Indoor and Energy quality assessment in buildings

Ph.D. Thesis

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Stupidity is not when you make a mistake for the first time.
Stupidity is when you repeat the same error!*

Bjarne W. Olesen

*Precious and encouraging words when I broke my first and last (… so far) grey globe sensor.

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Voglio ringraziare innanzitutto coloro che mi hanno permesso di intraprendere questo percorso, in particolare il professor Stefano P. Corgnati, per aver creduto in me ed essere stato punto di riferimento della mia formazione negli ultimi anni, e il professor Marco Filippi.

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I. SOMMARIO

Lo studio della qualità ambientale ha acquisito negli ultimi anni un'importanza sempre maggiore. Tale attenzione è evidenziata dal fatto che ormai non ci si sofferma più soltanto sull'importanza del mantenimento del benessere sottoscritto dalle normative in materia di comfort, ma si tende a fare sempre più attenzione alla domanda energetica necessaria al fine del soddisfacimento di tale benessere. Chiaramente, tale fattore, implica una sempre più accurata attenzione nella progettazione dell'involucro edilizio e del sistema impiantistico, nonché nella libertà o meno di azione degli occupanti. Oltre alla fase progettuale diventa indispensabile spostare l'attenzione anche alla fase di gestione e manutenzione, motivo per cui i monitoraggi energetici ed ambientali entrano a far parte del ciclo di vita di un edificio, allo scopo di ottimizzare sempre più il sistema edificio-impianti e ricercando un giusto equilibrio tra livelli di comfort e consumi energetici.

Obiettivo primario della ricerca è un'analisi critica dei metodi di valutazione del comfort ambientale, unita alla determinazione dei consumi energetici richiesti per mantenere determinati livelli di benessere e alla proposta di metodi di analisi e rappresentazione dei dati derivanti da simulazione e monitoraggio. Al fine di garantire un determinato livello di comfort negli ambienti confinati, lo studio si concentra anche sull'analisi della performance di sistemi radianti a basso consumo, attraverso sperimentazioni in campo o in camera termostatica. L'attività di ricerca si compone dunque di tre fasi di approfondimento.

La prima fase si basa sulla valutazione della qualità ambientale attraverso l'uso di categorie.

L'argomento del comfort, focalizzando l'attenzione sul benessere termoigrometrico, è normato a livello internazionale dagli standard EN 15251/2007, ISO 7730/2005 e ASHRAE 55/2004. I metodi di elaborazione dati e rappresentazione dei risultati proposti dalle normative (EN 15251 in particolare), vengono in questo lavoro confrontati tra loro e messi in discussione, indagando, attraverso un caso studio, sull'utilità di questi strumenti, sulla loro applicazione e sui loro limiti.

Il mantenimento di determinate categorie di comfort all'interno di un ambiente comporta chiaramente un dispendio energetico. La domanda di energia può essere diversificata a seconda della tipologia di involucro o di impianto, ma anche dal tipo di controllo impiantistico e imprescindibilmente dalle condizioni climatiche esterne. Allo scopo di dimostrare quanto detto, la seconda fase dell'attività trova espressione attraverso uno studio di simulazione energetica di un ambiente per uffici, mirata ad analizzare le domande di energia per riscaldamento e raffrescamento al variare dei livelli di qualità termica e dell'aria, nonché delle condizioni climatiche esterne. La simulazione energetica degli edifici è però solo uno degli strumenti che si possono utilizzare in questo tipo di analisi. La misurazione diretta dei consumi energetici è, infatti, un secondo metodo che sempre più sta assumendo importanza sullo scenario internazionale. Piani di monitoraggio energetico, affiancati a piani di monitoraggio ambientale, consentono di avere un quadro generale e dettagliato sia dei livelli di comfort in ambiente che dei relativi costi da sostenere, evidenziando inoltre il corretto funzionamento dei sistemi impiantistici e dei relativi controlli. La correlazione tra i due monitoraggi svolti in parallelo permette di poter fornire le informazioni necessarie al fine di una corretta valutazione energetico - ambientale di un edificio. Oltre all'elaborazione dei dati, lo studio affronta anche il tema concernente la loro rappresentazione,

sviluppandolo attraverso l'analisi di dati di monitoraggio energetici ed ambientali relativi ad un anno di osservazione di un edificio per uffici.
Elemento di unione tra le condizioni di comfort in ambiente ed i relativi consumi energetici, oltre chiaramente alla tecnologia costruttiva dell'edificio, è il sistema impiantistico. Nello specifico, negli ultimi anni, molti studi relativi al tema del comfort termo igrometrico hanno trattato l'impiego di sistemi radianti a basso consumo energetico per il controllo della qualità ambientale. Tra le molteplici tipologie di sistemi radianti su cui si continua a fare ricerca, in questo lavoro ne vengono analizzate due tra loro molto diverse, entrambe oggetto di analisi e sperimentazione: il primo caso è relativo all'uso di piastre radianti elettriche a parete, per il solo riscaldamento, mentre il secondo caso è invece uno studio relativo all'utilizzo di un sistema di attivazione termica della massa (TABS) durante il periodo di raffrescamento. In entrambi i casi sono state effettuate misurazioni dirette dei parametri ambientali e dei flussi scambiati, nel primo caso in camera termostatica, nel secondo caso direttamente sul campo (locale adibito ad ufficio).

I risultati ottenuti da tutte le analisi effettuate sono illustrati all'interno di articoli scientifici rivolti a riviste internazionali o pubblicati in proceedings di conferenze internazionali.

II. ABSTRACT

Interest on Indoor Environmental Quality (IEQ) increased more and more in the last years. This attention is evidenced by the fact that nowadays maintaining a certain level of comfort in the building, as it is prescribed by the standards, means to deal with a rising energy demand. For this reason increasing attention needs to be spent in the envelope and systems building design, as well in the building robustness at the occupants actions. Further than the design phase it becomes necessary to shift the focus on to the building management and maintenance too. To this aim energy and environmental long term monitoring are introduced in the building life cycle, with the objective to optimize the building-plant system and to look for a good balance between different levels of comfort and energy consumption.

Main objective of the research is the critical analysis of the indoor environment quality assessment existing methods, within the evaluation of the energy consumptions required to maintain specific comfort levels, and suggesting new methods of analysis and representation of data from monitorings or simulations. In order to reach high level of IEQ, the study also focuses on the performance evaluation of energy saving by radiant systems, through tests in thermostatic room or in situ. Research is therefore conceived in three deepening phases.

The first phase is based on the indoor environment quality assessment through the use of categories. Comfort, and particularly thermal comfort, is regulated by the standards ISO 7730/2005, EN 15251/2007, and ASHRAE 55/2004. Methods for data elaboration and representation suggested by the standards (specifically by EN 15251) are in this work compared and discussed, investigating, also through the use of a case study, the effective utility of these instruments, of their applications and limitations.

Maintaining specific comfort categories in a building often comport to spend energy. Energy demand can be varied depending on the envelope characteristics and quality, and from the systems controls and the outdoor climate conditions. With the aim to demonstrate what enounced, the second phase of the study is explained through an office room energy simulation, conducted with the aim to assess the heating and cooling energy demand variation with the thermal and air quality variation, as well as for different climate zones. Buildings energy simulation is however only one of the tools that can be used for this kind of analysis. Direct monitoring of the energy consumptions is in fact another method that is becoming more and more important. Energy monitoring plans, with IEQ monitoring plans, give a detailed overview about levels of comfort and related costs in a building, moreover investigating on the correct or wrong systems operation and controls. The correlation between the two measurements conducted simultaneously allows to give, as output of the analysis, a complete building energy and environment evaluation. In addition to the data processing, the study also addresses the results representation, through the analysis of energy and environmental data from one year of monitoring in an office building.

As mentioned above, the connecting element between ICQ in a room and the related energy consumptions, beyond the building thermo physical properties, is the installed plants system. In recent years many studies in literature about comfort in buildings treated the topic of low energy radiant

systems to reach the indoor environmental quality objective. Among the many typologies of radiant systems, this work faces with two kinds of them, very different one from each other, and both object of analysis and experimentation: the first is represented by vertical electric radiant plates for heating, and the second is about TABS (Thermal Active Building System) for cooling. In both cases energy and environmental measurements were carried out. In the first case the experiments took place in test rooms, in the second case they were performed in situ (office room). Differences between the two analysis and strategies adopted for the measurements during the operational time of the building using TABS are shown.

Results of the work are shown and widely explained in internationals journals and international conference papers.

III. LIST OF PAPERS:

Paper I - D. Raimondo, S.P. Corgnati, B.W. Olesen, Evaluation methods for indoor environmental quality assessment according with the comfort European standards. *Submitted to REHVA Journal*.

Paper II - S.P. Corgnati, E. Fabrizio, D. Raimondo, M. Filippi, Categories of indoor environmental quality and building energy demand for heating and cooling, Building Simulation: an international Journal, 4 (2011) 97-105, ISSN: 1996-3599.

Paper III - D. Raimondo, S.P. Corgnati, B.W. Olesen, Detection and representation of total energy use and indoor climate quality in buildings: application to an office building through in field monitoring. *Manuscript, under internal reviewing*.

Paper IV- A. Carullo, F. Causone, S.P. Corgnati, D. Raimondo, Radiant electrical plates for space heating and thermal comfort: an experimental study. IAQVEC 2010, August 15-18, Syracuse, NY.

Paper V - D. Raimondo, S.P. Corgnati, B.W. Olesen, Field test of a Thermal Active Building System (TABS) in an office building in Denmark. *Submitted to Energy and Buildings*.

Paper VI - B.M. Behrendt, D. Raimondo, Y. Zhang, J.E. Christensen, S. Schwarz, A system for the comparison of tools for the simulation of water-based radiant heating and cooling systems, Building simulation 2011, November 14-16, Sydney, Australia.

1. Introduction

Energy uses and indoor climate quality (ICQ) in buildings are strictly connected. Due to the increasing high quality of life in the last years, the need to maintain high levels of indoor comfort conditions and to improve, at the same time, the energy efficiency is a very relevant subject [1]: typically at growing levels of comfort indoor correspond in fact growing energy consumptions. To this aim, design of the building architecture and envelope and systems operation control should be increasingly optimized.

