid for the descending profile of metabolic rate.
A dedicated algorithm for data processing was developed. Its scheme is reported in Figure 6:

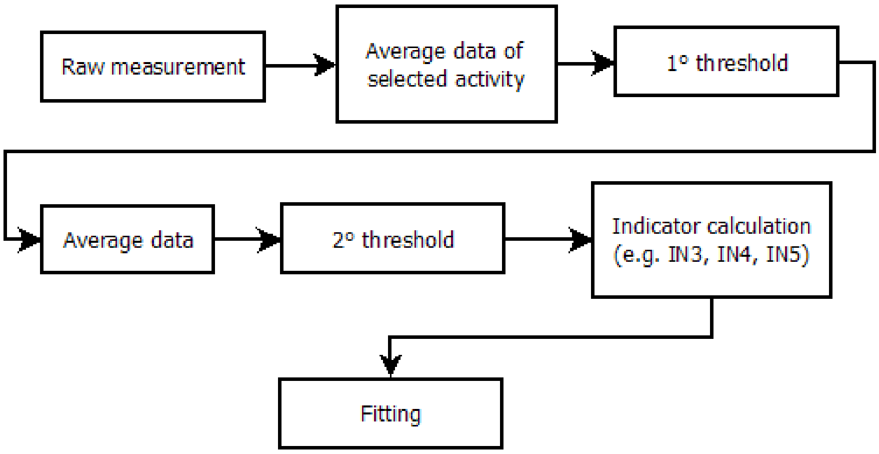


Figure 6 *Scheme of the data processing algorithm*

Initially, for each activity, a portion of the raw data acquired by the BH3 device was selected. The data average was computed, and a first threshold was determined using the Chauvenet's criterion to remove the outlier [93] (excluding those that were not within the range ±3 standard deviation). At this point, the average of the remaining data was re-calculated for every single activity performed, and a second threshold was applied to remove the outliers adopting a robust bivariate analysis, implemented through a MATLAB toolbox [94].
This first step of data processing was applied to all signals acquired from the respective subjects and for each activity performed. In Figure 7 is reported an example of the data obtained after the data processing is reported:

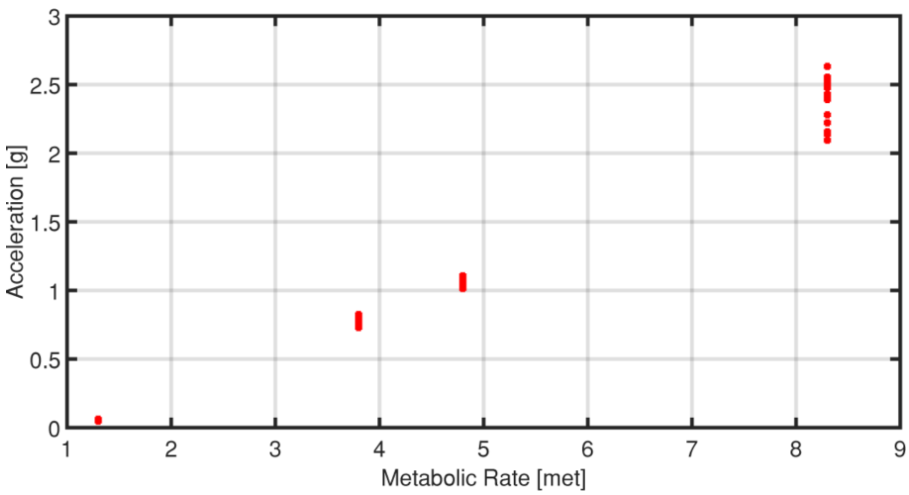


***Figure** 7 Example of acceleration data after data processing*

Finally, the indicators expressed by formulas (5), (6), (7) were correlated with the standard metabolic rate reported in Table 3 and the curves for the dynamic evaluation of metabolic activity were obtained. The results are shown in Table 4:

***Table** 4 Relationships for the dynamic evaluation of the metabolic rate based on indicators*

Equations	R^2	RMSE (2 σ) [met]
$\mathbf{M = 8.48 \cdot e^{\left(-\frac{IN5-0.42}{0.27}\right)^2}}$ (8)	97 %	0.48
$\mathbf{M = -17.5 + 17.9\cos(IN4 \cdot 2.6) + 18.8\sin(IN4 \cdot 2.6)}$ (9)	96 %	0.50
$\mathbf{M = \left(1.2 + \left(3.4 \cdot (1 - e^{-62.0 \cdot IN3})\right) + 15 \cdot \left(1 - e^{-2.22 \cdot e^{-14} \cdot IN3}\right)\right)}$ (10)	96 %	0.20
$\mathbf{M = 1.88 + (7.8 \cdot ACC_n) + (-4.4 \cdot HR_n) + (-16.6 \cdot (HR_n)^2) + (21.4 \cdot HR_n \cdot ACC_n) + (5.1 \cdot (ACC_n)^2)}$ (11)	96 %	0.23

This new methodology provides the curves for the real-time assessment of the metabolic rate expressed as a function of the personal parameters acquired simultaneously. Looking at the results in Table 4, it appears that, to compute an accurate value of *M,* the measurement of the heart rate and physical quantities (i.e., acceleration and *VMU* index) is needed. This suggests that the computing methodology proposed could be applied to wearable devices (e.g., smartwatches, wearable belts), enabling a real-time *M* measurement with an uncertainty of ±0.2 met. This outcome is referred to the sample population involved and to the activities performed.
Finally, a dedicated script was developed to allow the real-time evaluation of M. The dynamic measure of metabolic rate was used to perform the assessment of indoor thermal comfort in a real case study which will be presented in Chapter 5.

3.2 Dynamic predictive clothing insulation model

The study of the thermal insulation of clothing in a dynamic condition is a very complex challenge. Clothing adjustment is one of the most important of all the thermal comfort adjustments available to occupants in office buildings [52]. As reported in [55], occupants frequently adjust their clothing depending on the thermal conditions, as opposed to the assumption of constant clothing values above. So, the authors proposed an adaptive model that provide clothing insulation based on a measure of outdoor temperature.
Below, the mathematical relationships of the model are reported:

For $t_{a(out,6)} < -5°C$ $\qquad I_{cl} = 1.00$
For $-5°C \leq t_{a(out,6)} < 5°C$ $\qquad I_{cl} = 0.818 - 0.0364 * t_{a(out,6)}$
For $5°C \leq t_{a(out,6)} < 26°C$ $\qquad I_{cl} = 10^{(-0.1635-0.0066 * t_{a(out,6)})}$
Or $t_{a(out,6)} \geq 26°C$ $\qquad I_{cl} = 0.46$

The model allows calculating the clothing insulation based solely on measuring the outdoor air temperature at 6 am. It is possible to observe that it has been defined considering different temperature range. In particular, when the outdoor temperature is lower than -5 °C the clothing insulation is saturated to 1 clo, whereas when the outdoor temperature is greater than or equal to 26 °C, the value of clothing insulation is saturated to 0.46 clo. The model described is one of the most recent models which provides a dynamic estimation of I_{cl}. For this reason, in this thesis, the same research approach was used trying to understand what the best correlation with the context variables is (in this case the climate) which is represented by the external temperature.
Thus, starting from the work of Schiavon et al. [55], a measurement campaign was carried out to study the correlation between the clothing insulation and the outdoor temperature in order to provide a better evaluation of I_{cl}.
In this perspective, a questionnaire was provided to 14 subjects (7 female and 7 males) which were involved in this study. It contained a list of clothes and the corresponding clo values as reported in the Standard [36]. Within the survey conducted, the subjects were asked to annotate every day their clothes. Thus, every day, the clothing insulation of each subject was

computed by summing the clo values of each cloth. The data were collected for 6 months registering the clothing level both in the winter season and summer season.
Considering each month, the mean value of the clothing insulation was computed both for the male subjects and female subjects. Figure 8 shows the trends of the data:

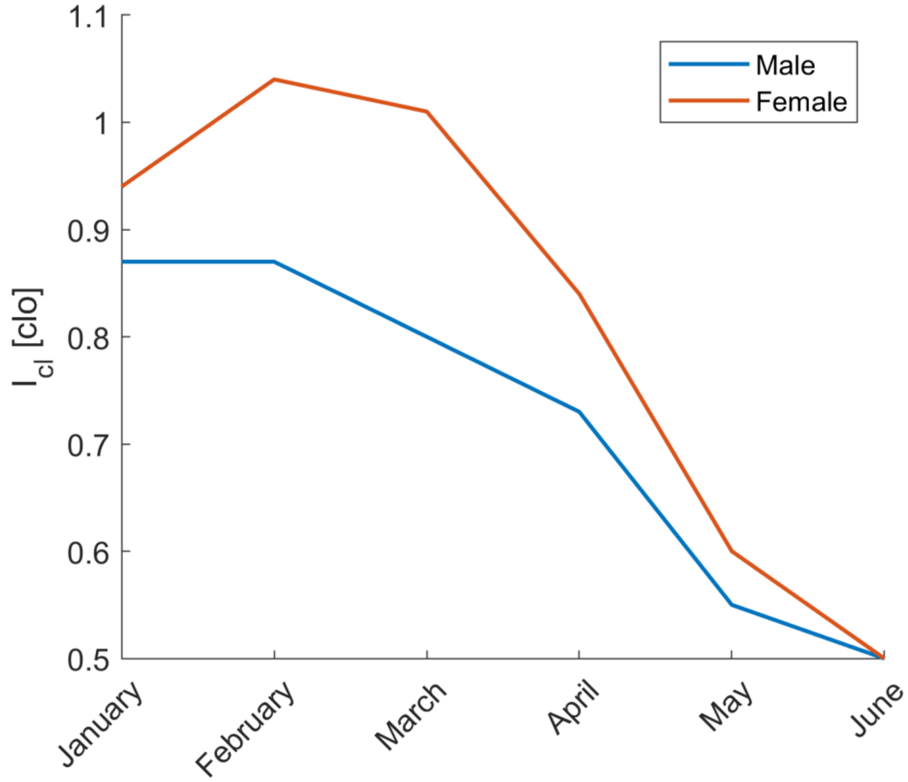


Figure 8 *The average value of the clothing insulation for both the male subjects and female subjects computed in each month*

It is possible to observe that the female subjects present a higher value of I_{cl} compared to the other ones.
To provide a general equation for the evaluation of I_{cl}, all the data were considered (both the male data and female data together). The clothing insulation data have been analysed and different correlations with the outdoor temperature were investigated. In particular:

- Correlation with the outdoor air temperature at 6 am;
- Correlation with the average of the air temperature computed with respect the previous day;

- Correlation with the average of the air temperature computed with respect the previous day considering the working hours (i.e., 08:30 – 18:30);

A linear fitting interpolation was performed and the mathematical relationships obtained are reported in Table 5:

Table 5 *Relationships for the clothing insulation based on the outdoor temperature*

Equations		R^2	**RMSE [clo]**
$\boldsymbol{I_{cl} = -0.02012 * t_{a(out,6)} + 0.97}$	(12)	0.63	0.09
$\boldsymbol{I_{cl} = -0.02246 * t_{a(n-1)} + 1.067}$	(13)	0.70	0.09
For $\boldsymbol{t_{a(n-1,working\ hours)} \leq 28\ °C}$ $\boldsymbol{I_{cl} = -0.02084 * t_{a(n-1,working\ hours)} + 1.093}$ For $\boldsymbol{t_{a(n-1,working\ hours)} > 28°C \quad I_{cl} = 0.5}$ (14)		0.77	0.08

Where I_{cl} is the clothing insulation [clo], $t_{a(out,6)}$ is the external temperature at 6 am [°C], $t_{a(n-1)}$ is the average of the air temperature computed with respect to the previous day [°C], and $t_{a\ (n-1,\ working\ hours)}$ is the average of the air temperature computed with respect to the previous day considering the working hours [°C].

Observing the equations in Table 5, it is possible to note that the evaluation of clothing insulation performed adopting the equation (14) (R^2 = 0.77) is more accurate compared to the other ones.

Figure 9 shows the linear fitting which presents the higher correlation coefficient (i.e., Eq. 14). It represents the equation applied for the dynamic assessment of the clothing insulation.

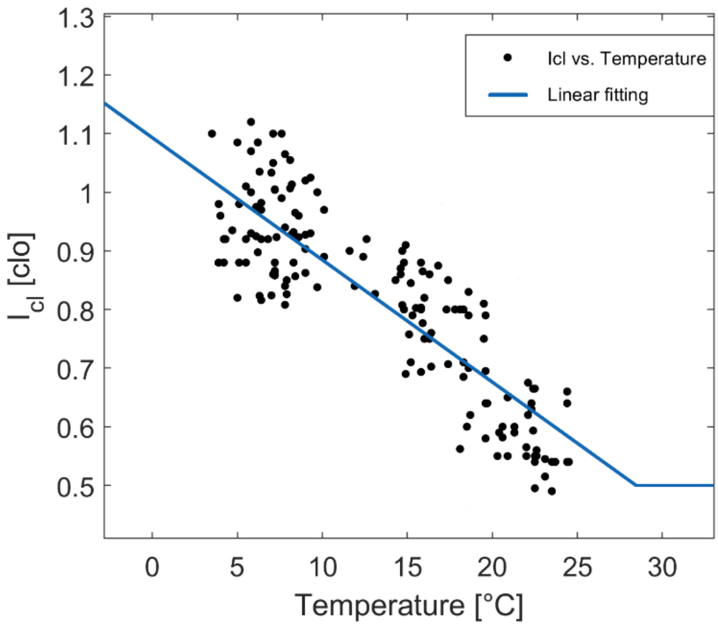


Figure 9 *The linear fitting interpolation between the values of the clothing insulation and the mean value of the external temperature computed considering the working hours.*

In most cases, in an office building, a dress code is required. According to this assumption, a threshold has been fixed to the equation (14). In particular, if $t_{a\ (n\text{-}1,\ working\ hours)}$ is much higher than 28 °C, the relationship (14) was saturated assuming the clo value equal to 0.5 clo.
The function (14) was adopted to evaluate the assessment of thermal comfort in a real case study in which the value of the outdoor temperature was provided by an external microclimate station.

Chapter 4.

Development of a virtual test bench for comfort management

The methodologies proposed (presented in Chapter 3) were integrated into a virtual environment consisting of a building simulation model with technical systems which allow the control of indoor air temperature by means of a PMV-based approach. In the following, the controller developed is described and the virtual test bench of a house and the integration of the controller are presented. Finally, the results are discussed.