The EPBD (Energy Performance of Buildings Directive) 2002/91/CE [2], which introduces the topic of the European approach to the energy certification of buildings, highlights how important it is to evaluate the ICQ level, with the objective to attribute to the building a given energy performance. In particular, it gives indications about the definition of the minimum energy performance requirements for new and existing buildings and about the building energy consumptions [3]. Due to the fact that energy demand may vary depending on the occupants comfort expectations, on the occupants adopted systems control strategies, and on the availability of natural resources (like natural light or fresh air), an indoor environment “declaration” becomes a needful tool to be enclosed to the energy statement. There is therefore a need to specify criteria for the indoor environment for design, energy calculations, performance and operation of buildings [1]. To this aim, in 2007, under a mandate of the European Commission, and strictly related to the EPBD, the Standard EN15251 “Indoor environmental parameters for assessment of energy performance of buildings, addressing indoor air quality, thermal environment, lighting and acoustics” [4] has been developed. According to this regulation, the IEQ evaluation can be performed both in the design and in the operational phase: in the first case through the use of energy simulation tools, or using the design values of the environmental parameters, in the second case monitoring the indoor environmental parameters. Same approach can be used for the energy demand/consumption interpretation.

Besides the EN 15251 [4], also the ASHRAE Guideline 10 [5] treats the overall indoor comfort. Differently by the first, related to the EPBD and dealing with energy consumption problems, the ASHRAE Guideline 10 has a descriptive, multi-disciplinary nature and an ergonomic approach, concerning the human response to the indoor environment [6].

In order to consider different aspects of ICQ and energy assessment in buildings, in this thesis both the topics are treated under different points of view. In accordance with what evidenced by the “road map” of figure 0, in which the objectives of the work are expressed under interrogative form, this research deals to:

- Improve the existing methods, proposed by the standards about comfort, for the long term climate quality assessment and data representation.
- Put in relation the indoor climate quality with the energy required to maintain certain levels of wellness in buildings, in order quantify how much thermal comfort and air quality levels affect

the building energy demand.

- Define a method for the ICQ and energy assessment in buildings, from the monitoring plan to the data elaboration and representation.
- Propose a tool able to represent in a synthetic way both the energy performance and the indoor climate quality of a building.
- Evaluate the energy performance and the thermal comfort potentiality of two different kind of radiant systems, with the aim to demonstrate their applicability in low energy buildings.

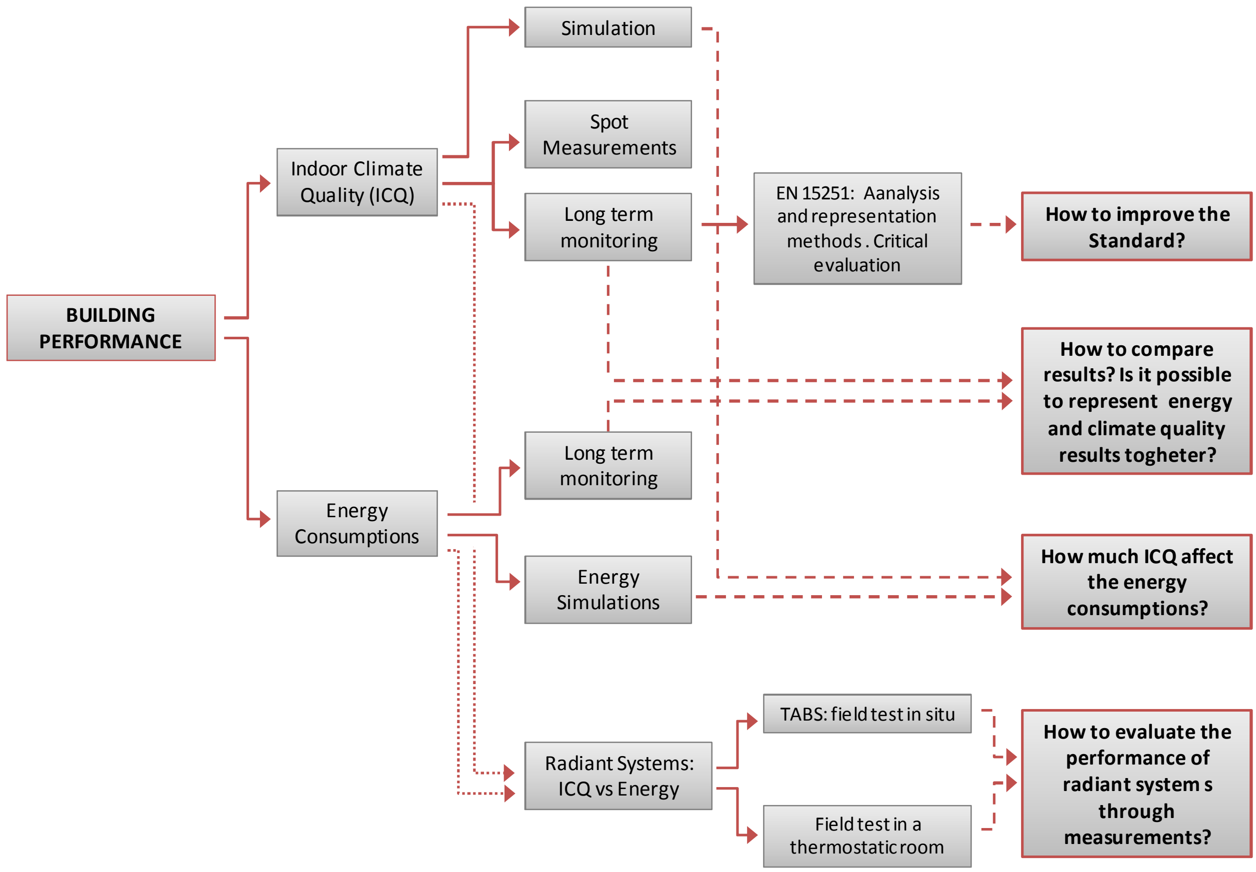

Figure 0: Thesis "Road map"

Note: The thesis treats the questions underlined by figure 0 through the use of case studies, of which punctual results of each analysis are widely described in the papers of chapter 8.

2. Indoor climate quality (ICQ) evaluation through the use of comfort categories

Criteria for acceptable thermal conditions are specified as requirements for thermal comfort (PMV, PPD, or operative temperature, air velocity and relative humidity) and local thermal discomfort (draught, vertical air temperature differences, radiant temperature asymmetry, surface temperature of the floor). Indoor environmental quality, according to the standard EN 15251, can be evaluated through different criteria based on the comfort indexes analysis. In existing buildings it can be performed through long term monitoring, which allows to collect data that can be elaborated in accordance with the standard prescriptions giving as output a classification of the climate quality. Also spot measures contribute to assess the indoor environment. The use of short term measurements, in fact, is useful for give a detailed picture of the IEQ in given examined configurations, in specific critical locations and times [12].

In this chapter both the indoor environment evaluations, long term and spot, are treated and discussed according with the comfort categories and the elaboration methods suggested by the standard EN 15251. Critical approach at the methodologies is here highlighted and suggestions for future improvements in the data elaboration are proposed.

In order to have knowledge of standard EN 15251 and thermal comfort evaluation, a short background about the topics is explained in the next paragraph.

2.1 Background on Standard EN 15251 and thermal comfort

2.1.1 Standard EN 15251

Standard EN 15251:2007 specifies the indoor environmental parameters that have an impact on the energy performance of buildings, and defines how to establish these input parameters for the building systems design and energy performance calculations. It defines the global comfort, as the sum of different aspects, i.e. thermal comfort, indoor air quality, visual comfort and acoustic comfort, and it recommends parameters of indoor temperatures, ventilation rates, illumination levels and acoustical criteria for the design of buildings, heating, cooling, ventilation and lighting systems at which to refer. It is mainly applicable to moderate thermal environments, where the objective to reach is the satisfaction of the occupants. These environments are single family houses, apartment buildings, offices, educational buildings, hospitals, hotels and restaurants, sports facilities, wholesale and retail trade service buildings [7].

EN 15251, in particular, utilizes an approach based on categories: four different categories may be used, depending on type of building, type of occupants, type of climate and national differences. These categories correspond to a different acceptability of the indoor environment (predicted percentage of satisfied occupants) (Tab. 1). The standard suggest to refer to categories in the building design phase, but they may also be used to give an overall, yearly evaluation of the indoor environment, according with the evaluation methods suggested by the standard for the long term assessment. In this case needs to be highlighted that this long term evaluation can be performed in the design phase through energy simulations, and in existing buildings through monitoring. In both cases results of the evaluations have to respect the ranges indicated by the standard. Examples of criteria suggested by the EN 15251 for a typical space with sedentary activity are shown in table 2.

Table 1- Definition of IEQ categories, according with EN15251.

Category	Explanation
I	High level of expectation. It is recommended for spaces occupied by very sensitive and fragile persons, with special requirements like handicapped, sick, very young children and elderly persons.
II	Normal level of expectation. It should be used for new buildings and renovations.
III	An acceptable, moderate level of expectation. It may be used for existing buildings.
IV	Values outside the criteria for above categories. This category should only be accepted for a limited part of the year.

NOTE: In other standards, like EN 13779 and ISO 7730, categories are also used, but named differently (like A,B,C or 1,2,3 etc.)

Table 2. Example criteria for PMV-PPD, operative temperature, relative humidity and ventilation (CO_2 concentration and ventilation flow rate for a low polluted office) for typical spaces with sedentary activity. [3]

Category	Thermal Comfort indexes		Operative Temperature ranges		Relative Humidity	Ventilation	
	PPD	PMV	Winter 1.0clo/1.2met	Summer 0.5clo/1.2 met		CO_2 Above outdoor	Flow rate q_p+q_b
	[%]	[/]	[°C]	[°C]	[%]	[ppm]	l/sm^2
I	< 6	>-0.2, <+0.2	21.0-23.0	23.5-25.5	30-50	> 350	2.0
II	< 10	>-0.5, <+0.5	20.0-24.0	23.0-26.0	25-60	350 - 500	1.4
III	< 15	>-0.7, <+0.7	19.0-25.0	22.0-27.0	20-70	500 - 800	0.8
IV	> 15	>±0.7	< 19.0-25.0<	<22.0-27.0<	<20-70<	> 800	-

The standard specifies that the indoor climate assessment of a building can be performed by evaluating the indoor environment of typical rooms representing different climate zones in the building. For these spaces the indoor climate can be evaluated for different phases:

1) Design: the standard specifies design values of indoor temperature during summer and during winter, of ventilation rates for residential and not residential buildings, of humidity, lighting and noise (some examples in Tab.2).