4.1 Development of the controller based on PMV virtual sensor

Generally, performing the standard control of indoor air temperature means to manually set a predefined indoor temperature. However, there is a lot of interest in how to optimize the selection of such set-point [38] also making use of the PMV model, as performed in [95]. To enhance this aspect, in this work an advanced controller (Figure 10) was developed and tested taking into account both the real-time measurements of M and methodology developed to estimate the I_{cl} as well as the other environmental quantities collected to evaluate comfort conditions. The controller is a Proportional-Integral-Derivative (PID) controller which takes as input the air temperature (t_a) and the set-point temperature (T_{set}), calculated with a PMV-based method, and provides as output the heat to be supplied to the house. In this simulation, the winter season was considered.

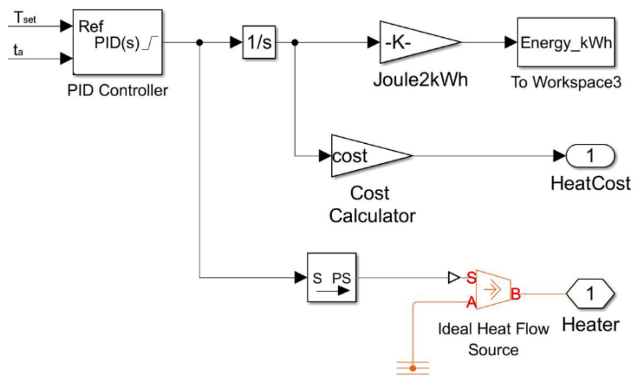


Figure 10 *PID controller applied to the simulation model*

The PID controller regulates the heat required to reach the set-point temperature of the simulated home environment. The set-point temperature, used by the PID controller to achieve comfort conditions, is determined from a virtual sensor that calculates the PMV. In particular, T_{set} represents the air temperature which allows the highest level of comfort (PMV = 0).
A root finding algorithm was used to obtain the value of the T_{set}:

$$T_{set} \mid pmv(T_{set}, t_r, v_a, p_a, I_{cl}, M) = 0 \qquad (15)$$

A Matlab routine based on the Dekker's algorithm, which uses a combination of bisection, secant, and inverse quadratic interpolation methods to find the roots of nonlinear functions, was adopted to compute the set-point temperature [96].

4.2 Integration of the controller into the simulation model

First of all, the model adopted for the metabolic rate was presented. The simulation model was performed in the Simulink environment.
Starting from the basic version of the model of a heating system (provided by Simulink libraries), some modifications were applied to implement a PMV virtual sensor and an air temperature controller based on such virtual sensor, as presented in the previous Section.
The PMV virtual sensor was modelled with two different working modes:

- as a traditional sensor, without the real-time metabolic rate measurement;
- as an innovative system with the real-time measurement of the metabolic rate as proposed in this work.

Thus, the virtual test bench is used to evaluate the impact that the PMV uncertainty has on the building management, in function of the metabolic rate error that can occur when constant values are used instead of continuous monitoring.
The basic version of the model consists of a heater, a thermostat, and a lumped parameters model of the house. The heat exchanges between indoor and outdoor environments through walls, windows and roof are modelled with the electrical-analog method for transient heat-flow, as already done in [97]. Figure 11 shows the modified simulation model.

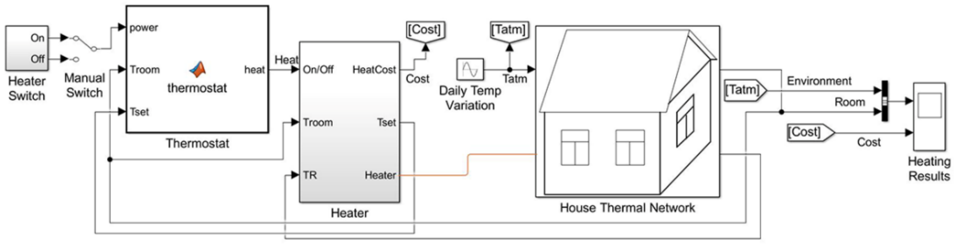


Figure 11 *Simulation model for the Heating house network*

To perform the test, the PID element was integrated into the simulation model of the heating house network. First, the initial value of the air temperature inside the house was set at 23 °C. The heater provides, or does not provide, sensible heat according to the set-point temperature. To run the control algorithm, the computation of the PMV was provided by a virtual sensor that gathered environmental variables from the model. In particular, the air temperature (t_a) was assumed to be equal to the room temperature of the modelled house. Since the simulation approach did not include the mass balance and the moisture, the air velocity (v_a) was set at a fixed value of 0.02 m/s and relative humidity (*RH*) at a value varying around the 50% with a uniform distribution with a range of ±2.5%. Considering that in this case, the virtual test bench is used to test the impact of the dynamic metabolic rate, the clothing insulation (I_{cl}) was fixed at 0.85 clo. Finally, the evaluation of the mean radiant temperature (t_r) was done with the angle factors methodology in agreement with the ISO 7726 [20]. The mean radiant temperature was computed from the indoor surface temperatures of the room and weighted with the view factors, calculated for a central position of a subject with respect to the surrounding walls.
During the simulation, the virtual sensor calculated the PMV index continuously and, consequently, the set-point temperature was computed according to the equation (15).
The same model was adopted for the clothing insulation parameter to evaluate the impact that the PMV uncertainty has on the building management, in function of the clothing insulation error that can occur when constant values are used instead of a dynamic evaluation. Conversely to the previous case, in this test, the PMV virtual sensor was modelled considering two working mode:

- as a traditional sensor, without the dynamic evaluations of I_{cl};
- as an innovative system with the dynamic measurements of the clothing insulation according to the expression presented in Section 3.2.

Also, in this simulation, the air temperature (t_a) was assumed to be equal to the room temperature of the modelled house. The air velocity (v_a) was set at a fixed value of 0.02 m/s and relative humidity (*RH*) at a value varying around the 50% with a uniform distribution with a range of ±2.5%. to perform this test, the metabolic rate was (*M*) fixed at 1.2 met. Finally, the evaluation of the mean radiant temperature (t_r) was done with the angle factors methodology in agreement with the ISO 7726.

4.3 Results of the virtual test bench

Adopting the model described in paragraph 4.2, this Section discusses the results obtained from the two simulated tests both for the metabolic rate and the clothing insulation.

4.3.1 Metabolic rate analysis

Considering the metabolic rate parameter, in both tests, an indoor temperature control was performed, based on a set-point temperature (i.e., derived from a PMV index). The difference

was in the M parameter, which is one of the six quantities for the calculation of the PMV value. In the first case, a dynamic profile of M was considered (i.e., the time-dependent value obtained with the wearable sensor and the application of the methodology previously discussed). The second case refers to a constant profile of M (i.e., a fixed value for the entire duration of the test, as generally done in the state of the art).
In this experiment, a typical 8-hour working day was simulated. The dynamic profile of the metabolic rate was modelled considering the activities which can be performed during the working hours. The metabolic rate profile used for both tests is shown in Figure 12.

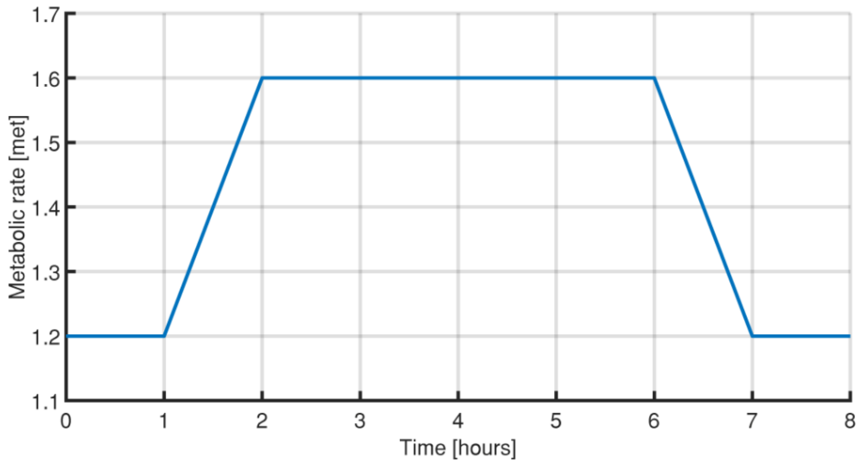


Figure 12 *Dynamic profile for the metabolic rate adopted in the simulation*

The profile simulated an initial activity typical of office work (1.2 met) with a gradual increase in the metabolic rate reaching 1.6 met which corresponds to standing activities and, after keeping this rate for 4 hours, the profile returned to the initial value. The values of M were derived from the compendium of metabolic activities provided by ISO7730.

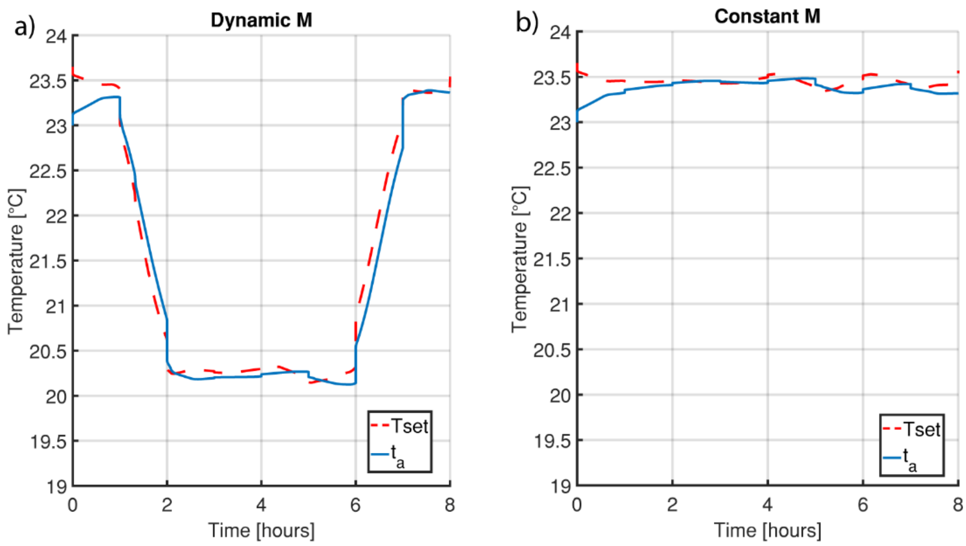


Figure 13 *Trends of the set-point temperatures and the air temperatures obtained by performing the two different controls: (a) with a dynamic profile of the metabolic rate; (b) with a constant value of the metabolic rate.*

Figure 13 shows the trends of the set-point and air temperatures when performing control strategy with a dynamic *M* (Figure 13a) and with a constant *M* (Figure 13b). As said in Section 4.1, the set-point temperature depends on the PMV evaluation, which is significantly affected by the metabolic rate.

It is possible to observe that in winter conditions, when implementing a control strategy that uses a constant value of *M* (Figure 13b), the indoor air temperature is kept almost constant. The heater provides continuous heat to the environment, while the real need of the occupant would be of having a lower air temperature as shown in Figure 13a, where the use of a dynamic *M* for the set-point calculation provided a variation of the T_{set}. In fact, an increase in *M* induces an increase in energy production by the human body that turns out to provide a lower comfort air temperature, therefore a lower T_{set}. The set-point temperature gradually decreased as a function of the metabolic rate increase. Conversely, when the metabolic rate decreased, the system responded correctly by calculating a higher set-point temperature to restore the comfort condition.

Comparing the two situations of the case study proposed, the use of a constant metabolic rate instead of real-time monitoring led to a variation on the PMV calculation propagated as a variation of 3.2°C on the calculation of the T_{set}. This change provided an impact in terms of comfort delivered to the occupants and efficiency in the management of the building.

Analysing the PMV calculated by the virtual sensor in both tests, the control based on a dynamic *M* provided an average PMV close to zero (mean value of the PMV: 0.03±0.09; Figure 14a- Dynamic *M*). Conversely, the control with a constant value of *M* (Figure 14a - Constant *M*) turned out to provide an environment near to the slightly warm sensation (mean value of the PMV: 0.3±0.3). This happened because the controller was not able to recognize the lowered heating need due to the increased occupants' activity. As a consequence, overheating occurred, which turned out to provide worse comfort conditions with higher energy consumption, as demonstrated in Figure 14b, where the energy consumptions recorded with a dynamic *M* (Figure 14b – Dynamic *M*) and with a constant value of *M* **(**Figure 14b– Constant *M*) are reported. The first simulation (dynamic *M*) turned out to have a cumulative energy consumption of 5.8 kWh against the 8.6 kWh of the second test (constant *M*).

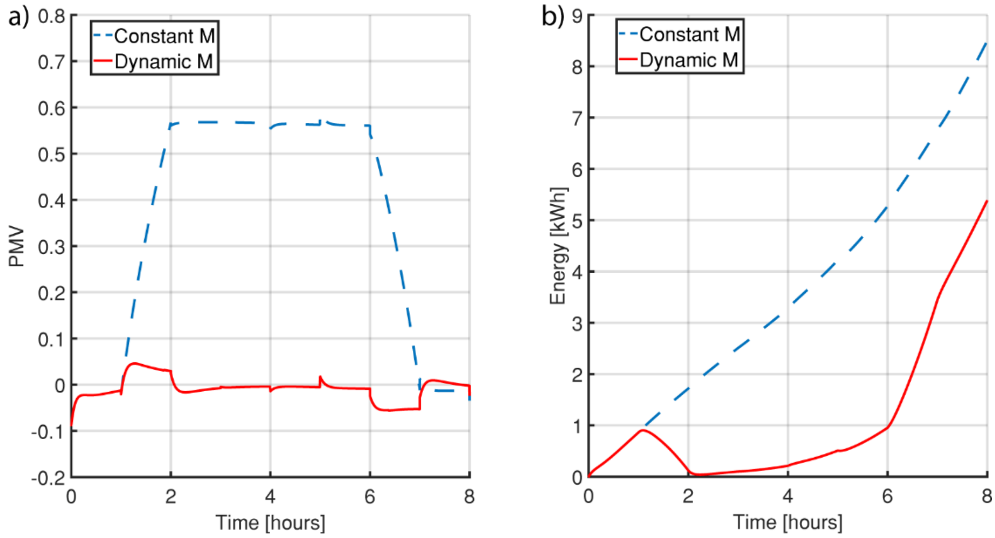


Figure 14 *(a) Trends of the PMV obtained by performing both the simulation cases; (b) energy consumption obtained by performing both control algorithms with a dynamic M and with a constant M*

This result leads to the conclusion that the monitoring of occupants' activity optimized the comfort management and produced a gap in energy consumption between the ideal control of the heating system and the traditional one. In the case proposed, a gap of 33% of energy saving was registered.