2) Calculation/Elaboration: the standard defines the building simulation as a cost effective way to analyze the performance of buildings, through which indicators of indoor environment can be calculated for different purposes. With this aim the standard, in annex F ("Long term evaluation of the general thermal comfort conditions"), suggests three different methods (A,B,C) to evaluate and represent the thermal comfort conditions over time (season, year), based on data from measurements in real buildings or obtained by dynamic computer simulations. These three methods are the followings:
   - *Method A*, "Percentage outside the range", is based on the calculated number (or %) of hours in occupied period when the PMV or the Operative Temperature are outside a specified range.
   - *Method B*, "Degree hours criteria", represents the time during which the actual operative temperature exceeds the specified range, during the occupied hours, weighted by a factor depending on how many degrees the range has been exceeded.
   - *Method C*, "PPD weighted criteria", represents the time during which the actual PMV exceeds the comfort boundaries, weighted by a factor which is a function of the PPD. This weighting factor, wf, is equal to 0 if the calculated PMV falls within a comfort ranges described in Table 1. If the value is over the upper/lower limit of the range, the wf is the ratio between the PPD calculated on the actual PMV and the PPD calculated on the PMV limit.

3) Measurements: the standard allows deviations from the selected criteria. Some national criteria express 'acceptable deviations' as an acceptable number of hours outside the criteria based on a yearly evaluation (like 100 to 150 h). This may also be given as weighted hours, where the level of deviation also is taken into account. With this aim the standard gives indications about where and how to measure for the evaluation of thermal quality, indoor air quality and ventilation, lighting and noise.

4) Subjective questionnaires: the standard suggests to consider the direct subjective reaction of the occupants as an instrument for the overall evaluation of the indoor environment. Daily, weekly, monthly evaluations using questionnaires for general acceptance of the indoor environment, thermal sensation, perceived air quality shall be used. Examples of questionnaires are included in the standard at the Annex H.

2.1.2 *Thermal comfort*

Thermal comfort has been defined as ''a state in which there are no driving impulses to correct the environment by the behaviour'' [11]. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) defined it as ''the condition of the mind in which satisfaction is expressed with the thermal environment'' [12]. As such, it will be influenced by personal differences in mood, culture and other individual, organizational and social factors [13].

Satisfaction with the thermal environment is a complex subjective response to several interacting and less tangible variables [14]. In general, comfort occurs when body temperatures are held within narrow ranges, skin moisture is low, and the physiological effort of regulation is minimized. Comfort also depends on behavioural actions such as altering clothing, altering activity, changing posture or location, changing the thermostat setting, opening a window, complaining, or leaving a space. In 1962, Macpherson defined six factors as those affecting thermal sensation: four physical variables (air temperature, air velocity, relative humidity, mean radiant temperature), and two personal variables (clothing insulation and activity level, i.e. metabolic rate) [15].

In order to reduce the economic and environmental cost of energy consumption, investigations covering many aspects related to thermal comfort in indoor environments have been conducted, like studies for identify models [16,17] and indices [18], or like experiments carried out in climate chambers [16,19] and field surveys [15,20]. Studies that allowed to define thermal comfort standards and evaluation methods [21,22], etc [13]. The most important findings are now the basis of national and international standards, e.g. [23,24]. The international comfort standards such as ASHRAE standards and the International Standards Organization (ISO) are almost exclusively based on theoretical analyses of human heat exchange performed in mid-latitude climatic regions in North America and northern Europe [14,23]. They were based primarily on mathematical models developed by Fanger on the basis of studies from special climate-controlled chamber experiments. Moreover, these standards are suitable for static, uniformly thermal conditions and are based on the hypothesis that regardless of race, age and sex.

Two different approaches exist to define the thermal comfort: the rational or heat-balance approach and the adaptive approach [25]. The rational approach uses data from climate chamber studies to support its theory, best characterized by the works of Fanger while the adaptive approach uses data from field studies of people in building [26]. Fanger's [16] comfort model incorporates the six factors mentioned by Macpherson, and the two-node model of Gagge et al. [18]. In an evaluation by Doherty and Arens [25], it was shown that these models are accurate for humans involved in near-sedentary activity and steady-state conditions. This approach is based on in controlled climate chamber on 1296 young Danish students, using a steady-state heat transfer model. In these studies, participants were dressed in standardized clothing and completed standardized activities, while exposed to different thermal environments. Participants were asking about their thermal sensation, using the seven-point ASHRAE scale (Fig. 1). The expanded equation related thermal conditions to the seven-point ASHRAE thermal sensation scale, became known as the ''Predicted Mean Vote'' (PMV) index. The PMV was then incorporated into the ''Predicted Percentage of Dissatisfied'' (PPD) index. Fanger's PMV-PPD model on thermal comfort is widely used and accepted for design and field assessment of thermal comfort [15].

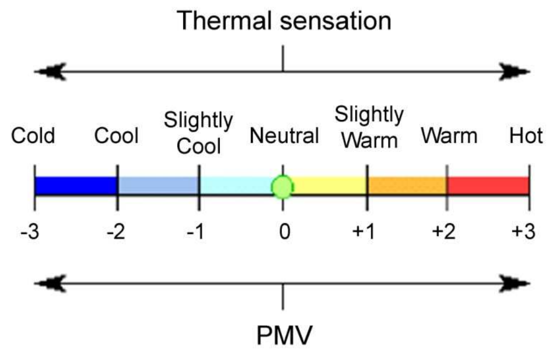

Figure 1- ASHRAE Thermal Sensation scale.

Adaptive approach derives from field studies, having the purpose of analyzing the real acceptability of thermal environment, which strongly depends on the context, the behaviour of occupants and their expectations. The adjustments have been summarized by De Dear [27-28] in three categories: behaviour adaptation, physiological adaptation and psychological adaptation. In recent years, different authors have encouraged field studies in addition to laboratory experiments, in order to get more reliable information about the actual workplace comfort and the relevant (interacting) parameters. Several studies about the topic are summarized in [13]. Standard EN 15251/2007 and ASHRAE Standard 55 deal with the theme suggesting similar approach at the issue. EN 15251 introduces a method in order to design or assess environments without mechanical cooling systems. This optional method is valid only in periods when the heating system is not operating, and in specific conditions: space must be equipped with operable windows and there shall be no mechanical cooling in operation. Mechanical ventilation with unconditioned air (in summer) may be utilized, but windows opening and closing shall be the primary mean of regulation of the thermal conditions in the space. Furthermore, the method can be applied only if occupants are engaged in near sedentary physical activities, with metabolic rates ranging from 1,0 to 1,3 met. It is also important that strict clothing policies inside the building are avoided, in order to allow occupants to freely adapt their clothing insulation. ASHRAE Standard 55 also introduces a similar diagram, deriving from the studies of Brager and deDear study, to be applied to free-running buildings too, based on the same assumptions enounced before. In Figure 2 the two diagrams proposed from the Standards are shown.

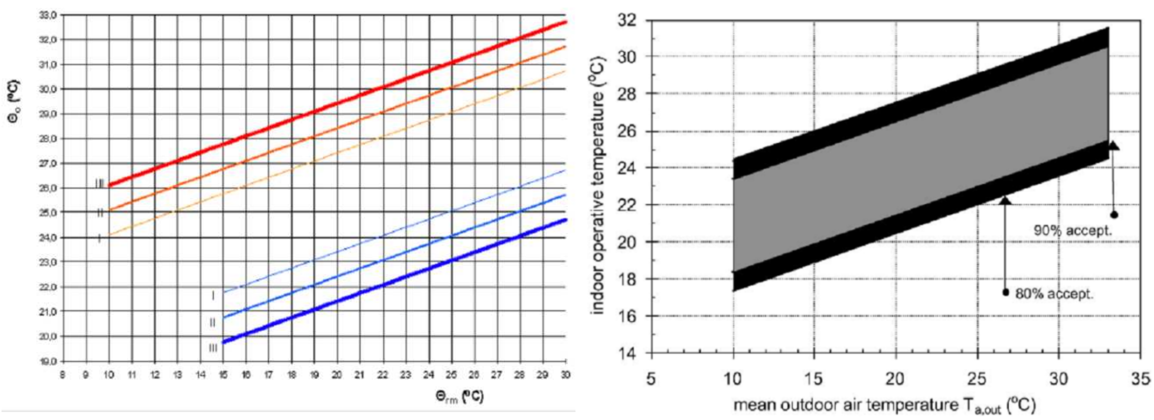

Figure 2 - Design values for the indoor operative temperature using the adaptive approach according with [4] and [12].

2.2 Long term monitoring

During the design stage, categories can be used to evaluate different design options and can be applied on data from computer energy simulations. In these calculations, the categories may be clearly adopted and performance indicators can be expressed as percentage of time where the indoor environment falls into different ranges. Similar approach can be used in the indoor climate measurements in existing buildings. In that case collect the data necessary for the evaluation is more difficult, but possible.

Examining separately the three evaluation methods suggested by the standard 15251 (annex F), and illustrated in 2.1.1, a critical analysis about the given and missed information from the three different processes has been performed. In order to carry out this analysis, data from a case study have been used an elaborated. The case study is an office building located in Denmark of which architectural characteristics, envelope thermophysical properties and installed plant systems are widely illustrated in Paper I. The office was normally occupied during daily time from 8:00 to 18:00, from Monday to Friday. In the building measurements about air and operative temperature, relative humidity and CO_2 concentration were collected each 10 minutes for one year. Simultaneously, an external weather station collected data about air temperature and relative humidity, wind direction and velocity, and solar radiation.

Complete elaborations and comments about results are shown in Paper I. Here just some results about thermal comfort evaluation, referred to the summer season, are illustrated with the aim to compare the three methods. Results are related to two rooms of the building, characterized by different heating and cooling systems, one mechanically ventilated (A) and the other one naturally ventilated (B) [PaperI].

In order to process the data as indicated by *Method A*, the thermal performance was evaluated in terms of percentage of time outside the range, according with the four categories of operative temperature and PMV suggested by the standard (Tab. 2). Outcomes of the elaboration are shown in figure 3.

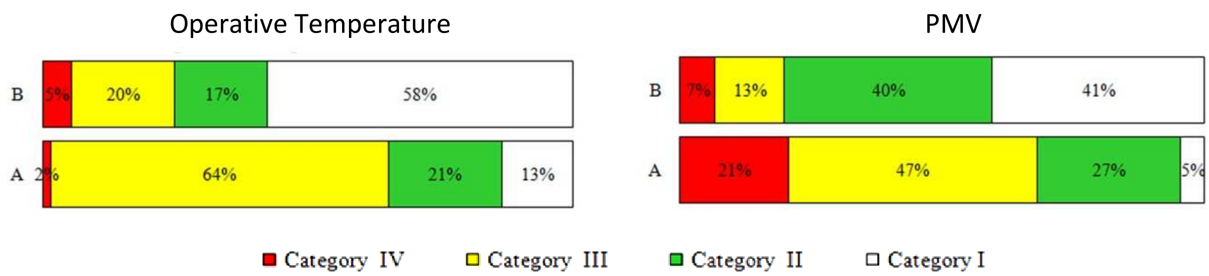

Figure 3. Indoor Operative temperature and PMV evaluation, expressed in percentage of time in four categories, in summer period.

Through this kind of representation the percentage of time when the monitored (operative temperature), or the calculated (PMV) parameters fall in a specific range of category is represented. This method allow to make an overall overview of the analyzed environment during a certain period of time, but without giving information about the variables trend in the time , for example is not possible to know if, in the case study, the temperature in category III was lower than 23 °C or higher than 26°C.

From figure 3 it can be seen that the operative temperature and PMV evaluations, even if both representing the application of Method A, showed some differences in the results: the operative temperature evaluation gave slightly better results compared to the PMV evaluation. While the first considers just the measured operative temperature, the PMV calculation depends by physical parameters (air temperature, relative humidity, air velocity, mean radiant temperature) and subjective parameters (thermal resistance of the clothes and metabolic rate). This fact can highlight significant problems in the accuracy of the prediction (for example, the accuracy by evaluation of the clothing and activity is not good enough to estimate the difference between classes of PMV). In this case study the physical parameters, except the air velocity, were monitored in continuous. Trough spot measurements performed in different periods of the year, it was however possible to establish that the air velocity was averagely around 0.10 [m/s]. For the PMV calculation the air velocity value was then kept constant as 0.10 [m/s]. Regarding the subjective parameters, the metabolic rate used in the analysis was the one indicated by standard ASHRAE 55 for "Office activity-Filing, seated", 1.2 [met]. Also the clothing insulation value was kept constant: 0.5 [clo] in summer period and 1 [clo] in winter period. Due to these assumptions, the PMV calculation does not represent the real PMV of a specific occupant in the room during the monitored time, justifying what previously mentioned. Different is for the same evaluation referring to the operative temperature. This time the problem that could be encountered depend by the accuracy of the measurement of mean radiant temperature, which often is higher than 0.5 -1.0 K. For many buildings the difference between air and mean radiant temperature is however less than 2 K, and then this accuracy will not be so important.

Method B allows to quantify the amount of degree hours of overheating or overcooling respect to the selected category. In case of monitoring in existing building this method, giving these indications, can be useful for regulate the systems settings in order to don't waste energy. Figure 4 shows the amount of degree hours over category I, II and III. From this representation emerge how, in Room A in particular, the temperatures in the room were lowers than the limits prescripts by the standard. Thanks to this representation, over understanding that the percentages outside the ranges of Method A, shown in figure 3, were representing low temperatures, consideration about the temperature setting in the room and about the control system regulation can be done. (In this specific case the air temperature in the room was set too low, at 23°C, while the range of category I, as it is written in tab.2, goes from 23.5 to 25.5°C)

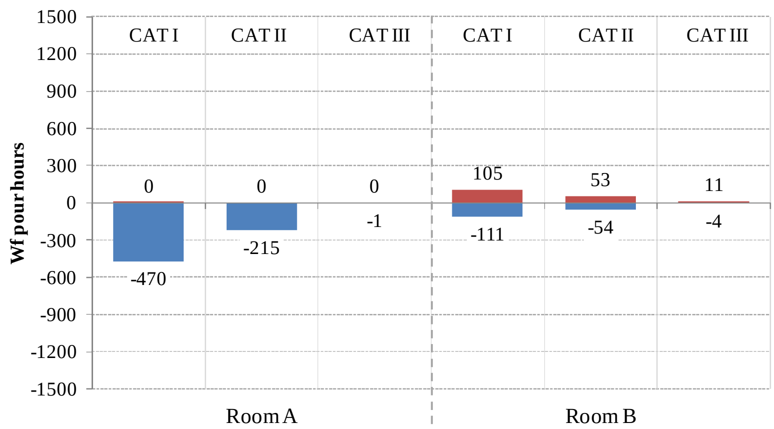

Figure 4. Degree hours criteria applied to Rooms A and B for the summer period.

From *Method C* the data indicate the sum of the weighted factors, function of the PPD, multiplied for the number of hours when the PMV exceeds the category range. While method B was based on the evaluation of operative temperature, here the results represent the dissatisfaction of the people. In this case the too low temperatures of the mechanically ventilated room (A) are also evident, because negative values in the graph indicate that thermal discomfort was perceived for low temperatures. Like it was for method B, also this method can help in the system setting for the indoor climate control.

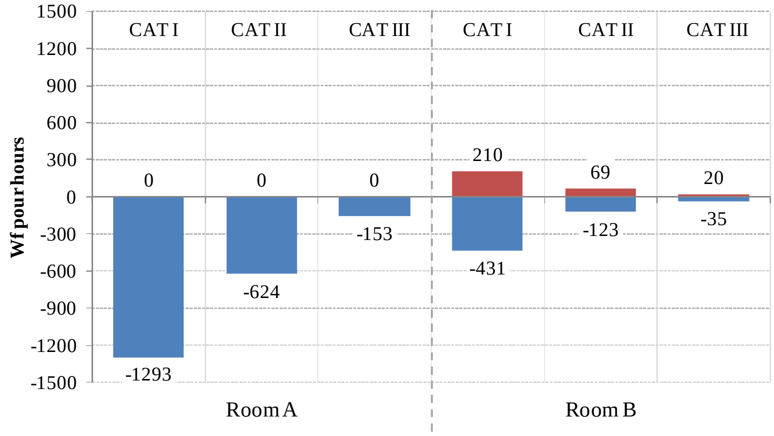

Figure 5. PPD weighted criteria applied to Rooms A and B for the summer period.

From the comparison of the three criteria emerge that Method A, even though is a good instrument to show results, besides being the most applied in the representation of the comfort evaluation (in fact it is also suggested by the standard in the Annex H), it does not allow to clarify the reasons, and the problems, that determine a good or a bad thermal quality in the rooms, because it does not show any distribution of measured temperature. Different is, for example, for Method B and C. Here it is easy understandable that if ICQ in Room A was not evaluated so good, the cause can be identified in the low temperatures. These results highlight a problem in the systems control: the cooling system combined with the mechanical ventilation was cooling too much the environment, with consequent wasting of energy. With an optimized control indoor temperatures can be improved, leading to energy saving too.

For better understand the outcomes of criteria A and B, the operative temperature profiles are shown in figure 6. Looking at the graph, the percentage of time when the temperature in room B exceed the upper limit of the range (Category $IV^{(+)}$, To>27°C) is negligible, while it cannot be ignored when the temperatures are below than the lower limit (Category $IV^{(-)}$, To<22°C). Following the same principle, in Room A the operative temperatures fluctuate between Category I and Category $IV^{(-)}$.

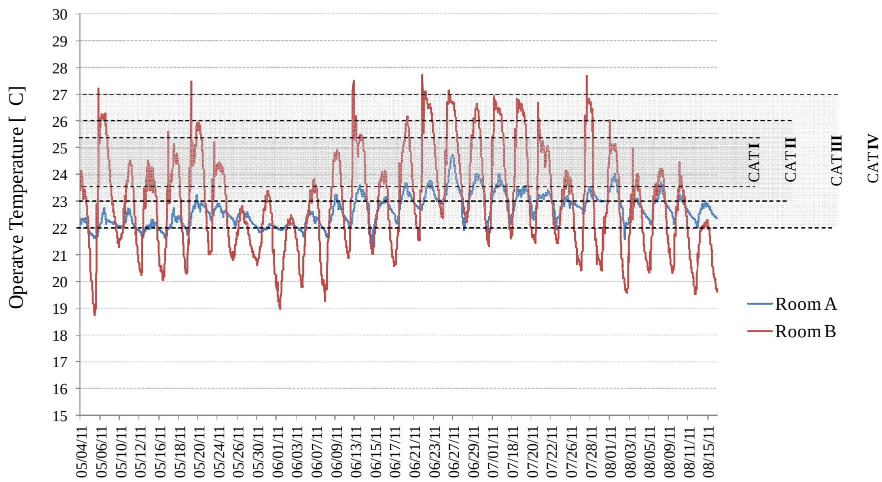

Figure 6. Operative temperature profiles during the occupied hours for Rooms A and B in summer period.

Looking at the ranges of values indicated in Table 1, and splitting these ranges in two parts as described in the previous example, Table 2 can be translated in Table 3.

Table 3. PMV, PPD, operative temperature and relative humidity comfort ranges for typical spaces with sedentary activity, dividing the categories indicated by [3] in lowers and uppers categories respect to Category I.

Category	Thermal Comfort indexes		Operative Temperature range		Relative Humidity
	PPD	PMV	Winter 1.0clo/1.2met	Summer 0.5clo/1.2 met	
	[%]	[/]	[°C]	[°C]	[%]
IV $^-$	> 15	PMV < - 0.7	< 19.0	< 22.0	< 20
III $^-$	< 15	- 0.7 <PMV< - 0.5	19.0-20.0	22.0-23.0	20-25
II $^-$	< 10	- 0.5 < PMV< - 0.2	20.0-21.0	23.0-23.5.0	25-30
I	< 6	- 0.2 < PMV< +0.2	21.0-23.0	23.5-25.5	30-50
II $^+$	< 10	+ 0.2 < PMV<+0.5	23.0-24.0	25.5-26.0	50-60
III $^+$	< 15	+ 0.5 <PMV< +0.7	24.0-25.0	26.0-27.0	60-70
IV $^+$	> 15	PMV > + 0.7	> 25.0	> 27.0	> 70

Wanting to implement the missing information in the elaboration of Method A, the same approach described by the standard can be referred to the splitted categories indicated in Table 3. Doing this operation, operative temperature and PMV evaluation could be represented as in Figure 7.

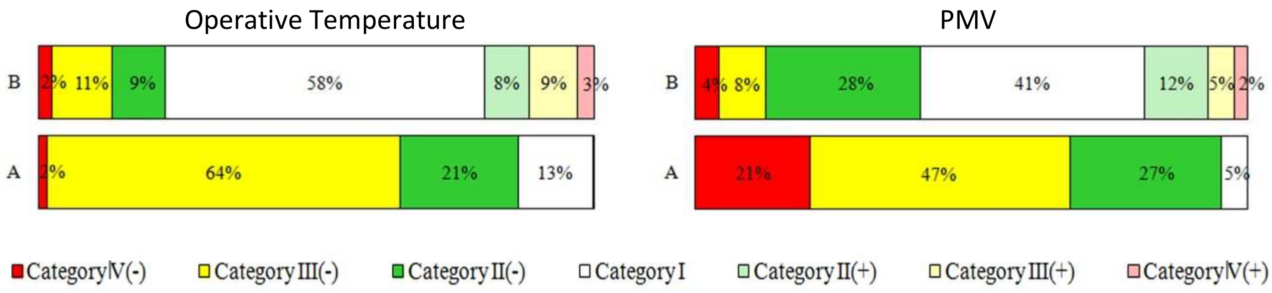

Figure 7. Indoor Operative temperature and PMV evaluation, expressed in percentage of time in categories, in summer periods, according with the values ranges of Table3.