4.3.2 Clothing insulation analysis

The same simulation approach conducted for the metabolic rate was used for the test considering the I_{cl} parameter. Thus, also in this case, the indoor temperature control was performed based on a set-point temperature (i.e., derived from a PMV index). The difference with respect to the previous case regards the clothing insulation parameter and how it was considered to perform the tests. In the first case, a dynamic evaluation of I_{cl} was adopted to perform the control of the indoor temperature while in the second case the I_{cl} was considered as a constant.

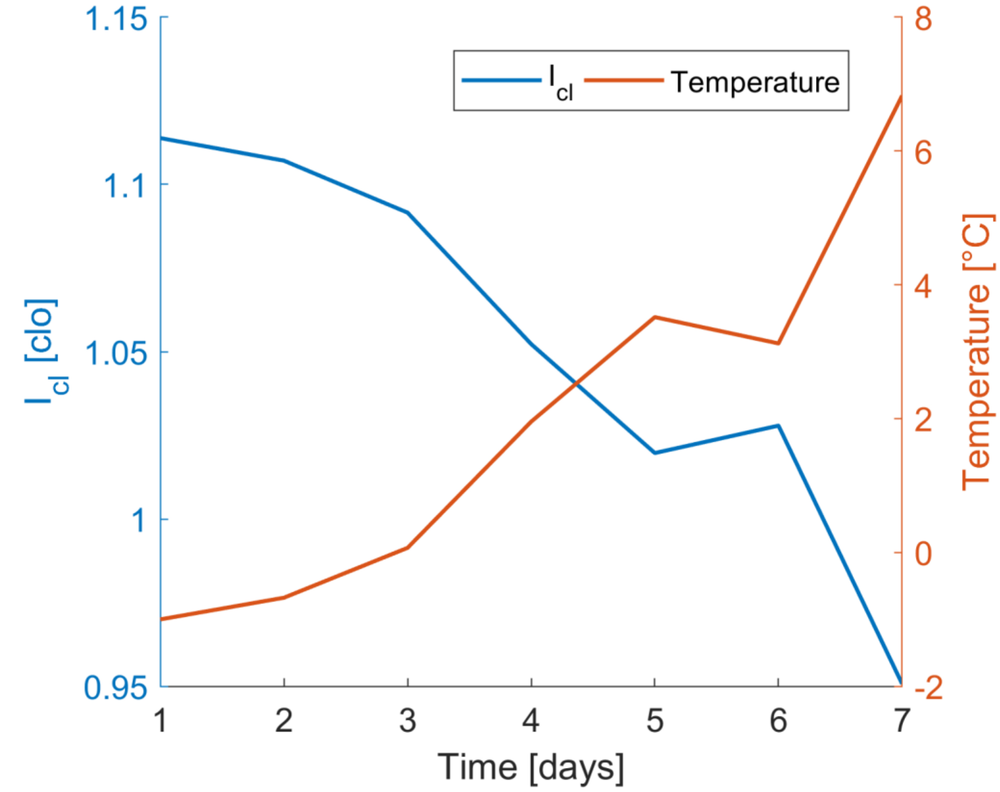
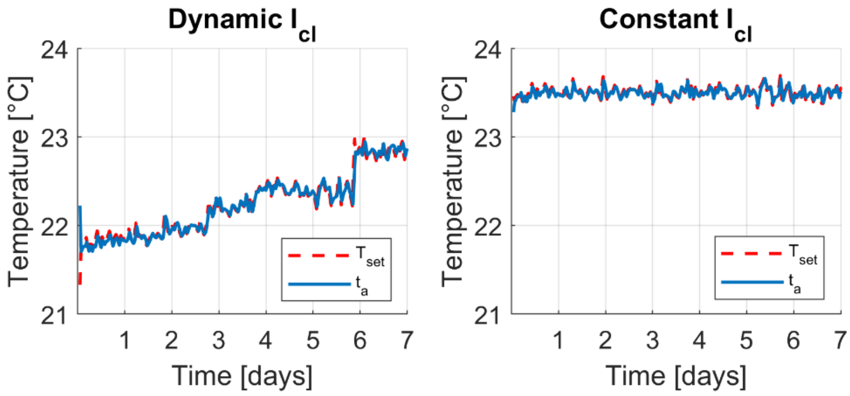


Figure 15 *Trends of the clothing insulation performed by the equation (14) and the average value of the outdoor temperature during the period considered for the simulation*

Regarding the simulation tests for the clothing insulation, 7 days were considered to perform the analysis (in which the external temperature changes rapidly) to observe how the system responds. Figure 15 shows the trends of both the clothing insulation and the average value of the outdoor temperature during the period considered for the simulation. The dynamic evaluation of I_{cl} was performed by means of the relationship (14).



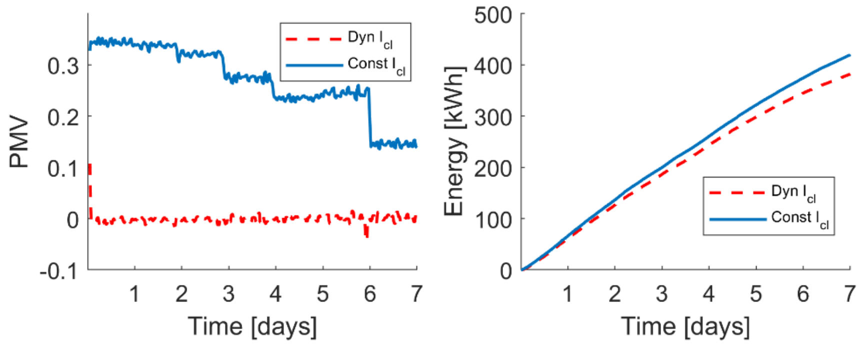
(a) (b)

Figure 16 *Trends of the set-point temperatures and the air temperatures obtained by performing the two different controls: (a) with a dynamic evaluation of the clothing insulation; (b) with a constant value of the clothing insulation.*

Figure 16 shows the trends of the set-point and air temperatures when performing control strategy with a dynamic I_{cl} (Figure 16a) and with a constant I_{cl} (Figure 16b). It is possible to observe that in the winter season, when implementing a control strategy which adopts a constant value of the clothing insulation (Figure 16b) the indoor temperature is kept almost constant. On the contrary, a variation on the T_{set} is provided adopting a control strategy which uses a dynamic evaluation of the clothing insulation (Figure 16a). In particular, it is possible to observe that the T_{set} initially decreases according to the low value of the external temperature (Figure 15). In fact, based on the expression (14) a low value of external temperature means a high value of the clothing insulation. With the increasing of the outdoor temperature, the clothing insulation value decreases. Consequently, the value of the T_{set} computed becomes higher.

Comparing the two situations of the case study proposed, the use of a constant value of the clothing insulation instead of a dynamic evaluation of it led to a variation on the PMV calculation propagated as a variation of 1.3°C on the calculation of the T_{set} and a maximum variation of 2.9°C on the evaluation of the T_{set}.

Observing the PMV data obtained in the simulation case, it is possible to note that performing a control of the environment by means of a constant value of I_{cl} led to obtain a mean value of the PMV equal to 0.3±0.1 (Figure 17a), whereas in the second case (i.e., adopting a dynamic evaluation of I_{cl}) the mean value of the PMV is equal to 0.00±0.02 (Figure 17a).



(a) (b)

Figure 17 *(a) Trends of the PMV obtained by performing both the simulation cases; (b) energy consumption obtained by performing both control algorithms with a dynamic evaluation of I_{cl} and with a constant value of I_{cl}*

Moreover, the energy consumptions with a dynamic evaluation of I_{cl} and with a constant value of I_{cl} are reported (Figure 17). The first simulation (in which the dynamic evaluation of clothing insulation was considered) provides a cumulative energy consumption equal to 384.7 kWh (Figure 17b) against the 420.3 kWh of the second test (in which a constant value of the clothing insulation was adopted, Figure 17b). Thus, a gap of 8.5% of energy saving was registered.

4.4 Uncertainty analysis

In Section 4.3 the systematic error was evaluated. This error occurs when the physiological variables are not measured in real-time but they were assumed as a constant. In this Section, the uncertainty of the two methodologies developed was analysed to compare it with the systematic error trying to understand how these methods impact on the comfort management compared to the case in which fixed values are set for the physiological variables.
The uncertainty analysis was performed with a Monte Carlo simulation for both the methodologies proposed for the assessment of the personal parameters (discussed in Chapter 3). The analysis was performed with the purpose of studying the impact of the methods developed in terms of PMV, T_{set} and energy saving. The investigation was conducted using the model described in Section 4.2. The uncertainty of the dependent variables caused by the uncertainty of the independent input variables is analysed through:

- selection of ranges and distributions of the model variables;
- generation of a random sample of the model variables;
- evaluation of the model for each variable input;
- uncertainty analysis.

Input variables are considered independent, as generally done in literature. After the range selection for each variable, the increment is considered in the order of the accuracy required for the input parameters. Consequently, the procedure applied assigns a Gaussian distribution to the variables (i.e., metabolic rate and clothing insulation). Increments represent the uncertainty of their estimation. Then the samples are randomly selected and combined to build the sets of input variables and evaluate the relative PMV values, the T_{set} values and the energy consumptions.
Regarding the metabolic rate parameter, the proposed measurement technique provided an uncertainty of ±0.2 met, referring to the sample population and the tasks conducted in the presented experiment (Table 4). On the contrary, the uncertainty obtained for the clothing insulation is referred to the discrepancy between the subjective responses of the users to the questionnaire proposed for the clothing evaluation and the external temperature with which they were correlated (i.e., ±0.08 from the equation (14)).
In Table 6, the results obtained from the analysis were reported and they were compared to the ones discussed in Section 4.3.

Table 6 *Results obtained performing the sensitivity analysis compared to the ones obtained in Section 4.3*

	UNCERTAINTY DUE TO THE SYSTEMATIC ERROR NOT APPLYING THE PROPOSED TECHNIQUES			**UNCERTAINTY OF THE PROPOSED TECHNIQUES**		
	PMV	**T_{set} [°C]**	**Energy saving [%]**	**PMV**	**T_{set} [°C]**	**Energy saving [%]**
Metabolic rate	±0.3	±3.2	±33	±0.2	±2.3	±10
Clothing Insulation	±0.1	±1.3	±8.5	±0.1	±0.6	±1

The uncertainty due to the systematic error derived from the analysis conducted in Section 4.3. Therefore, considering a constant value for both the personal parameters to perform the comfort management by using a PMV- based approach, led to variations in terms of PMV, T_{set} and energy consumption which are higher compared to the ones that are obtained (i.e., random error) by applying the methodologies developed in this work for the real-time and dynamic assessment of the subjective parameters.
Thus, in light of the results achieved with the uncertainty analysis, it is advantageous to adopt the methods since they allow having both a human-centred evaluation of comfort conditions and an improvement in terms of comfort management.

Chapter 5.

Application to a real case study

In this chapter, the application in a real case study is presented. A low-cost system for thermal comfort monitoring (i.e., Comfort Eye system) and the methodologies developed were used in a demo room to perform the assessment of the indoor thermal comfort. Moreover, the device was integrated with a building management system. The goal is to demonstrate that such solution can lead to the optimization of the comfort conditions and improved the energy efficiency.
Series of sensors, actuators, and control systems were installed in the test room to validate the methodologies developed. The system detects both the internal and external conditions of the building to improve the classical and basic level of automation. A network of sensors and actuators allow to control the windows (i.e., opening/closing), the shaded curtains adjustments, turning on/off/ and adjust the status of the fan coil, turning on/off the lighting system.
In Section 5.1 the description of the demo room is reported. Moreover, Section 5.2 presents a new modular version of the Comfort Eye system while Section 5.3 discusses about the components and the system architecture.

5.1 Description of the demo room

The system was tested in the meeting room (12x5.70x3m) of the headquarter of Focchi S.p.A., located in the industrial area of Poggio Torriana (RN), in central Italy (latitude: 44°.05'N, Longitude: 12°.41'E, altitude: 52.90m). The zone is characterized by a hot summer Mediterranean climate (Köppen climatic classification) [98]. The Focchi S.p.A. has become a leader in the sector of building enclosures, dealing directly with both design, production, and installation. In this case, the implementation of comfort management system was extended with the concept of the intelligent buildings including a low-cost device for thermal comfort monitoring. The room is a living lab for the development and the experimentation of innovative features for intelligent buildings to gain integration with plants and automation systems. The test room is characterized by a continuous facade on 3 sides.
A map of the demo room is reported in Figure 18:

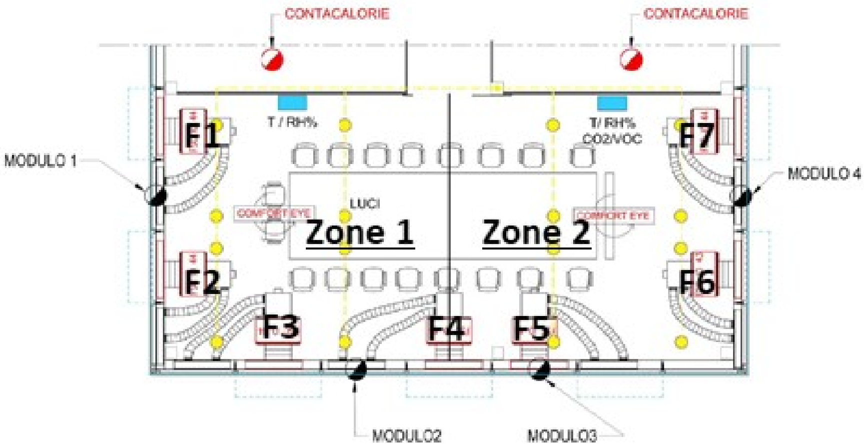


Figure 18 *Map of the demo room*

The room was virtually divided into two sub-zones in order to provide a bi-zonal microclimatic control. Thus, in each zone was installed the Comfort Eye system. The actuator systems were distributed within the zones. 7 fan-coils were divided as follow: the fan-coils F1, F2, F3, F4, were included in the zone 1; whereas the fan-coils F5, F6, and F7 were included in the zone 2. It was possible to switch on, off and adjust fan-coil heat flow. In addition, the actuators network allows to control:

- lifting, lowering of shading curtains installed within the environment,
- automatic opening and closing of the windows (divided into 3 sides),
- turning on/off lighting luminaires within the room (divided into 4 sides, two groups of luminaires are included in the zone 1 and the other two groups are included in the second zone)

Moreover, in the demo room, several environmental sensors are installed to monitor both the outdoor and indoor conditions (e.g., the relative humidity, the air temperature, the air quality, the internal and external brightness).