From this proposed implementation at the criteria "outside the range", it is possible to get the information highlighted before. It is in fact clearly visible that the operative temperature in summer for Room A was always lower than the limit of Category I. Room B presents, on the other hand, values falling in categories both lowers and higher than Category I, describing the fluctuation of the profile shown in Figure 6. Same considerations can be done for the PMV evaluation. In Paper I similar analysis is shown for other environmental parameters, with as many interesting results.

2.3 Short term evaluation

Spot measurements are useful for give a detailed picture of the ICQ in particular configurations, like in specific critical locations and times [12]. To this aim, in parallel to the long term monitoring, also spot measurements should be carried out. Spot measurements can be useful in the determination of homogeneous climatic zones too, that are important to be defined in the planning of the long term monitoring. Moreover they can be used for to examine critical points, where local discomfort due to drought risk or elevate difference of temperature, for example, between feet and head, is present.

In order to evaluate the actual thermal comfort of the occupants, the six parameters (see *2.1.2*), four physicals and two personals, need to be collected. The physical variables can be measured and logged through dedicated instruments, while the personal variables can be collected through printed or online questionnaires. Having all these information is then possible to calculate the PMV and the PPD indexes. From the questionnaires the Thermal Sensation Vote (TSV) can be evaluated too, using the ASHRAE thermal sensation scale. PMV and TSV can subsequently be compared.

In the case study spot measurements were performed two times: one time in winter and the other time in summer. In both cases the aim of the measurement was the evaluation of local discomfort at the occupants work stations and the homogeneous distribution of the air temperature, relative humidity and lighting level in the rooms. As before, only elaboration about the summer spots are shown. More detailed information and complete analysis are respectively illustrated in Paper I and in Annexes 9.1.1-9.1.2.

During these measurements physical parameters were monitored. These parameters were: air temperature, operative temperature, air velocity, relative humidity and lighting level. Sensors were fixed on a portable stand at different heights, corresponding to the height of the head, of the body and of the ankle of a stand or seated person. In each room at least 5 points were tested for 15 minutes each. Results about the monitored environmental parameters are shoved in figure 8. From this first analysis can be evaluated the absence of local discomfort due to the temperature difference at different heights, as well as the presence of draught. In this case the three methods listed in the long term evaluation paragraph cannot be applied, because the time of monitoring is too short. The collected parameters can however be referred to the comfort categories described by the Standards.

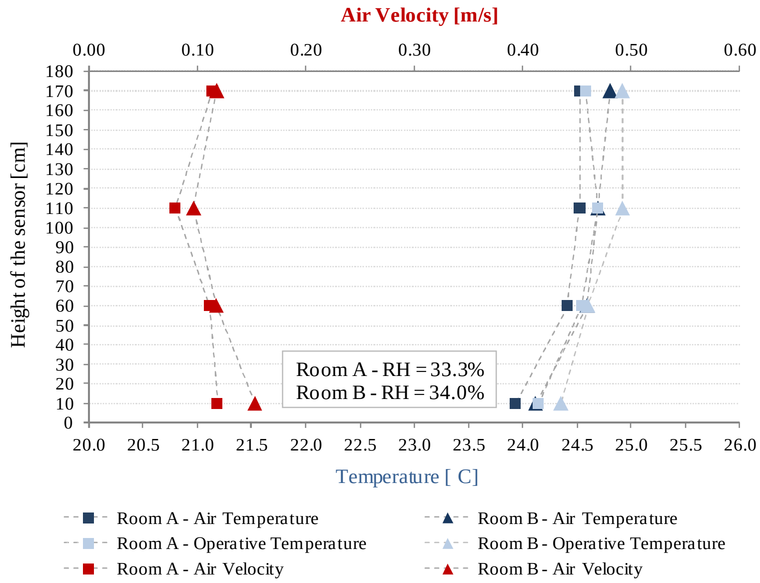

Figure 8. Summer spot measurements. Average value of air temperature, operative temperature and air velocity at different heights for Room A and B.

During the physical measurements people were asked to fill subjective questionnaire about the comfort sensation, in terms of thermal quality, air quality, light, noise and about the symptoms perceived in the room. People were furthermore asked to give information about the clothes that they were wearing, the position of their desk in the room, sex, age, height and weight. With the collected data and with the physical measurements, it was possible to calculate the PMV and the PPD indexes in the rooms. Results from calculations and from questionnaires can be summarized in the synthetic graph of figure 9.

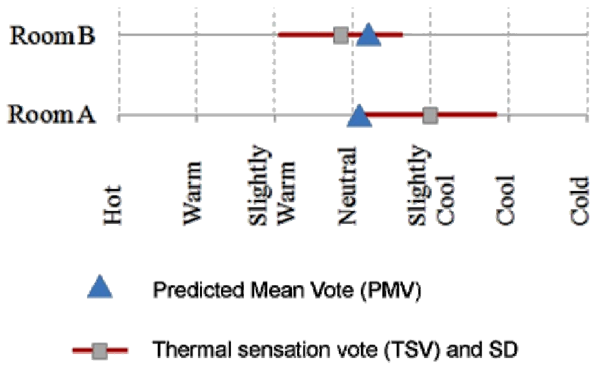

Figure 9. Predicted Mean Vote (PMV) vs Thermal Sensation Vote (TSV).

From the graph emerge that the calculated PMV is close to the value 0 (Neutrality) in both cases (A and B), but while in the naturally ventilated room (B) the TSV almost coincide with the PMV, in the mechanically ventilated room (A) people were averagely perceived the environment slightly cool. From the entire analysis (Annexes 9.1-9.1.1-9.1.2) has emerged how occupants that work in mechanically ventilated offices have bigger expectations in terms of thermal environment than people that work in naturally ventilated offices. However the TSV depends by a combination of factors, including the expectations of the indoor environment deriving by previous experiences. For this reason eventual differences between TSV and PMV values can be furthermore justify by the difference of outdoor temperature during the spot monitoring days compared to the outside average temperatures of the previous days.

3. Comfort categories and Energy consumptions

In the previous chapter classification of the indoor environment has been described, and comfort categories indicated by the comfort Standards has been explained too. The missing information of the previous analysis is that maintaining suitable indoor climate conditions is a real need for the occupants' well-being, and require strictly thermal comfort conditions and high levels of indoor air quality in buildings represents an high expense of energy, with consequences in terms of environmental impact and costs. Indoor Climate Quality, considering both thermal and indoor air quality, has in fact a primary impact not only on the perceived human comfort, but also on the building energy consumption. Due to its direct correlation with operating energy consumptions, in the recent years, the topic of the level of IEQ in buildings has become more and more important [30].

This issue is clearly expressed by the European Energy Performance of Buildings Directive 2002/92/EC [2], together with the most recent 2010/31/EU [31], which underlines that the level of indoor environmental quality required by occupants should be always clearly defined before expressing judgments about the building energy consumption, and both ratings should be shown together.

As already introduced, the comfort standard EN 15251 proposes different types of classification of the indoor environment. These types of classification are based on criteria used for energy calculations, whole year computer simulations of the indoor environment and energy performance, long-term measurement and subjective responses from occupants. In particular among these points, some refer to possible actions to do in case of new building, while others refer to existing buildings.

Thank to the analysis of two different case studies, the first conducted by using a simulation model (with Energy Plus simulation tool), while the second monitoring environment and energy parameters in an existing building, it is possible to answer at some questions about the existing correlation among Comfort and Energy consumption, like:

- What is the effect in terms of energy consumption of a variation of recommended indoor temperature ranges and air change rates as it is expressed in EN 15251 Standard?
- How to assess, in practice, thermal comfort and total energy consumptions in existing building?
- Which level of detail needs to be achieved in the analysis?
- How to elaborate and represent the results?
- Is it possible to use a single tool for describing the total (energy and environment) performance of a building?

3.1 . Comfort categories variation and effect on the energy demand

In mechanically controlled buildings, the desired level of indoor climate comfort, from which derive the control strategies adopted for the HVAC systems, is the main responsible of indoor environmental quality, energy consumptions and environmental costs. [30,32]. Relaxing the IEQ requirements, widen for example the variation of temperature ranges and ventilation air flow rates (moving from Category I to Category III, but maintaining acceptable thermal comfort the IAQ level), both the environmental impact and the energy cost can potentially be reduced. To ascertain the consistency of what has just been claimed, a case study consisting in a typical mechanically controlled office room (reference room for validation tests of EN 15265 [10]) has been used (Fig.10). Characteristics about envelope and adopted systems are explained in Paper II. The room has been analyzed for different external surfaces solar and external exposure (Case A, Case B).

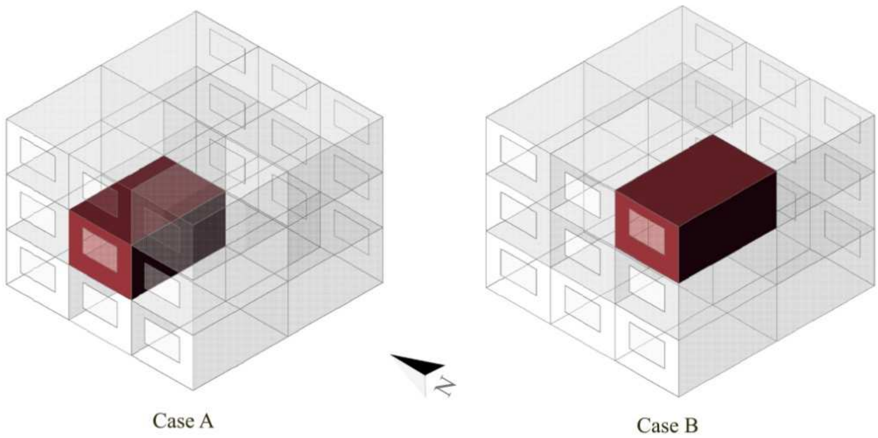

Figure 10. Analysed rooms in the case study building.