5.2 Upgrade of the Comfort Eye measurement system

In this work, a low-cost system (i.e., Comfort Eye) which follow the Fanger model, was adopted to perform thermal comfort assessment in the real case study. The device works replicating the operation of an indoor microclimate station. Starting from the base version, a modular version of the Comfort Eye system was developed and it was improved integrating it with a building management system (BMS).
As presented in [99] the concept of the Comfort Eye is based on an IR scanning system, represented by an array of the thermopile. It is installed on the ceiling of the room and it

measures the indoor surface temperatures and sends them to the control unit, which calculates the mean radiant temperature and the PMV index. The IR sensor is a commercial solution (array of eight thermopiles arranged in a row, built-in electronics and a silicon lens), which provides a temperature measurement of eight consecutive points with a resolution of 1°C each.

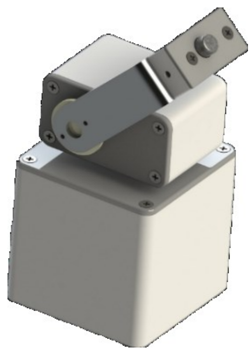


Figure 19 *IR scanning unit of Comfort Eye system*

The embedded microcontroller, implemented within the software, allows the automatic scanning (thanks to two servos assembled together with the IR sensor) of indoor surfaces to evaluate temperature distribution. A central unit is equipped with environmental sensors to measure physical quantities (i.e., air temperature, relative humidity and air velocity). According to ISO 7726 [20] and ISO 7730 [36], thermal comfort parameters should be estimated for several positions in the environments.
Calibration and performances of the device were previously investigated [100]. Moreover, the user can interact with the device through Android devices (i.e., smartphone, tablet) where he had to provide the input parameters required to the microcontroller such as characteristics of the room (height, width, length) and personal factors (metabolic rate and clothing insulation) for the evaluation of thermal comfort.
The device was designed for real-time estimation of thermal comfort condition for several positions inside the room, differently from standard methods for evaluation of thermal comfort. It does not include integration with Building Management System. Furthermore, the subject parameters set within Android device are considered constants, referred to the standard. For this reason, a new prototype of this sensor was conceived to compensate for these aspects.
Starting from the base version of the system, a modular version of the Comfort Eye system was developed. In particular:

- a different microcontroller was adopted (compared to the first version of the system) to have greater flexibility in terms of interactions with other systems or devices;
- independent nodes of measurement were used. They are able to communicate autonomously with a central unit.
- in addition, the Comfort Eye system was integrated with a BMS.

The following paragraphs discuss about the low-cost device for thermal comfort monitoring both in terms of hardware and software.

5.2.1 Hardware

The main hardware upgrade of the monitoring system regards a different choice of microcontroller. This choice allows having a greater flexibility in terms of interactions and communications with the other systems (e.g., BMS, wearable sensors).
In this study, the Raspberry Pi 3 Model B, third-generation Raspberry Pi, was adopted. Its keys application regards industrial/home automation, IoT applications, Server/Clouds Server.
It is powered by a +5.1 V micro USB supply. Exactly how much current (mA) the Raspberry Pi requires is dependent on what it is connected to it. Generally purchasing a 2.5 A power supply will provide with ample power to run the Raspberry Pi. Typically, the model B uses between 700-1000 mA depending on what peripherals are connected. It is equipped with Broadcom BCM2387 chipset, 1.2 GHz Quad-Core ARM Cortex-A53, 1 GB of RAM, an Ethernet port (RJ45 port), wireless connectivity (802.11 b/g/n Wireless LAN and Bluetooth 4.1 (Bluetooth Classic and LE)), 4 USB port 2.0, 40 pins header and boot of the operation system from Micro SD card, running a version of the Linux operating system or Windows 10 IoT. Figure 20 shows the Raspberry board.

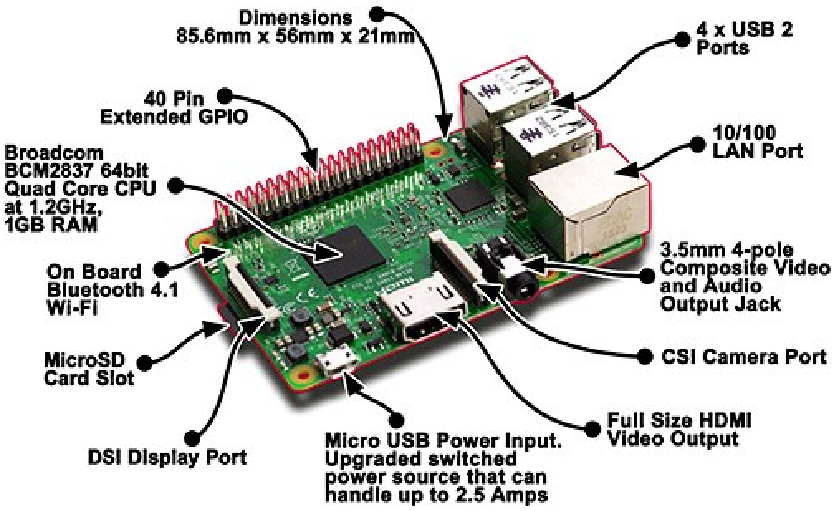


Figure 20 *Raspberry P3 Model B board pinouts*

The idea of the new monitoring system is to adopt a modular system which uses information provided by the independent measurement nodes installed in the environment. A central unit correctly merges the data acquired by the nodes.

In this thesis, the monitoring system consists of two independent measurement nodes which are equipped with IR scanning systems (described above) that are fixed on the ceiling of the room. The environmental sensors are directly installed on the components of the room and not in the central unit, as in the previous version. The central unit is placed inside the control panel and communicates with a BMS. Moreover, different commercial protocols such as Bluetooth protocol (which allow connection between the microcontroller and the wearable sensor) and Modbus protocol (which allow the communication between the microcontroller and the BMS), were used.

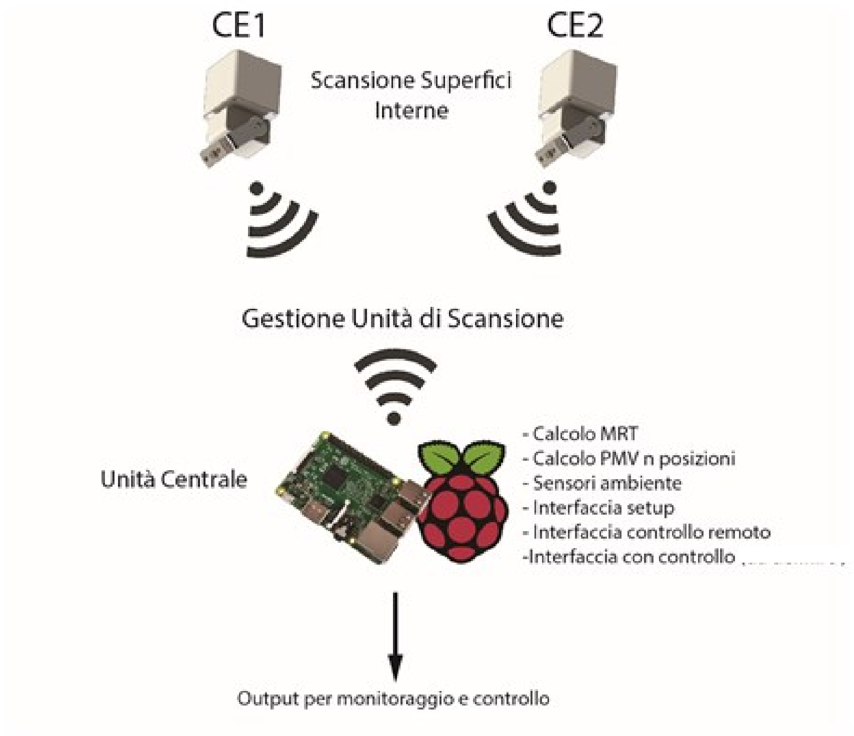


Figure 21 *Scheme of the concept of the new Comfort Eye system*

5.2.2 Software

The developed software allows the central unit to merge data provided by the ambient sensors installed inside the room. Thus, the monitoring system evaluates the indoor thermal comfort for the positions of interest.
The system architecture consists of two main parts:

- a microcontroller (i.e., Raspberry) equipped with the algorithms for thermal comfort assessment,
- a BMS.

The assessment of indoor thermal comfort is based on the Fangers' model. Therefore, the PMV index is automatically computed by the algorithms installed into the microcontroller and the BMS performs comfort management by means of e.g., the shading systems, opening/closing windows, the HVAC system, turning on/off lighting system, to adjust the environmental conditions. To allow both the communications and data transmissions between the systems, two main protocols have been adopted:

- PoE (Power over Ethernet) protocol, which provides both electricity supply and data exchange between IR scanning units and microcontroller;
- Modbus protocol, which provides communication between the microcontroller and the BMS.

Modbus is a serial communication protocol; it is widely adopted in industrial communications, and it is currently one of the most popular connection protocols among industrial electronic devices. Modbus enables communication among many devices connected to the same network.

Specific functions (based on Python open-source language) have been developed and installed on the Raspberry board. Python is considered an interpreted language because Python programs are run by an interpreter. There are two ways to use the interpreter: a command line or script. In the "command line" mode, Python programs are written line by line. After writing a line of code at the Enter key (or Enter, depending on the keyboard), the interpreter immediately analyses and processes the result immediately. As an alternative to the command line, it is possible to write a program in a file (called a script) and use the interpreter to execute the contents of the file.

By convention, files containing Python programs have names ending with ".py". As the software is open source, a lot of implemented libraries for Raspberry interaction with different sensors or devices exist, and they can be called at the beginning of the program by calling the "import" <library> routine.

The microcontroller was programmed so that the indoor comfort parameters can be calculated on board without further processing (i.e., the need of a PC as for the microclimate station).

First of all, a MySQL database was installed on the Raspberry board. There is no a direct link between the tables of the database but they are used both to store the comfort data and environmental data to perform computations. The database consists of 7 tables which are reported below:

- "comfort_data", where all the data and the variables relative to the comfort are stored (e.g., mean radiant temperature, PMV, relative humidity, air velocity)
- "surface_temperatures", in which each indoor surface temperature data is stored;
- "raw_pixel_temperatures", which contains the data provided by IR scanning units;
- "extern_temperature", where the values of outdoor temperatures are located. Moreover, in this table, both the values of the set-point temperatures and the indoor *CO2* are reported.
- "static_room_geometry", contains information about dimensions of the room;

- “static_room_positions”, where the positions of interest for thermal comfort evaluation and the subject parameters (i.e., metabolic rate, clothing insulation) are saved;
- “static_scanning_angles”, in which all the angle positions that have to be assumed by IR scanning systems are stored.
- “sub_BH3_parameters”, which contains the metabolic values computed by the newly developed algorithm.

Pymodbus, which is an embedded python library, is a full Modbus protocol implementation using twisted for its asynchronous communications core. The main program implemented on Raspberry board is represented by Pymodbus asynchronous server.
Once the system is started, Server (i.e., Raspberry board) starts communication and it reads the Client registers (i.e., BMS system) where environmental data such as the air temperature of each zona, relative humidity, outdoor temperature and the *CO2* measured, are stored.
Both the IR scanning units are connected to the database and read the “static_scanning_angles” table, in which previously tilt and pan angle values for automatic scanning were stored, in order to perform the scanning of the indoor surfaces. The measured values of the scanning units are stored in the “raw_pixel_temperatures” table. Subsequently, all the operations that allow the evaluation for thermal comfort are performed. To accomplish this action several embedded libraries were implemented in python language, which is easily importable on the microcontroller. In particular, 11 programs were developed and many python libraries were used. Some examples of the most useful libraries are:

- MySQL, which allows executing all the queries required in order to connect with the database
- Pymodbus, which allow the communication with BMS system

The main python functions implemented are described below:

Modbus_server.py

It consists of Pymodbus asynchronous server that allows connection with BMS. The asynchronous server is a high-performance implementation using the twisted library as its backend. Within this function, there is a loop function that cyclically repeats. This script allows reading Client registers in which environmental data which are provided by ambient sensors, are stored.

Emissivity.py – Dimension.py – Params_room.py

No inputs are required in these functions because they simply allow the connection to the internal database on the Raspberry board in order to read:

- the emissivity values of each surface that were previously saved in the specific table,
- the size of the room,
- the positions in which the evaluation of thermal comfort is needed.

Compute_T_surfaces.py

This algorithm requires both emissivity and air velocity values to compute the average values of indoor surface temperatures. The script allows the connection to the internal database in order to read the raw pixel measurements provided by the IR scanning systems. Then a dedicated data processing algorithm provides the average value of indoor surfaces temperatures.

Compute_MRT_PMV.py

This algorithm performs the calculation of the mean radiant temperature (t_r) for multiple positions in the room. Mean radiant temperature is defined as the uniform blackbody temperature of an imaginary enclosure with which a person exchanges the same heat by radiation. Its measurement is not direct and it is usually carried out by means of different methodologies and instruments whose general details and accuracy requirements are reported in ISO 7726 standard. According to [101], the method based on the calculation of the angle factors and contact (or remote) surface temperature measurements appears as one of the best solutions for a correct estimation of t_r. For generalization, t_r is computed from the weighted average of the internal temperatures t_i, and the respective view factor to a subject $Fs-i$ for N surfaces, according to the following equation:

$$t_r = \sqrt[4]{\sum_{i=1}^{N} (F_{s-i} \cdot t_i^4)} \quad (16)$$

The view factors between a seated or standing subject and the internal surfaces have been documented and developed into charts. A mathematical expression developed by Cannistraro et al. [102] was used to calculate the view factors between a subject and internal surface:

$$F_{s-i} = F_{max} \cdot \left[1 - e^{\frac{-(\frac{a}{c})}{A+B(\frac{a}{c})}} \right] \cdot \left[1 - e^{\frac{-(\frac{b}{c})}{C+D(\frac{b}{c})+E(\frac{a}{c})}} \right] \quad (17)$$

The coefficients A, B, C, D, E, and F_{max} are parameters which depend on each surface position relative to the subject's orientation and posture (seated or standing). The coefficients a, b and c are parameters that define the geometry of the internal surfaces (width, height, and distance) relative to the centre of the subject.