In the study heating and cooling energy consumptions related to the different thermal and indoor air quality categories were calculated by means of energy dynamic simulations and compared in terms of both heating/cooling (delivered) energy and primary energy requirements. To select the indoor environment requirements, thermal comfort and ventilation categories from I to III suggested by the standard EN 15251 were adopted. Besides evaluating the change in energy demand due to variation of the systems control, the same ratings have been carried out also varying the outdoor climate conditions, in order to determine which factors are more influencing in the energy demand determination. Results about the simulations performed for the city of Turin are shown in Table 4.

Table 4: Primary Energy for space heating and space cooling for different comfort categories (operative temperatures and ventilation rates) – Case A, Turin.

Comfort category	Ventilation rate (L/(s·m²))	Operative temperature (℃)	Heating (kWh/m²)			Cooling (kWh/m²)		
			Comfort category			Comfort category		
			III	II	I	III	II	I
			19–25	20–24	21–23	22–27	23–26	23.5–25.5
III	0.8		16.06	17.06	18.10	21.59	23.39	24.34
		Difference	Ref.	6%	13%	ref	8%	13%
II	1.4		19.20	21.74	24.63	19.56	21.82	22.58
		Difference	20%	35%	53%	–9%	–1%	5%
I	2.0		28.58	32.95	37.78	18.01	20.64	21.99
		Difference	78%	105%	135%	–17%	–4%	2%

During the heating season the primary energy increased more at the ventilation rate increasing than at the temperature category variation. In both cases the energy demand raised passing from category III to category I. Different it was for the cooling, where the energy costs rose for an increase of the operative temperature, but fall for an increase of the ventilation rates. This is because, for the Turin climate, where the outside air temperature is often below the internal air temperature, an increase in the natural ventilation flow rates in summer allows a free cooling of the indoor environment. During the heating season, however, the outside temperature was always lower than the preferred temperature; here the increasing in the ventilation rates lowered the indoor temperature, thus required the mechanical heating.

Simulations were performed in three different European cities, characterised by significantly different wheatear condition along the year: Moscow, Turin and Athens. Envelope thermophyisical properties changed according with the climatic zone (see Paper II). Due to cold winter weather conditions, the simulations for Moscow were performed both without and with a ventilation air heat recovery, which was characterized by a mean seasonal efficiency of 75%. In figure 11 main results obtained for the three cities are compared. Primary energy for heating is put in relation with primary energy for cooling: in the first case ventilation rate was set to category II and operative temperature was varying, while in the second case was the operative temperature was fixed to category II and the ventilation rate changed of category.

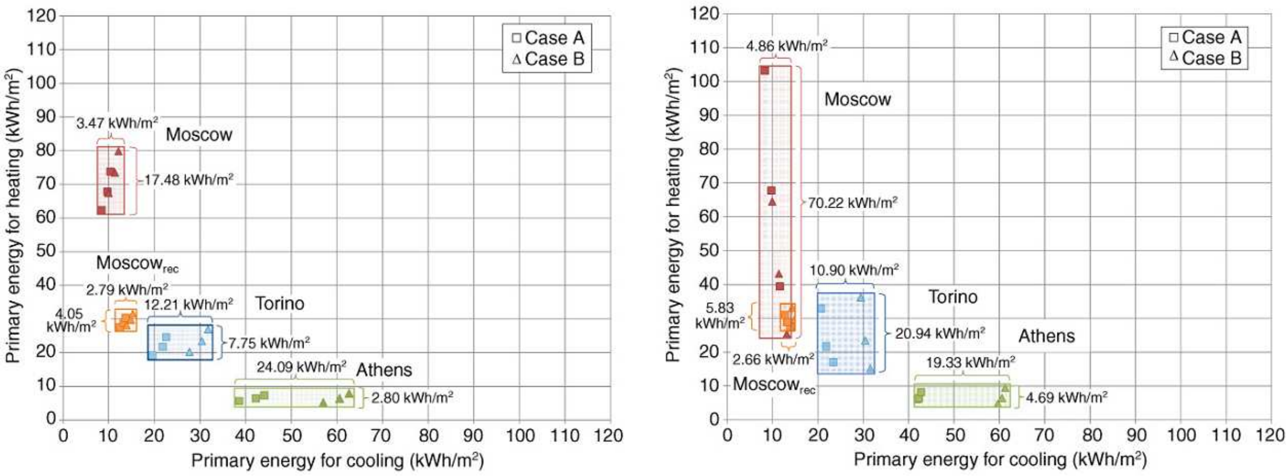

Figure 11. Primary energy for heating vs. primary energy for cooling at the variation of the operative temperature category (ventilation rate category set to II) (left), and at the variation of the ventilation rate category (operative temperature category set to II) (right). Cases A and B, for Athens, Turin and Moscow.

From the elaborations it resulted that primary energy demand for cooling in Athens was much higher than the primary energy demand for heating, and independent by the operating temperature categories. Contrarily was for the city of Moscow without heat recovery. In the case of Turin, both primary energy demand for heating and cooling had a significant contribution. The variation of the ventilation rate category had a considerable effect on the energy demand increasing, especially in the city of Moscow. Data show therefore that in cold climates, a change in the ventilation rate category affects the heating energy demand much more than a change in the operative temperature category.

Primary energy was also plotted as a function of the cooling and heating degree days (determined from the IEWC weather file statistics). From figure 12, where results are illustrated, emerge than the slope of an hypothetical tendency curve was higher in the cooling mode than the one of the heating mode. This also points out the fact that for an increase of degree-days, more primary energy must be consumed for cooling than for heating purposes. In order to compare homogeneous results, the case of Moscow with heat recovery is not considered in this graph.

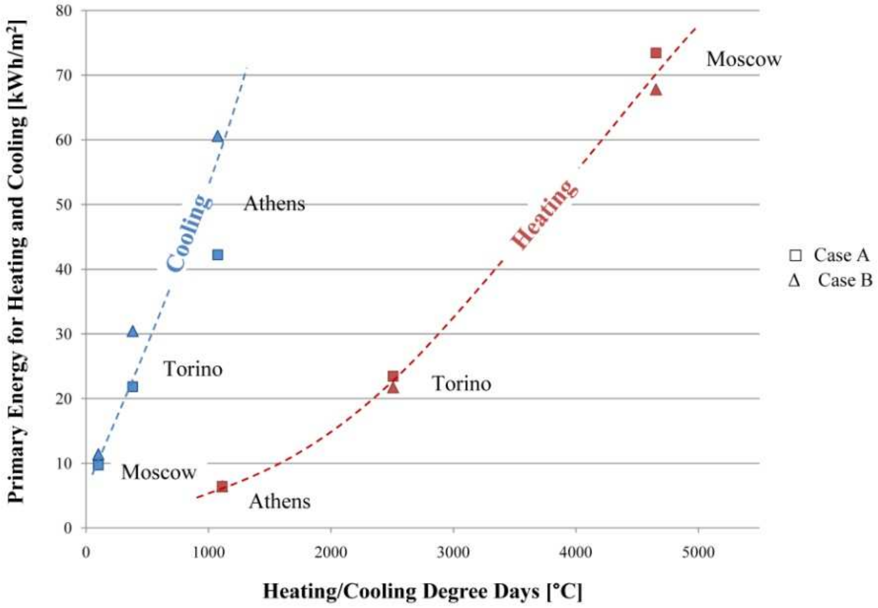

Figure 12. Primary energy for heating/cooling as a function of the heating/cooling degree days for operative temperature category II and ventilation rate category II.

It can be said, in general, that in cold climate, the energy requirements for heating are prevalent and the influence of expected indoor air quality level prevails on primary energy demand: due to this reason, it is always desirable the thermal recovery from ventilation air. With reference to this aspect, in the analyzed locations, the range of variation of the primary energy demand for heating can go up to 70 kWh/m^2 for a variation in the ventilation rates in the coldest climate without heat recovery, while the same quantity varies only of about 17 kWh/m^2 for a variation in the operative temperatures; in the warmest climate, both the variation are negligible and equal to 2-3 kWh/m^2. On the other hands, in hot climate the energy requirements for cooling are prevalent and the influence of expected indoor thermal quality level prevails on primary energy demand. With reference to the this aspect, in all the analyzed locations, the range of variation of the primary energy demand for cooling due to a change in the ventilation rates is similar to the one due to a change in the operative temperatures and is equal to 19-24 kWh/m^2 for the warmest location, while it decreases to around 5 kWh/m^2 for the coldest location. More detailed and extensive calculations that confirm these claims are available on Paper II.

These aspects should be taken carefully into account when designing and operating an HVAC system in each one of those climates: in fact, the developed study highlights significant influences of the ICQ selected categories on the building energy demand. In cold climates, for example, the energy requirements for heating are prevalent and the influence of expected indoor air quality level prevails on primary energy demand. Due to this reason, in cold climate it is always desirable to use a thermal recovery in order to save energy. In these cases the increasing of ventilation rates determine a important increasing also in terms of energy demand. On the other hands in hot climates are prevalent the energy requirements for cooling, and the ventilation rates does not affect so much the energy demand as in the cold climates case.

3.2 Assessment of climate quality and total energy consumption in existing buildings.

In existing building thermal comfort and energy demand can be assess through energy simulations or field measurements. This second option includes several activities that need to be developed in order to collect enough data for to make an exhaustive and correct evaluation. Useful data for elaborations need to be collected through dedicated instruments. The quality of the monitoring also depends by the precision and by the accuracy of the sensors, further the proper installation of them. Measured data can be collected by simple data-loggers, and then sporadically downloaded, or can be transmitted by a wireless system to a gateway. In this case information are sent to a server platform, that can provide automatically at the data elaboration. Right collocation of the sensors has a key role in the building thermal and energy evaluation. Two different monitoring plans need to be developed: one for the environmental variables collection, and another one for the energy consumptions accounting. In order to define the building monitoring plans, architectural spaces, intended uses, plant systems characteristics, terminal devices, control strategies, number of occupants in the rooms, etc. need to be known. Site surveys, technical drawings and historical data about environmental quality and energy consumptions, from previous measurements or from billets, should be known too [33].

Energy and environment monitoring can be planned for collecting data in continuous for longer or shorter periods of time, but it is convenient to plan measurements for at least one year. Just in this way a complete building and system behaviors during summer and winter seasons, and during the free running time can be performed.

Climate quality and energy monitoring plans can be developed starting from schematic diagrams. For describing the energy use of a building, for example, the diagram can be developed according to the approach proposed by the standard EN 15603:2008 [34], and subsequently revised and integrated in the system boundary for net delivered energy scheme introduced by [35,36] and adopted by REHVA task force "Nearly Zero Energy Buildings" (nZEB) [37,38]. That diagram is a schematic drawing in which energy carriers are illustrated and where all energy uses of a building, or part of its, can be taken into account. General representation of these diagrams, related to the comfort and energy carriers, are respectively showed in figures 13 and 14.