Once the position of the subject in the room is defined, each surface is divided into 4 rectangles and then the angle factors are retrieved.

The mean radiant temperature is then used to calculate the PMV index according to the Fanger's theory of the human thermal balance.

The input required for PMV algorithm are:

- relative humidity [%]: measured by environmental sensors installed in the room
- air velocity [m/s]: based on the fan-coil status, its value varied between 0.03 m/s and 0.2 m/s
- mean radiant temperature [°C]: calculated by the algorithm described before

- air temperature [°C]: measured by an environmental sensor installed in the room
- metabolic rate [met]
- clothing insulation [clo]

The measures of the personal parameters and the functions for their evaluation are discussed in the next paragraphs.
PMV is computed by a mathematical model derived by Fanger:

$$PMV = (0.303 \cdot e^{-0.036M} + 0.028) \cdot [(M - W) - 3.05 \cdot 10^{-3} \cdot [5733 - 6.99 \cdot (M - W) - p_a] + -0.42 \cdot [(M - W) - 5815] - 1.7 \cdot 10^{-5} \cdot M \cdot (M - p_a) - 0.014 \cdot M \cdot (34 - T_a) - 3.96 \cdot 10^{-8} \cdot f_{cl} \cdot [(T_{cl} + 273)^4 - (T_r + 273)^4] - f_{cl} \cdot h_{cl} \cdot (T_{cl} - T_a)] \quad (18)$$

The evaluation of partial water vapour p_a, can be done thought following mathematical expression:

$$p_a = 0.001 \cdot RH \cdot p_s \quad (19)$$

Where RH [%] is the relative humidity and the term p_s refers to saturated vapour pressure, that can be approximately computed by:

$$p_s = 100 \cdot e^{\left(18.596 - \frac{4030.18}{Ta + 285}\right)} \quad (20)$$

The ratio of a clothed man's surface area to a nude man's surface area f_{cl} can be estimated using the following expressions:

$$f_{cl} = 1.00 + 1.290 \cdot I_{cl} \quad (21)$$

$$f_{cl} = 1.05 + 0.645 \cdot I_{cl} \quad (22)$$

Where I_{cl} [m^2·°C·W^{-1}] is the thermal resistance of clothing. Equation 3.6 should be applied for I_{cl} < 0.078, otherwise equation (22). The surface temperature of clothing T_{cl} [°C] is iteratively calculated by:

$$T_{cl} = 35.7 - 0.028 \cdot (M - W) - I_{cl} \cdot \left[3.96 \cdot 10^{-8} \cdot f_{cl} \cdot [(T_{cl} + 273)^4 - (T_r + 273)^4 + f_{cl} \cdot h_{cl} \cdot (T_{cl} - T_a)]\right] \quad (23)$$

The convective heat transfer coefficient h_{cl} [W·m^{-2}·°C^{-1}] can be valued by means of the maximum value of the following expressions:

$$h_{cl} = 2.38(T_{cl} - T_a)^{0.25} \quad (24)$$
$$h_{cl} = 12.1\sqrt{v_{ar}} \quad (25)$$

All these parameters are computed on board the microcontroller. In addition, the set-point temperatures of the two zones are evaluated by minimizing the PMV value.

5.3 System architecture

The scheme of the system architecture is shown in Figure 22:

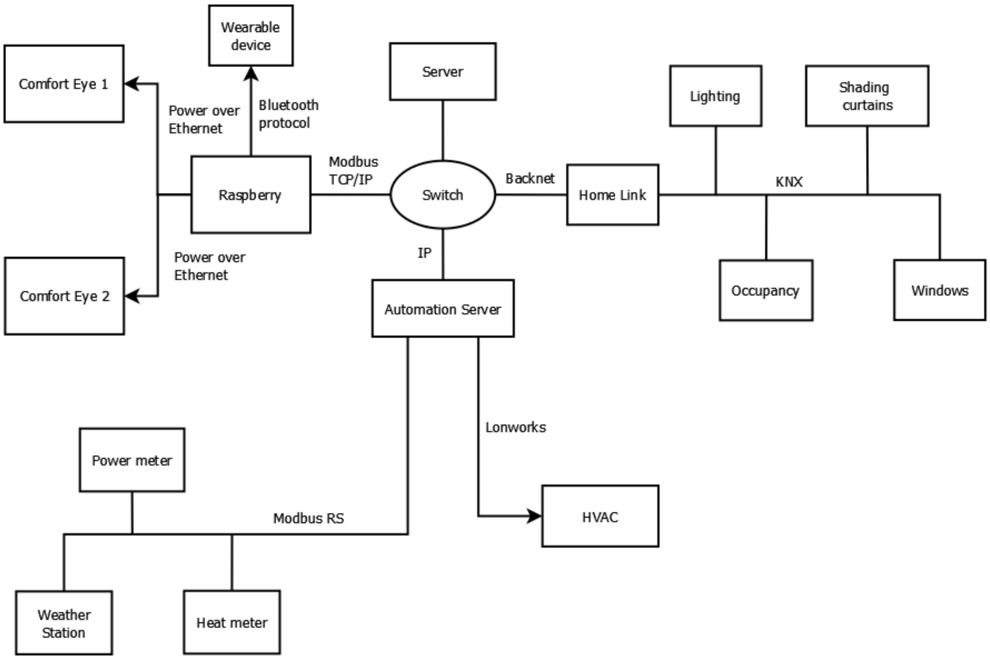


Figure 22 *Scheme of the system architecture*

During both the design phase and the development phase of the demo room, the new version of the Comfort Eye has been introduced. As said, the system is based on an IR (infrared) sensor installed on the ceiling of the room which moves to scan the environment.
The advantage obtained by adopting the low-cost monitoring system is the ability of the system to have both spatial information and accurate information on the level of thermal comfort within the environment (compared to a classic thermostat that performs a precise measurement), thus allowing the implementation of thermal comfort control logic of advanced type. In Figure 23, a scheme of the demo room which represents the IR scanned areas is reported:

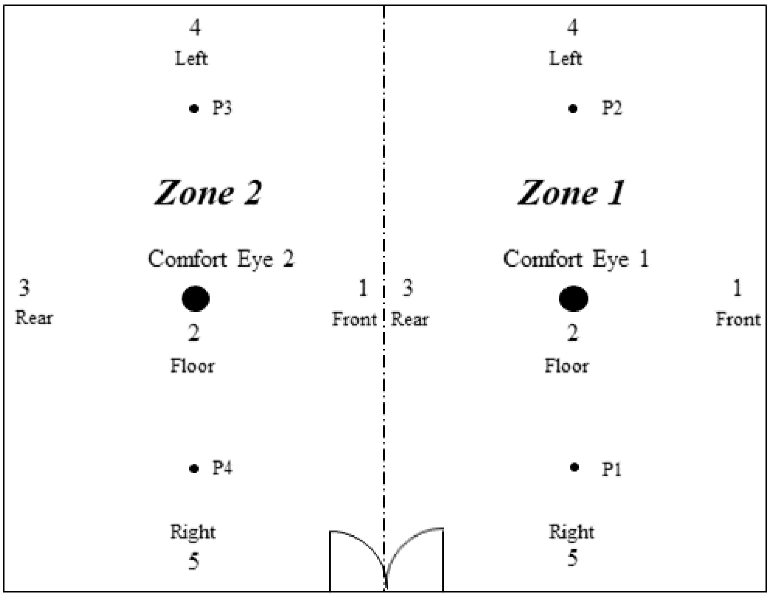


Figure 23 *Scheme of the Demo room considering the IR scanned zones*

As said, the room is virtually divided into two zones and the Comfort Eye system was installed in each of the two zones, respectively. The Comfort Eye scans the competence zone continuously and calculates the PMV index by further dividing each zone into two sub-zones. In particular, the positions P1, P2, P3, and P4 represent the points in which the evaluation of PMV was performed.

In each zone, the set-point temperature (T_{set}) was computed. The set-point temperature represents the value of the air temperature that, if achieved, would generate the highest level of thermal comfort in the environment (PMV = 0). As reported in the virtual simulation of the test bench (Section 4.1), also in the real case study, the root-finding algorithm was performed to evaluate T_{set}. Thus, the actuator system (i.e., windows and heating/cooling system) works to reach the set-point temperature in the two areas.

Furthermore, the number of the wall (reported in Figure 23) indicates the scanning order of the indoor surfaces performed by each Comfort Eye. In particular:

1. Front surface,
2. Floor surface,
3. Rear surface,
4. Left surface
5. Right surface

Generally, the room is characterized by 6 values of indoor surface temperature. So, the temperature value of the ceiling surface, which represents the surface in which the system is installed, it is estimated by the air temperature value. Since two Comfort Eye systems have been installed, the algorithm allows characterizing the total indoor surface temperatures by the following considerations:

- The value of the Front surface is represented by the average value of the data which are acquired by Comfort Eye 1,
- The value of the Rear surface is represented by the average value of the data which are acquired by Comfort Eye 2,
- The values of the Left surface, Right surface, Ceiling surface are represented by the average value of each surface data acquired by both Comfort Eye1 and Comfort Eye 2.

When the microcontroller is switched on, an automatic procedure (service) called “demofocchi.service” starts. The system begins to carry out the entire procedure to perform the assessment of thermal comfort inside the room by communicating with the BMS system through Pymodbus library. The PMV index is computed considering dynamic measurements of metabolic rate obtained applying the methodology presented in Section 3.1.2.

In Figure 24, an example of the integration between the control logic adopted for winter thermal comfort of the zone 1 and the real-time evaluation of metabolic rate, is reported (the same for the zone 2).

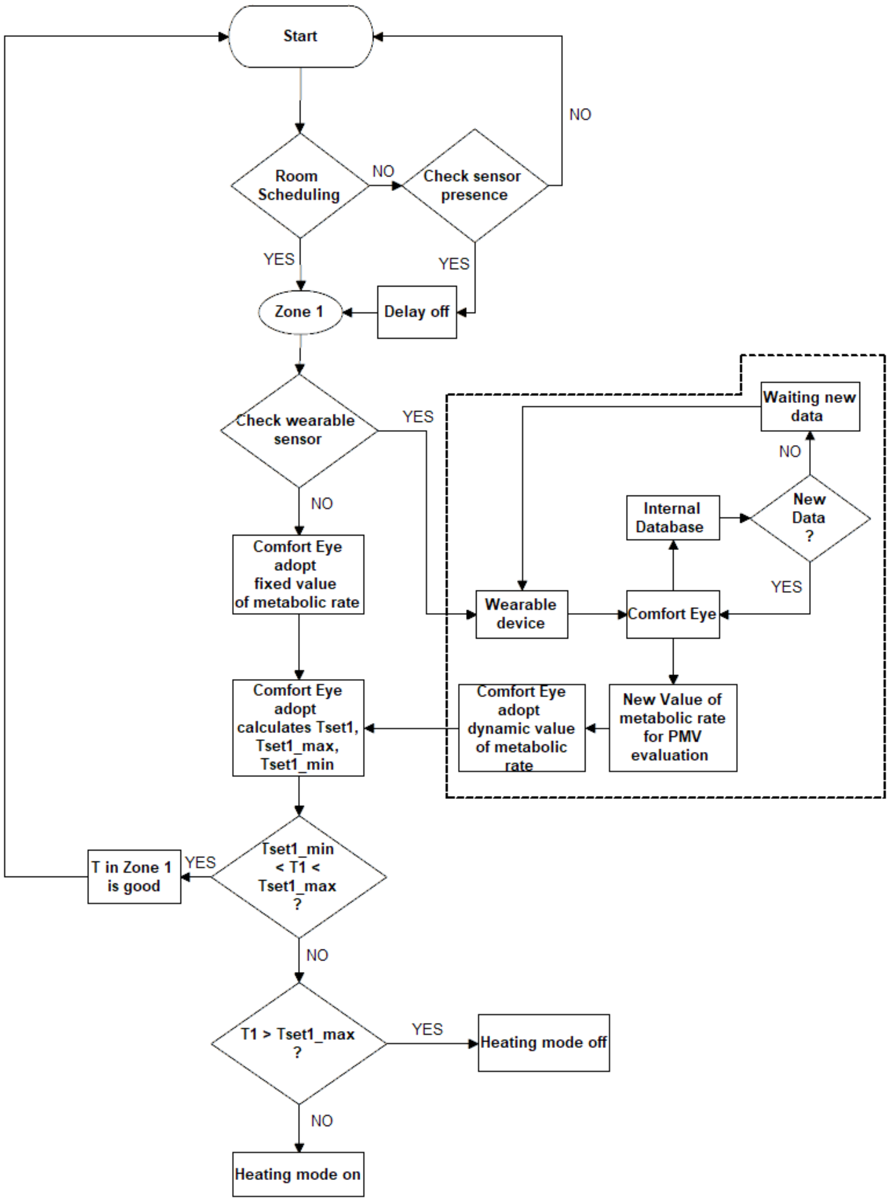


Figure 24 *Example of the scheme of the control logic for the winter season with the integration of new methodology developed for the real-time evaluation of the metabolic rate*

The area surrounded by the dash-dot line highlights the integration of the developed methodology for the dynamic evaluation of the metabolic rate.
Once the occupant wears the wearable sensor BioHarness 3.0, the microcontroller is able to connect to the device through Bluetooth connection protocol. Consequently, an automatic procedure performs the metabolic rate evaluation and sends data to "sub_BH3_parameters" table (installed in the internal database of the microcontroller). Afterwards, the data are used to compute PMV index. At the same time, the microcontroller provides the evaluation of clothing insulation by applying the relationship discussed in Section 3.3. If the wearable device is turned off, the system considers a fixed value of metabolic rate to evaluate the thermal comfort observing all the conditions in the control logic.
Referring to the Figure 22, the Comfort Eye system is powered by PoE technology (Power over Ethernet). PoE technology allows Ethernet cables to supply power to network devices through the existing data connection. The data captured by this sensor, along with the other environmental sensors installed in the room, are managed by an embedded microcontroller to process and calculate thermal comfort index (i.e., PMV) in multiple places in the room.
The Modbus TCP/IP protocol allows data exchange between microcontroller and BMS system.
The power meters and the heat meters are installed to allow monitoring of energy consumptions. The first ones consist of three elements which monitor power consumptions due to the lighting, fan-coil management, and general consumption, respectively. The second one consists of two elements that allow the monitoring of heat consumptions of the two zones. Modbus RS protocol provides the communications between power meters, heat meters, and weather station, with the building management system. Additionally, the LonWorks protocol allows management of HVAC system by the BMS. HVAC system consists of seven underfloor air distribution (UFAD) which are installed close to the glazed walls.
Finally, the control unit is connected to an HomeLYnc. It is a device which integrates different communication protocols (KNX, ModBus, Backnet) with a logic controller that allows complex logic programming. It provides the management of the actuator system.

Chapter 6.

Validation and Results

This Section discusses about the results obtained adopting the methodology proposed for real-time evaluation of metabolic rate in a real case study. The real-time measures were provided to the low-cost system by using a wearable device which was presented in Section 3.1.2. Subsequently, the developed model for the assessment of clothing insulation was discussed. Lastly, a thermal comfort analysis and energy saving analysis are presented.

6.1 Metabolic rate analysis performed in the real-case study

In this Section, the results obtained applying the proposed methodology for the real-time assessment of *M* presented in Section 3.1.2, were discussed.
A dedicated algorithm which evaluates the metabolic rate was developed. It permits:

- the acquisition of the data by using the BH3 sensor,
- the storage of the data into the internal database,
- the evaluation of the *IN5* indicator,
- finally, it applies a threshold to the metabolic activity computed.

The analysis was conducted during the summer season, where cooling was provided by the HVAC system presents in the demo room. Different tasks were performed by three subjects considering a real-time and continue evaluation of metabolic rate to obtain the indoor thermal comfort level. The total duration of each test was 30 minutes divided into three sessions of 10 minutes. During the first session, the occupant conducted sedentary work in front of the PC; in the second session the subject walked into the room and in the last he/she returned to the sedentary activity.
Since the metabolic rate may present very wide fluctuations of the values (especially during the walk) which cause the abrupt change of the set-point temperature, a threshold has been adopted. Therefore, if the metabolic rate computed widely change with respect to the previous one, a maximum increment of 0.1 met have been considered for it. It has been observed that a unitary change in metabolic rate leads to a variation of ±1°C on the set-point temperature.
Consequently, if there is no threshold, the BMS does not have the time to optimize system management (especially fan-coils).
A first trial was conducted considering acceptable values for the metabolic rate within the range between 1 met and 1.5 met. In this case, all the values lower than 1 met were considered equal to 1 met. Conversely, all the values above 1.5 met were considered equal to 1.5 met. The results are shown in Figure 25:

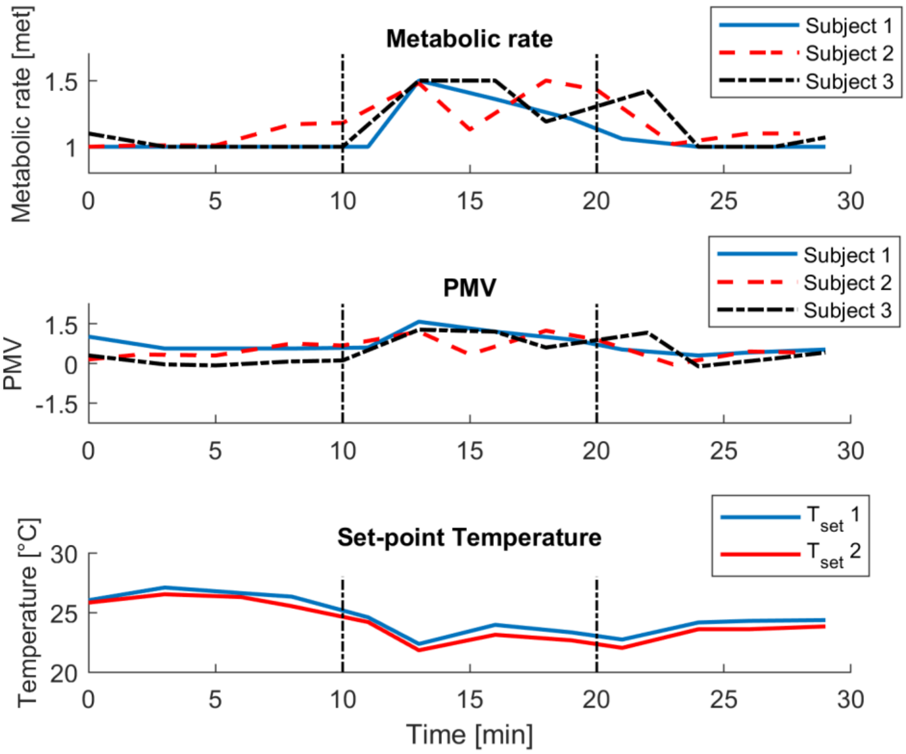


Figure 25 *Time-series of the metabolic rate of each subject, PMV values, and setpoint temperatures*

The chart above reports the trend of the metabolic rate of each subject, the average value of the PMV and the set-point temperatures.
It is possible to observe that an increase in metabolic rate (a symptom that the subject has increased its activity), corresponds to a higher value of the PMV. Consequently, the system of comfort monitoring provides to the BMS a lower set-point temperature in order to restore a comfort condition.
For a better visualization of the data, in Figure 26 the average values of the PMV computed in each position of interest, the values of the set-point temperatures, and the values of *M* are reported.

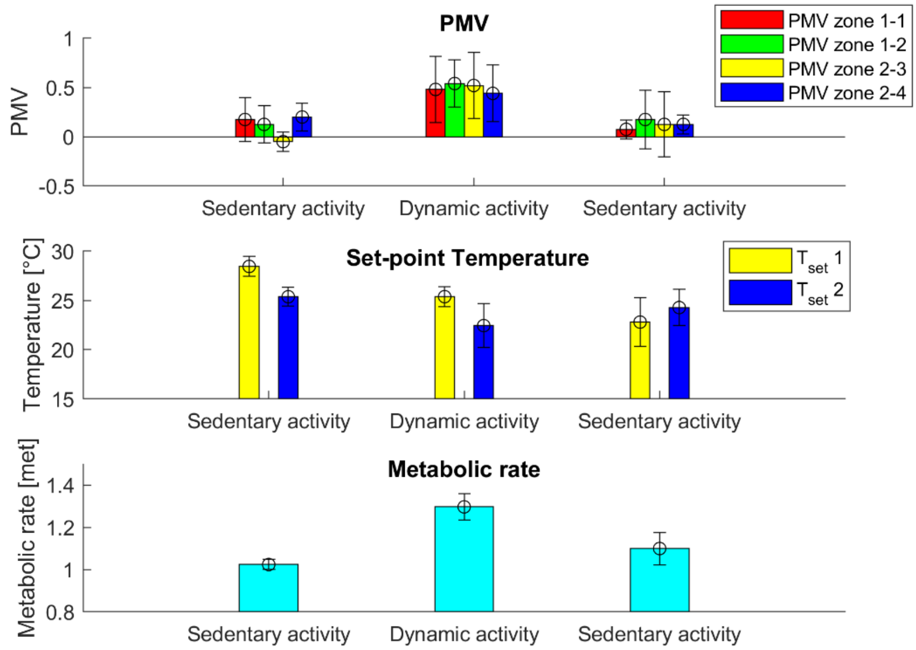


Figure 26 *The average data of the PMV, setpoint temperatures and metabolic rate considering each activity*

The values of the quantities are described in Table 7:

Table 7 *The average value of the parameters related to activities performed by the subject*

	Metabolic activity [met]	PMV				Set-point temperature [°C]	
		Position 1	**Position 2**	**Position 3**	**Position 4**	**Zone 1**	**Zone 2**
Sedentary activity	1±0.02	0.2±0.2	0.1±0.2	-0.1±0.1	0.2±0.1	28.5±1	25.4±1
Dynamic activity	1.3±0.1	0.5±0.3	0.5±0.2	0.5±0.3	0.4±0.3	25.4±0.9	22.4±2.2
Sedentary activity	1.1±0.1	0.07±0.1	0.2±0.3	0.1±0.3	0.1±0.1	26.2±1.3	24.3±1.8

To prevent that the indoor air temperature suddenly decreases creating a possible discomfort sensation, the BMS can regulate the air flow of the fan-coils (i.e., fan-coils off (0%), partially

active (66%), totally active (100%)). So, the value of the air temperature it is gradually regulated based on the fan-coils status. Since an increase in metabolic rate corresponds to an increase in the value of the PMV, the system acts consistently computing a lower set-point temperature to adjusts the thermal sensation.
In addition, to highlight that the system is able to independently manage the control of the zones, a further test was performed. In this case, in the zone 1, a constant value of the metabolic rate (1.1 met) was applied, while in the zone 2 the dynamic evaluation of *M* was adopted.

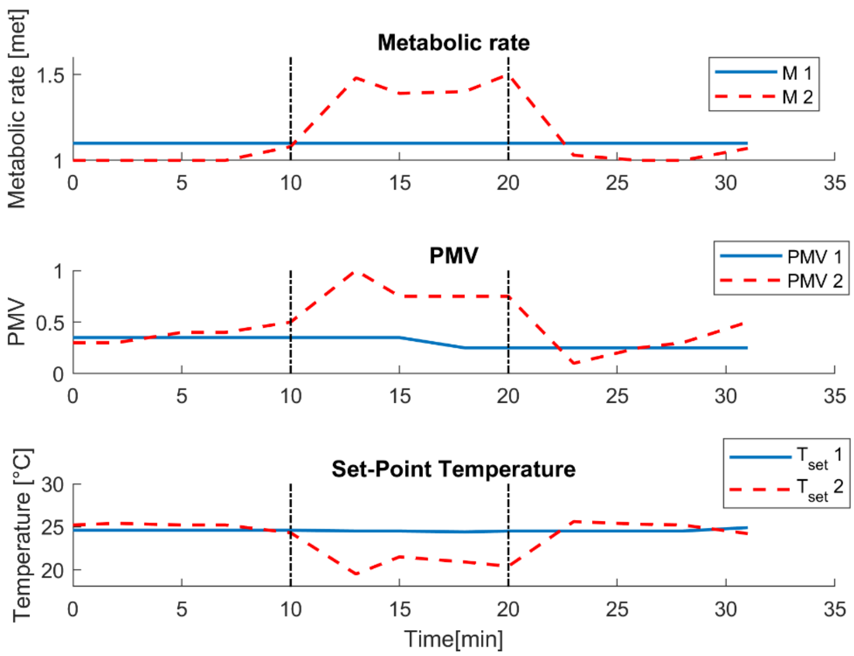


Figure 27 *Time-series of metabolic rate, PMV values, and setpoint temperatures*

It is possible to observe that PMV values in zone 1 (i.e., PMV 1) are stable because in this area a constant value for the metabolic rate (i.e., M 1) was considered. On the contrary, in the zone 2 where the dynamic measurements of the metabolic rate were performed (i.e., M 2), the PMV values are much higher than zone 1 (i.e., PMV 2). The comfort monitoring system responds correctly as it provides a lower set-point temperature value for Zone 2 that is the one where the subject presents a higher metabolic rate. Despite the system acting correctly, the PMV value does not quickly decrease because of the thermal inertia of the room. In this case, it is important to underline that the system of comfort monitoring is able to handle the two zones independently.

6.2 Dynamic evaluation of clothing insulation

Since the clothing insulation is widely affected by the subjective component, the occupants frequently adjust their clothing based on the thermal conditions. Thus, provide a correct value of the clothing insulation for thermal comfort assessment is a very difficult challenge.
In this work, to provide a dynamic predictive evaluation of I_{cl}, a first approach was developed. A mathematical expression which correlates the clothing insulation with the measure of the outdoor temperature was found. In particular, the average value of the external temperature (which was evaluated with respect the previous day considering the working hours) was used to evaluate I_{cl}. In Figure 28, the scheme of the algorithm developed to perform the evaluation of I_{cl}, is reported.

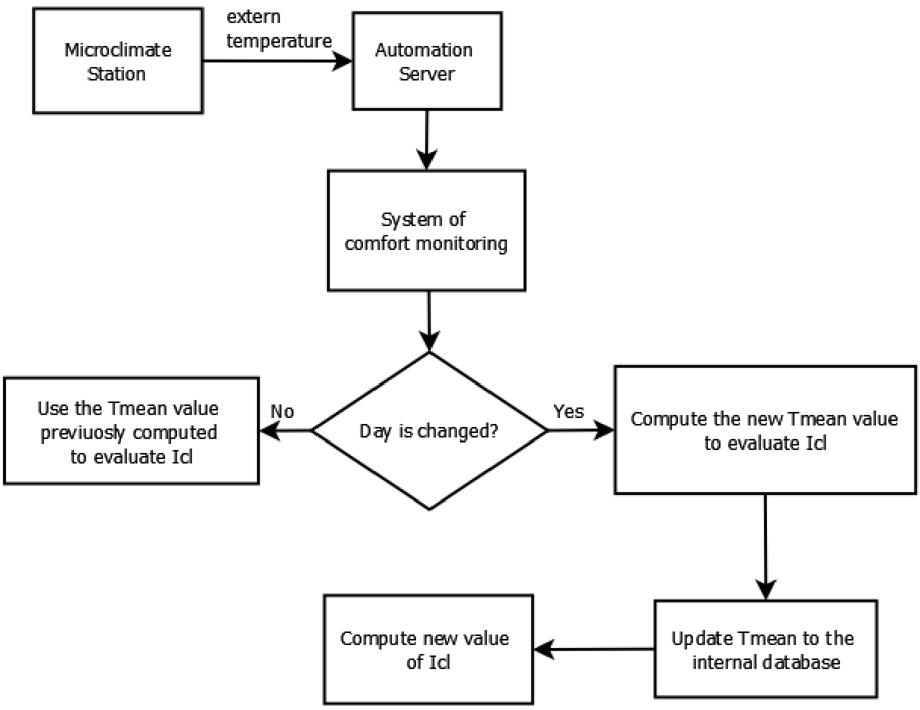


Figure 28 *Scheme of the algorithm which performs the evaluation of the clothing level*

The outdoor air temperature is acquired during the whole day and it is stored into the internal database installed into the microcontroller. Every day, the system performs check to verify is the day is changed. Thus, if this condition is verified, it performs the average of the external temperature with respect to the previous day to compute the new value of I_{cl} by using the expression (14). Otherwise, the system continues to use the average value of the external temperature previously saved in the database to compute the clothing level.