In this thesis, starting from simple diagrams, several steps have been done:

- Different levels of detail have been insert in the climate quality and energy analyses
- For each level of detail, and for different periods of time, different kind of data elaborations and result representation are proposed, both for climate quality and for energy analyses
- A new representation method, which include climate quality and energy analyses results, is proposed too.

3.2.1 Levels of detail in the analysis

Both total energy use and comfort quality can be expressed with different levels of detail, in terms of kind and grade of information, deepening the analysis from the entire building to the single rooms. Energy evaluation, for example, can be addressed for four different levels of detail, while only three levels can be enough for the comfort analysis.

The four proposed levels of detail for the total energy assessment, as indicated in figure 13, are:

- *Level 1: Delivered primary energy* – It indicates the total primary energy delivered to the building, at the net of the exported energy (if presents), obtained by multiplying the delivered energy (Level 2) by a primary energy factor that takes into account the extraction of the energy carrier, its transport to the utilization site, as well as for processing, storage, generation, transmission, distribution and delivery [39].
- *Level 2: Delivered energy* – It is the energy needed from a building for heating, cooling, ventilation, domestic hot water, lighting and appliances. Represents the energy delivered to the building (electricity, fuel, district heating, etc.), but also the renewable energy produced on site (solar energy, geothermal energy, etc.).
- *Level 3: Net energy needed by the technical systems* – It represents the thermal or electrical energy required by the building technical systems (heating system, cooling system, ventilation system, etc.). This energy is from the delivered energy to the building or from on site renewable energy (Level 2).
- *Level 4: Space net energy needed* – It is the net energy required for a single room or zone of the building. It is the energy supplied by the technical systems (Level 3) to the rooms' terminal devices (radiant systems, radiators, convectors, diffusers of the ventilation systems, lighting equipments, appliances, etc.).

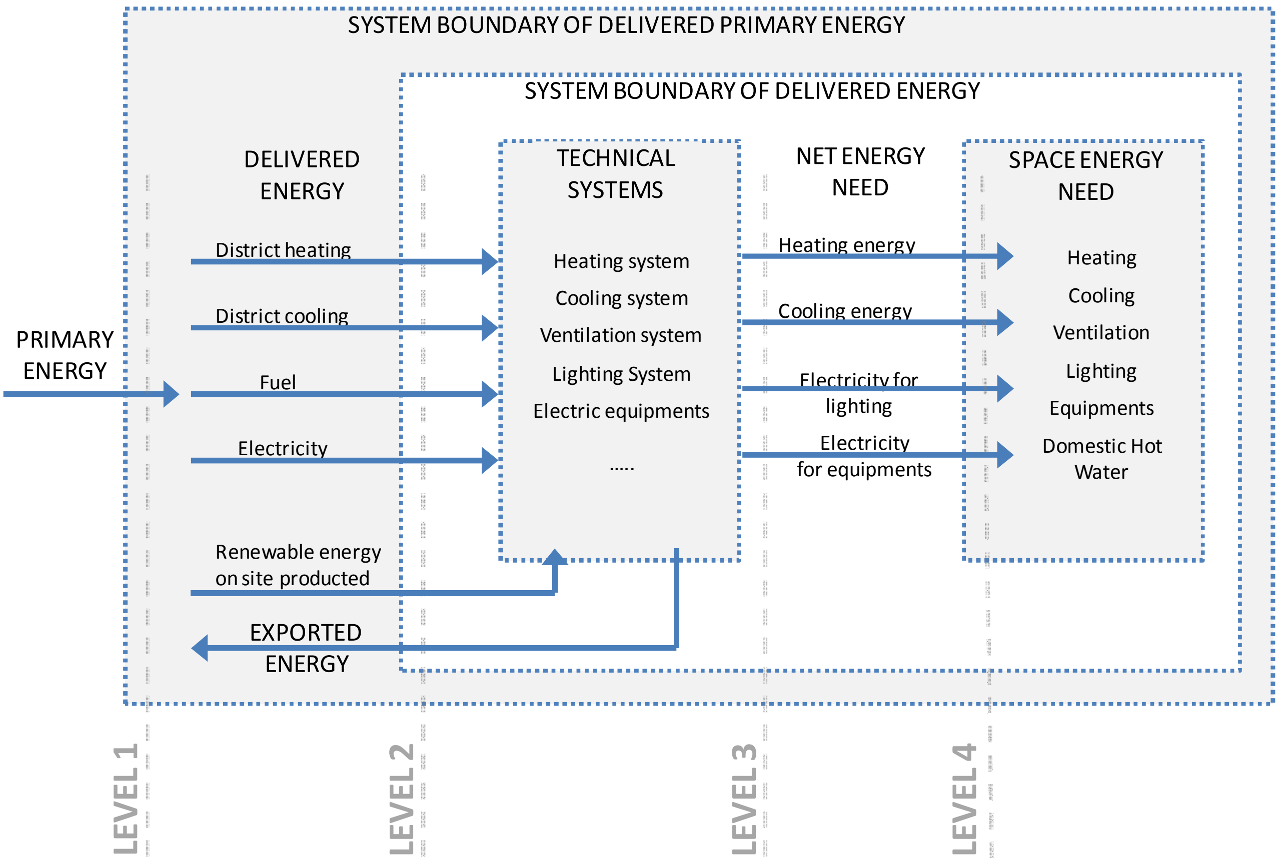

Figure 13. Energy flow scheme and levels of detail in the analysis of building total energy use.

The three proposed levels of detail for the climate quality assessment, as indicated in figure 14, are:

- *Level 1: Whole building indoor climate analysis* – It describes the indoor climate quality of an entire building considering, in a single evaluation, the performance of different thermal zones and of all the single rooms of which the building is composed.
- *Level 2: Single indoor climate zone evaluation* – It is the ICQ evaluation related to a group of rooms characterized by similar kind of installed systems, exposure and intended use. In these rooms the environmental parameters are almost the same, and in the comfort analysis a single room can be representative of the entire thermal zone.
- *Level 3: Indoor climate quality evaluation in specific rooms* – Represents the ICQ assessment in a specific room, in which particular environmental conditions need to be respected.

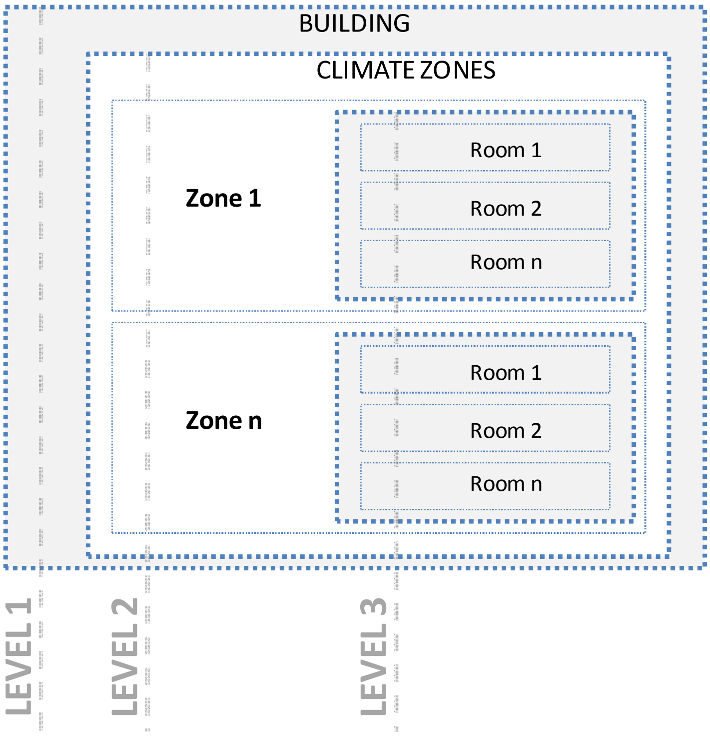

Figure 14. Levels of detail in the analysis of indoor climate quality.

Aimed to demonstrate the applicability of the proposed schemes, the same building already used in the case study of Chapter 3 is object of this analysis too. Information about the building can be found in Paper I and Paper III.

Energy carriers of the building are shown in diagram of figure 15. Based on the general representation aforementioned, the four levels of detail have been identified:

- Level 1: delivered primary energy to the building
- Level 2: delivered energy to the building (electricity and district heating)
- Level 3: energy needed by the main technical systems; 3a) energy needed by the single divisions of the technical systems.
- Level 4: energy needed by a single zone (a 268 m^2 office room, in this specific case study).

In the example of figure 15, further information are given: also the measurement points, defined during the design phase of the monitoring plan, are indicated by red dots. These points are distributed for the different levels of detail and they indicate where the energy carrier is monitored and consequently assumed for the building energy evaluation.