Figure 29 shows the trends of the average values of both the outdoor temperature and clothing insulation computed in each month.

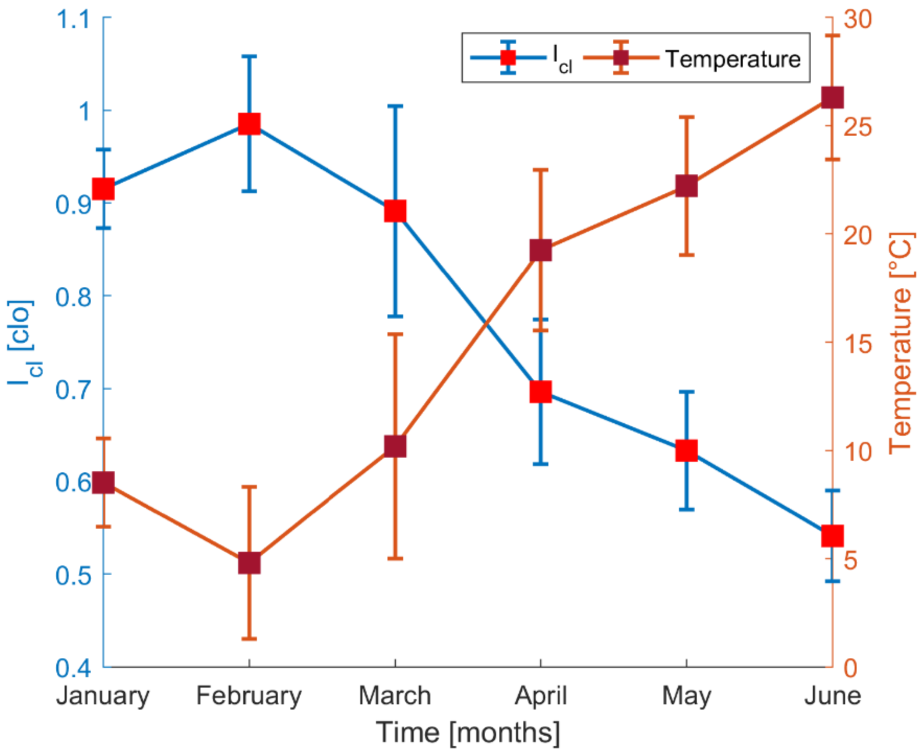


Figure 29 *Trend of the average values of both the clothing insulation and outdoor temperature*

Since an increase in the external temperature corresponds to a decrease in I_{cl}, the formula (14) computes a coherent value of I_{cl}. In fact, considering the winter season (i.e., January, February), its value is close to 1 clo, as well as usually considered in the Standard. The same consideration is valid for the summer season (i.e., June) where the value of clothing insulation is close to 0.5 clo (i.e., 0.54 clo). In the middle period (from March to May) the temperature starts to increase and the value of I_{cl} gradually decreases according to them.

In addition, observing a weekly trend of the parameters in March (Figure 30), it is possible to note that in the middle season the average values of the temperature suddenly change even from one day to the next. In fact, considering a week of March (e.g., from 1/03 to 7/03 in Figure 30) there was a gap in terms of temperature equal to 12 °C within the week considered. For this reason, it is important to have a system that takes into account the variation of climatic conditions, and that is able to adapt to the rapid changes in weather which occur more and more frequently due to climate change.

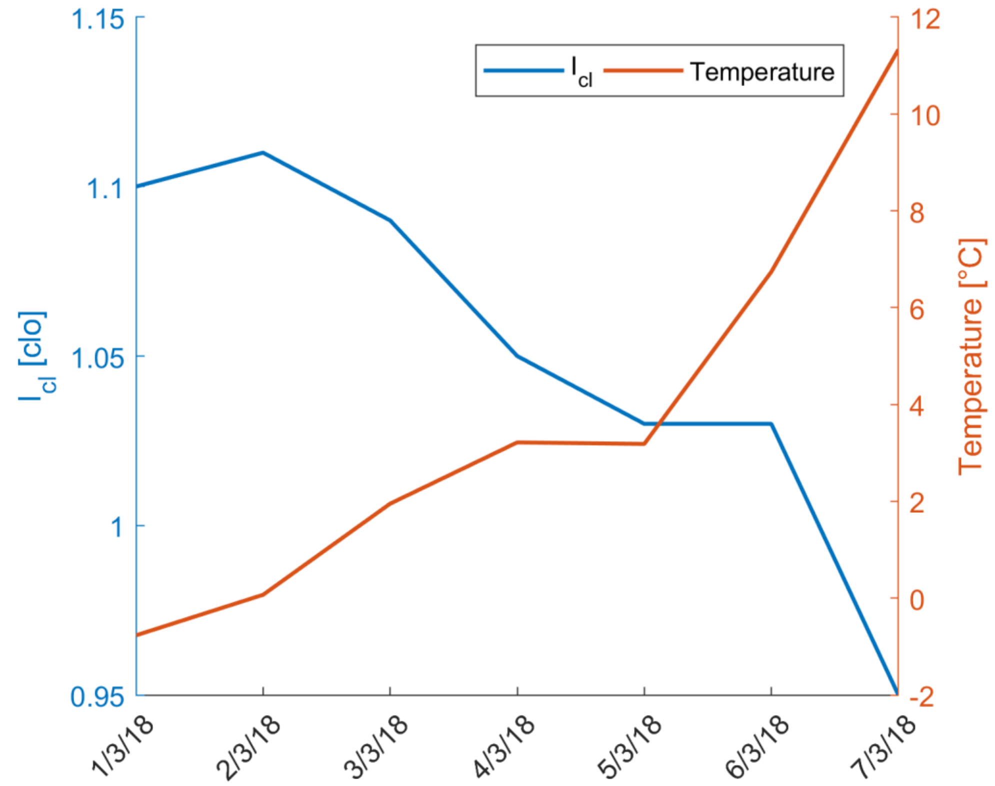


Figure 30 *The weekly trend of the outdoor temperature and the clothing insulation in March*

In Table 8 the mean values of both the outdoor temperature and clothing insulation are reported:

Table 8 *The average value of both the outdoor temperature and clothing insulation*

Month	**Temperature [°C]**	**I_{cl} [clo]**
January	8.5±2.0	0.91±0.04
February	4.8±3.5	0.98±0.07
March	10.2±5.2	0.89±0.11
April	19.2±3.7	0.69±0.07
May	22.2±3.2	0.63±0.06
June	26.3±2.8	0.54±0.05

In the transition period (from the cold to the warm season), both the variation of the I_{cl} and external temperature is much higher compared to the other ones. Based on the previous assumption, in March a greater variability of the parameters was observed. Therefore, the fluctuations of the temperature affect the I_{cl} value according to the relationship (14).

6.3 Thermal comfort analysis

The monitoring system has been installed in March 2017 and it is still going on in acquiring data. In this paragraph, the thermal comfort analysis is performed considering the PMV data both in the summer season and in the winter season. Furthermore, the energy analysis was conducted analyzing the data of the electric power consumptions stored by the BMS. Within the demo room, four positions of interest were identified to evaluate the PMV index.
The Comfort Eye system computes the PMV data every 2 minutes. Consequently, the BMS performs actions in order to adjust the indoor conditions.
The thermal comfort analysis was conducted considering 3 days in which only the working hours were considered.
The environmental control was carried out by using both an automatic procedure (which use the integration between the Comfort Eye system and the BMS to perform the management of the environmental conditions) and a manual procedure (which consists to set a fixed value for the indoor temperature).
First of all, Figure 31 reports the PMV data acquired performing the manual control of the environmental conditions:

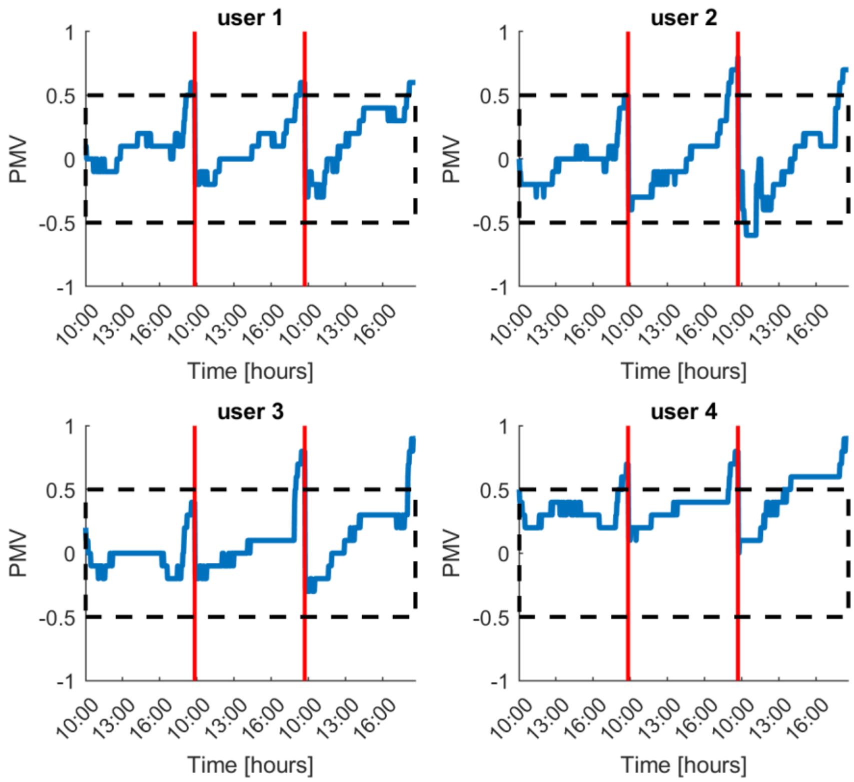


Figure 31 *PMV values of each subject acquired during 3 days in which the manual control of demo room was applied*

The chart shows that by adopting a standard control provides a good level of comfort. Moreover, in Figure 32 and Figure 33, the trends of the PMV index obtained by using the automatic control of the room (both in the summers season and in the winter season), are reported:

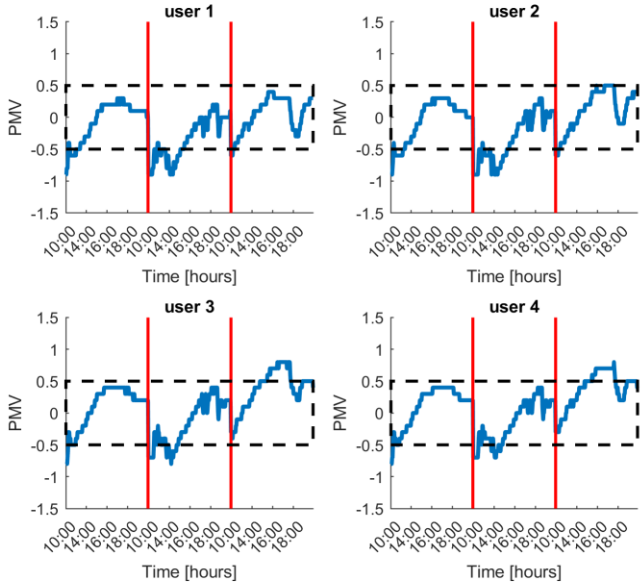


Figure 32 *The values of the PMV index of each user acquired during 3 days in which the automatic control of the demo room was applied (winter season)*

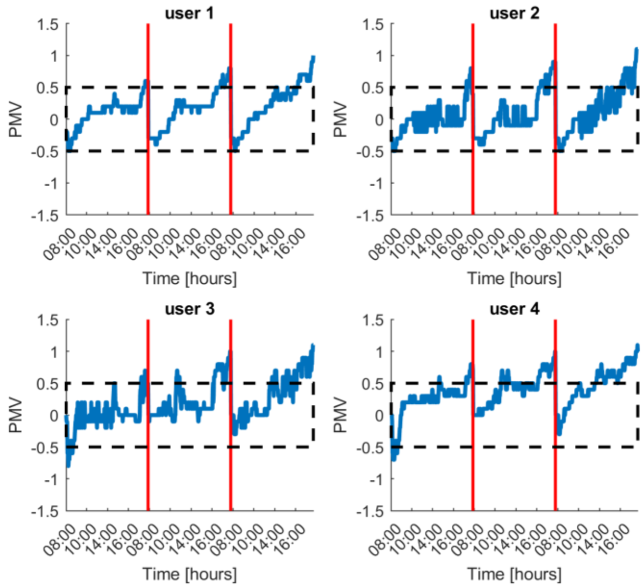


Figure 33 *The values of the PMV index of each user acquired during 3 days in which the automatic control of the demo room was applied (summer season)*

Comparing the data reported in Figure 32 and Figure 33 it is possible to observe that performing the environmental control through the Comfort Eye system allows keeping the PMV values in the optimal range for the indoor thermal comfort (i.e., ±0.5) during the working hours. The occupant's demand in terms of thermal comfort is satisfied as in the case previously reported (i.e., the manual control of the indoor conditions).
Since the BMS performs a bi-zone control, in Table 9 the average values of the PMV for both zones (both for the position 1 and position 2 which belong to the zone 1 and both for the position 3 and position 4 which belong to the zone 2) are reported:

***Table 9** Mean values of PMV index for both winter season and summer season considering Zone 1 and Zone 2 when the low-cost monitoring system is turned on*

	Winter Season		**Summer Season**	
	PMV Zone1	**PMV Zone2**	**PMV Zone1**	**PMV Zone2**
Day 1	-0.1±0.3	0.1±0.3	0.04±0.2	0.1±0.3
Day 2	-0.3±0.3	-0.1±0.3	0.1±0.3	0.3±0.2
Day 3	0.1±0.3	0.4±0.3	0.2±0.4	0.4±0.3

In the demo room, the zone 1 is north-oriented so generally colder than zone 2 which is south-oriented.
According to the room exposure, the data reported in Table 9 show that in the winter season, the zone 1 is characterized by an average value of the PMV index lower than the zone 2. Conversely, in the summer season, the PMV index is higher for zone 2.
The continuous monitoring of the physical parameters allows to indirectly consider the inertia of the environmental change. Since the PMV is calculated in real-time it is affected by the continues environmental variations.
Furthermore, in Figure 34 and Figure 35, the profiles of the mean radiant temperature are reported.

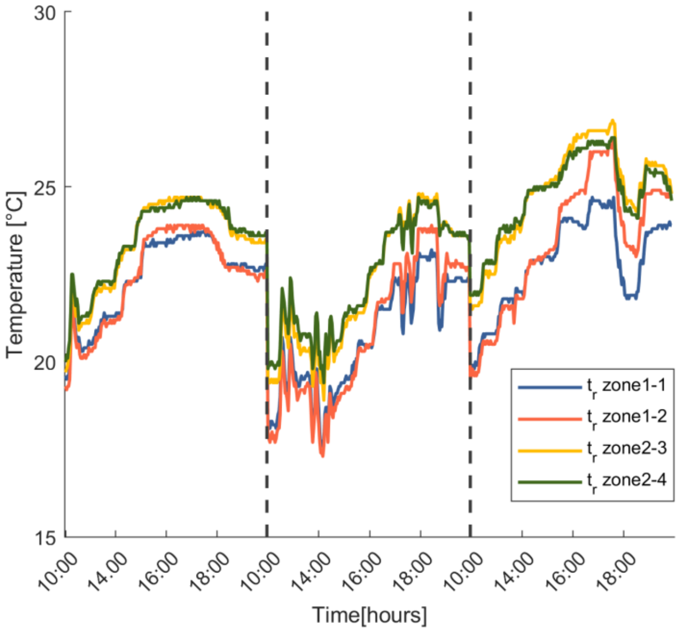


Figure 34 *Profile of the mean radiant temperature in each position considering the winter season*

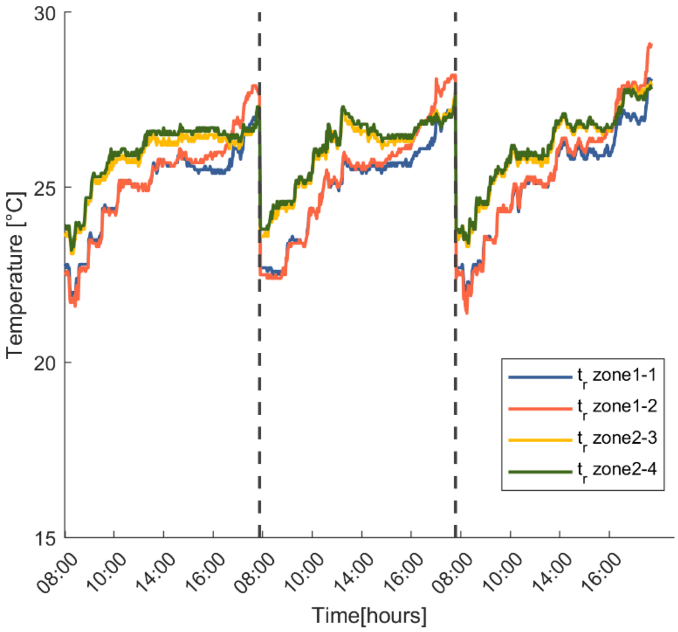


Figure 35 *Profile of the mean radiant temperature in each position considering the summer season*

In Table 10, the average values of the mean radiant temperatures are reported:

Table 10 *The average values of mean radiant temperature for both the winter season and the summer season considering the zone 1 and the zone 2*

	Winter Season		**Summer Season**	
	MRT Zone1 [°C]	**MRT Zone2 [°C]**	**MRT Zone1 [°C]**	**MRT Zone2 [°C]**
Day 1	22.5±1.2	23.4±1.2	25.1±1.4	26.0±1.0
Day 2	20.7±1.7	22.2±1.6	25.1±1.5	26.0±1.0
Day 3	23.1±1.6	24.8±1.3	25.3±1.6	26.1±1.2

As shown in the figures above, the mean radiant temperature was computed considering the positions of interest. However, observing the graphs, it is possible to deduce that the indoor environment is characterized by two main zones. In particular, the zone 2 which is the most affected by solar radiation, shows a higher value of the mean radiant temperature.
Finally, a further advantage from the integration of the Comfort Eye system with the BMS was the energy savings achieved.
The energy analysis was carried out by comparing the data of the energy consumptions, which were acquired adopting the automatic control of the environment performed by the Comfort Eye system, with those obtained when the system (i.e., Comfort Eye) is switched off and the environmental control was manually performed by setting a constant value of the indoor air temperature. In Figure 36 the PMV data are reported considering the occupancy of the room:

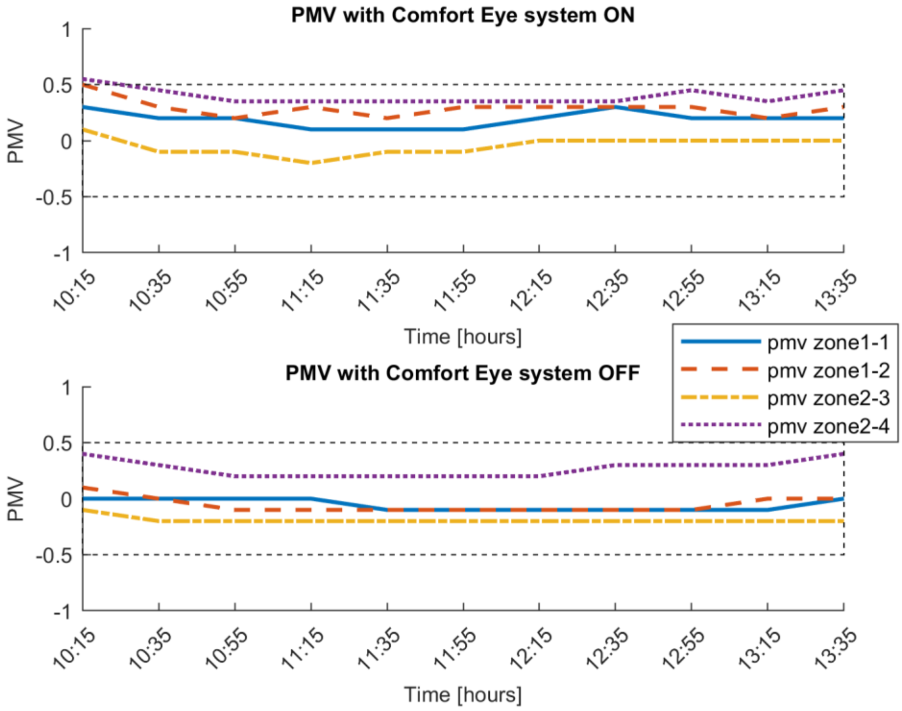


Figure 36 *PMV data acquired considering the occupancy of the room*

When the automatic control of the room was applied, the value of the outdoor air temperature (i.e., 35.1 °C) was much higher than that acquired when the monitoring system of comfort was turned off (i.e., 30.3 °C). This scenario represents a great stress condition for the system. The results of the energy analysis are reported in Table 11:

Table 11 *The energy saving achieved by comparing the data obtained by performing the automatic control of the room with those obtained by using the manual control of the room considering periods in which the room was occupied*

<table>
<tr><th colspan="2">Energy consumption [kWh]</th><th>Energy saving</th><th>Total energy saving</th></tr>
<tr><td>Zone 1 ON</td><td>12.4</td><td rowspan="2">9.7%</td><td rowspan="4">22.2%</td></tr>
<tr><td>Zone 1 OFF</td><td>13.7</td></tr>
<tr><td>Zone 2 ON</td><td>5.7</td><td rowspan="2">40.1%</td></tr>
<tr><td>Zone 2 OFF</td><td>9.6</td></tr>
</table>

Moreover, the data of the electric power consumption are reported in Table 12:

Table 12 *The electric power consumption of the HVAC system*

Energy consumption [kWh]		**Energy saving**
ON	1.3	23.2%
OFF	1.7	

Using the monitoring system based on Comfort Eye technology has led to considerable energy savings, ensuring an optimal level of indoor thermal comfort (the PMV values are included in the range ±0.5). As shown in Table 11, the second area of the room presents a greater energy saving than the zone 1. The second zone is most affected by the solar radiation due to the orientation of the demo room. Thus, performing monitoring of the environmental condition by means of the Comfort Eye allows obtaining the optimization of environmental management systems (i.e., opening/closing windows, HVAC system, etc…) and consequently the optimization of the energy demand of the room, differently from what is done by manually setting an optimal value of the indoor air temperature.

Chapter 7.

Conclusions

Providing comfortable environments is a key aspect to enhance the well-being and productivity of the occupants. In this perspective, this work investigates how the use of wearable devices could improve the use of the Fangers' model when applied to real-time monitoring and control, given the possibility to measure physiological parameters to estimate the occupants' activity. To this end, a new methodology that allows the real-time measurement of the metabolic rate *M* has been developed. A wearable device, which provides simultaneous acquisition of physiological quantities, was adopted and different indicators were obtained as a function of the number of physiological parameters taken into consideration.

Finally, the curves to estimate metabolic rate depending on indicators were obtained. The proposed measurement technique provided an uncertainty of ±0.2 met, referring to the sample population and the tasks conducted in the presented experiment. To test its potential use in building operation (monitoring and control), a test was performed in a virtual environment to compare results obtained adopting a PMV-based approach to control the indoor air temperature in two different cases. Two simulations were conducted for the heating season: one including a controller based on dynamic *M* profile and another one based on static *M*. In both tests the occupants' activity was simulated by a profile ranging from 1.2 met to 1.6 met. The results showed that, under the conditions of the proposed test, the use of a constant *M* provided a variation of 3.2°C on the calculation of the PMV-based comfort temperature with respect to the adoption of the dynamic *M*, with a consequent condition of overheating and a gap between ideal and actual management in the order of 33%.

According to the above observations, the proposed methodology has been adopted in a real case study. A new modular version of the low-cost system (i.e., Comfort eye) was developed and used to perform the assessment of the indoor thermal comfort. In addition, it was integrated with the BMS installed in the demo room. The Comfort Eye allows both real-time and multipoint thermal comfort monitoring, differently from the conventional methods which perform a single-point measure for thermal comfort (i.e., microclimate station). Moreover, it is easily installable and has a minor cost than the traditional devices.

This device requires a continues measurements of the environmental quantities (i.e., relative humidity, air temperature, mean radiant temperature and air velocity). The results show that when the room is occupied, the low-cost system is able to maintain the indoor comfort levels within the optimum range ±0.5 in both winter season and summer season applying a PMV-based approach to control the environmental conditions, in agreement with the standard methodology applied for monitoring the indoor conditions.

The Comfort Eye system provides measures of comfort levels according to the Fangers' model. As said, this model is widely affected by the personal factors (i.e., metabolic rate and clothing insulation). Regarding *M*, the developed methodology for the real-time evaluation of *M* has been adopted in the real case study. Different tasks have been carried out to evaluate the dynamic measure of metabolic rate parameter. It has been observed that moving from the sedentary activity, which is characterized by 1.2 met for metabolic rate, to a dynamic activity within the working environment causes an increase in PMV; consequently, it was observed that the system is able to perform actions to enhance the indoor conditions. Furthermore, a sub-zone control of the environment was carried out by the HVAC system. The results obtained, considering a constant value of metabolic rate with those obtained considering the dynamic evaluation of metabolic rate, was compared.

The data show that the system is able to independently manage the two zones in which the control is performed. In fact, considering the area where the dynamic evaluation of M is adopted, the thermal comfort monitoring system returns a lower value of the set-point temperature than that obtained in the area where a constant value of metabolic rate was chosen. The value of set-point temperature represents the temperature which allows reaching the highest level of comfort. It is computed by minimizing PMV function (i.e., PMV = 0).

Regarding the clothing insulation parameter, the subjective component significantly influences the dynamic evaluation of clothing insulation. The occupants frequently adjust their clothing depending on the thermal conditions, so trying to find an effective methodology for the dynamic estimation of this personal parameter is a very difficult challenge. In this work, a new relationship was obtained. The mathematical expression allows estimating I_{cl} by correlating it with the measurement of the average temperature of the previous day which was computed considering the working hours (R^2 = 0.77). The model adopted allows obtaining a coherent estimation for the clothing insulation value based on the trend of the outdoor air temperature. The relationship was obtained by performing a collection of data which involved 14 subjects. Within the tests, a questionnaire was given to the user in which he registered his level of clothing for 6 months. Moreover, a test was performed in a virtual environment to compare results obtained by adopting a PMV-based approach to control the indoor air temperature in two different cases. Two simulations were conducted for the heating season: one including a controller based on dynamic evaluation of the I_{cl} and another one based on static I_{cl}. The results showed that, under the conditions of the proposed test, the use of a constant I_{cl} provided a variation of 1.3°C on the calculation of the PMV-based comfort temperature with respect to the adoption of the dynamic evaluation of I_{cl}, and a gap between ideal and actual management in the order of 8.5%.

Moreover, the uncertainty analysis of the two methodologies developed was evaluated to compare it with the systematic error trying to understand how these methods impact on the comfort management compared to the case in which fixed values are set for the physiological variables. The systematic error was evaluated in terms of PMV, T_{set} and energy consumptions for both the physiological parameters. As said, regarding the metabolic rate was obtained a variation of ±0.3, of ±3.2°C, and of ±33% for the PMV, the T_{set} and energy consumptions respectively. On the contrary for the clothing insulation parameter was obtained a variation of ±0.1, of ±1.3°C, and of ±8.5% for the PMV, the T_{set} and energy consumptions respectively. The uncertainty analysis showed that by applying the methodologies proposed a decrease of the error is obtained. In particular, for the metabolic rate was obtained a variation of ±0.2, of ±2.3°C, and of ±10% for the PMV, the T_{set} and energy consumptions respectively. On the contrary, considering the clothing insulation it was obtained a variation of ±0.1, of ±0.6°C, and of ±1% for the PMV, the T_{set} and energy consumptions respectively

Finally, the integration of the Comfort Eye within the control logic of the BMS and the adoption of the new methodologies for the dynamic evaluation of personal parameters furnishes a reliable description of the human aspect for thermal comfort assessment. A further

advantage of such integration is a greater improvement of the microclimate control. In particular, the continuous adjustments of the set-point temperature (which mainly depend on the new methodologies proposed for the assessment of the personal parameters that affect the PMV) allows enhancing the energy saving in terms of both energy consumption and electric power. On the contrary, performing standard control (i.e., manually setting the indoor temperature) showed greater energy waste.
In conclusion, the benefit of the proposed approach has been demonstrated in terms of improved comfort delivered to the occupants and optimized building energy management. In the future work, to validate the preliminary results obtained in this work, the sample population (i.e., age and contextual factors) should be enlarged. Moreover, considering that the wearable device adopted in the tests is accurate but expensive, and generally not used by occupants in daily life, different solutions (e.g., smartwatches) should be tested with the proposed methodology.

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