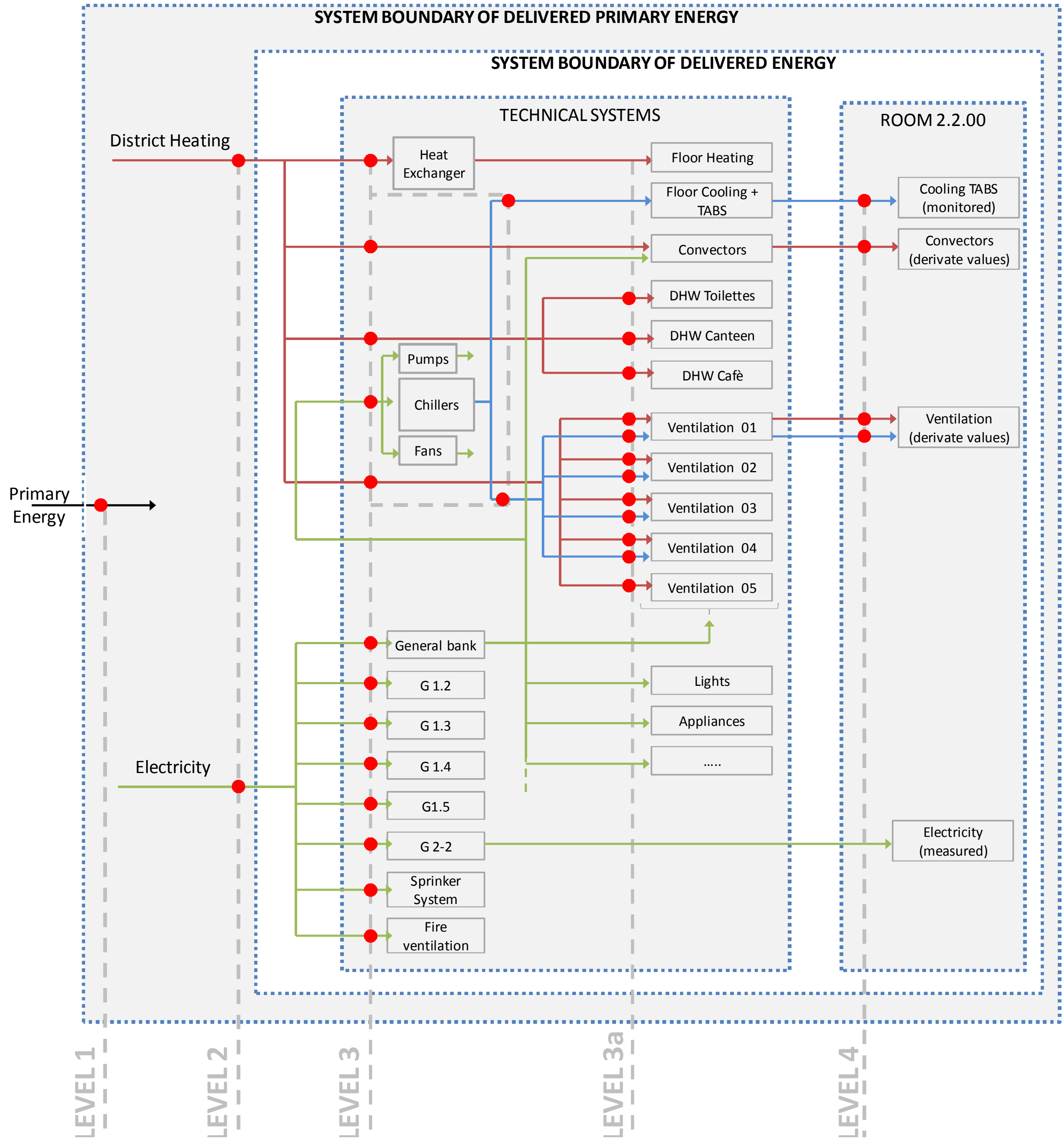

Figure 15. Building systems energy flow scheme, with evidence of the monitoring points, and of the levels of detail in the analysis. In the diagram different kind of energy flows are indicated with different colors: black - primary energy, red - thermal energy for heating, blue - thermal energy for cooling, green - electricity.

Indoor climate quality in the building can be represented according to the proposed method too, by dividing the building in different thermal zones and drawing a diagram on the basis of the one described in figure 14. The indoor climate zones are characterized by the kind of installed systems, the exposure and the intended use. In the case study, in each selected and representative room, indoor climate parameters were collected. Air temperature, operative temperature, CO_2 concentration and air relative humidity were monitored. Through these parameters indoor climate quality analysis could be performed for each single room, for each single thermal zone or for the entire building. Figure 16 shows the diagram for the indoor climate quality evaluation in which monitored rooms are grouped in indoor climate zones. Also in this case, points of evaluation are highlighted and distributed among the three levels of detail.

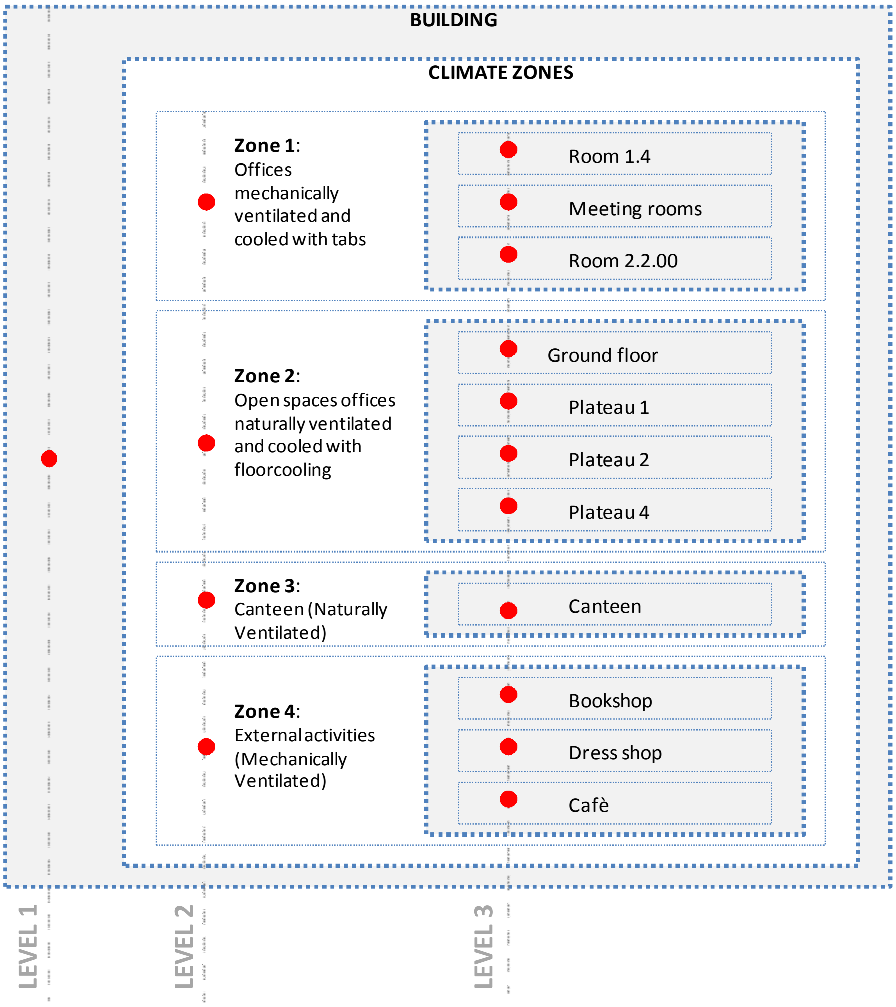

Figure 16. Diagram for the ICQ evaluation, with evidence of the evaluated spaces and of the levels of detail.

3.2.2 Data elaboration and representation

Energy consumptions and indoor climate quality can both be assessed for long or short time. Collected data from on site monitoring can be processed for different periods of time, like years or seasons, otherwise it can be useful to focus on specific range of time, like months, weeks or days. Independently by the length of these intervals, analysis can be performed for all the levels of detail listed in the previous paragraph, allowing to evaluate the performance of the entire building, of an indoor climate zone, or of a single space.

Energy and comfort data elaboration and representation, though following a similar approach, present differences according with the output and the information to achieving from the monitoring. In order to better explain the approaches, it is appropriate to face separately energy and ICQ evaluations.

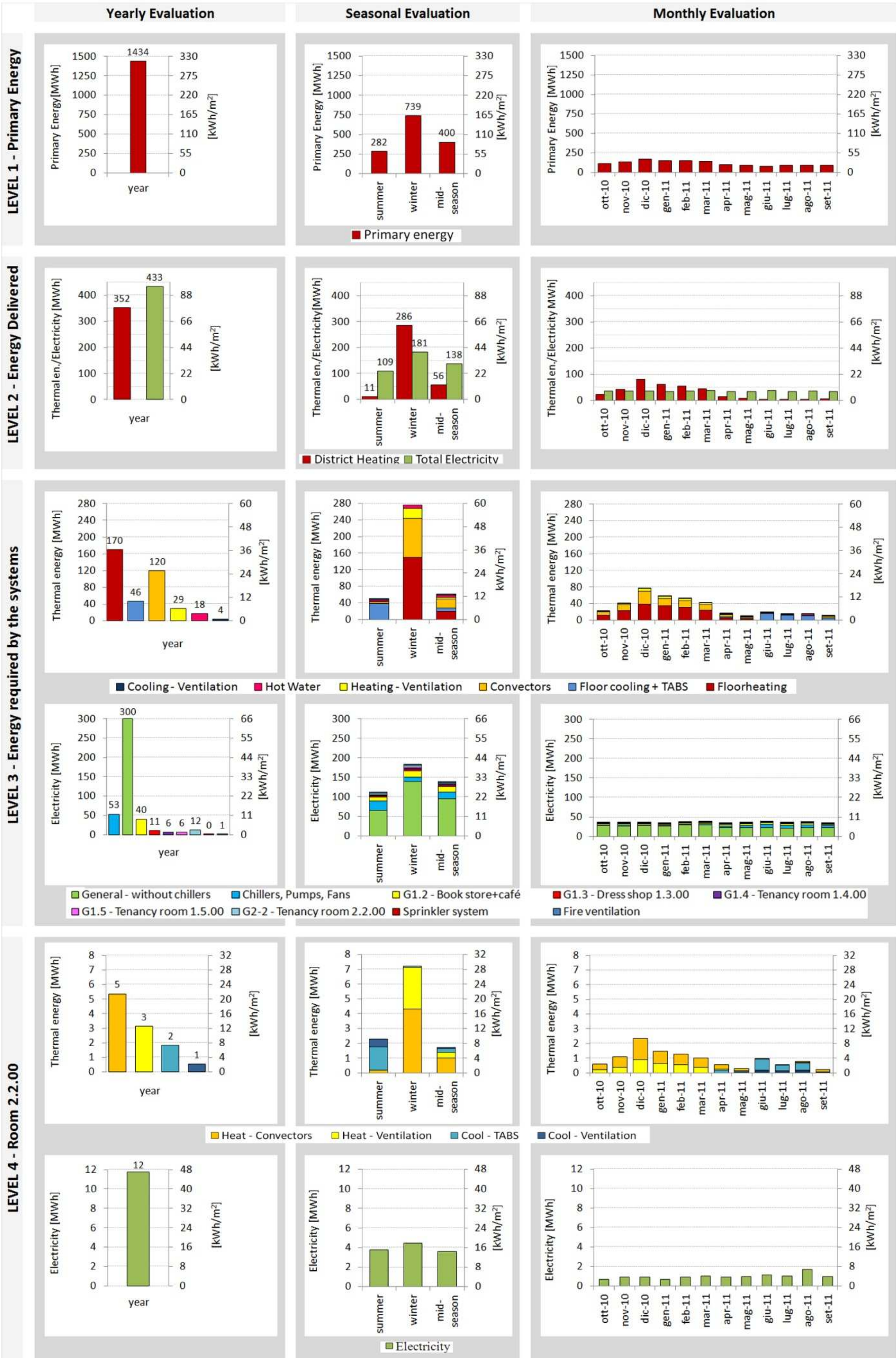

Figure 17. Building energy evaluation for different levels of detail and for different periods of time.

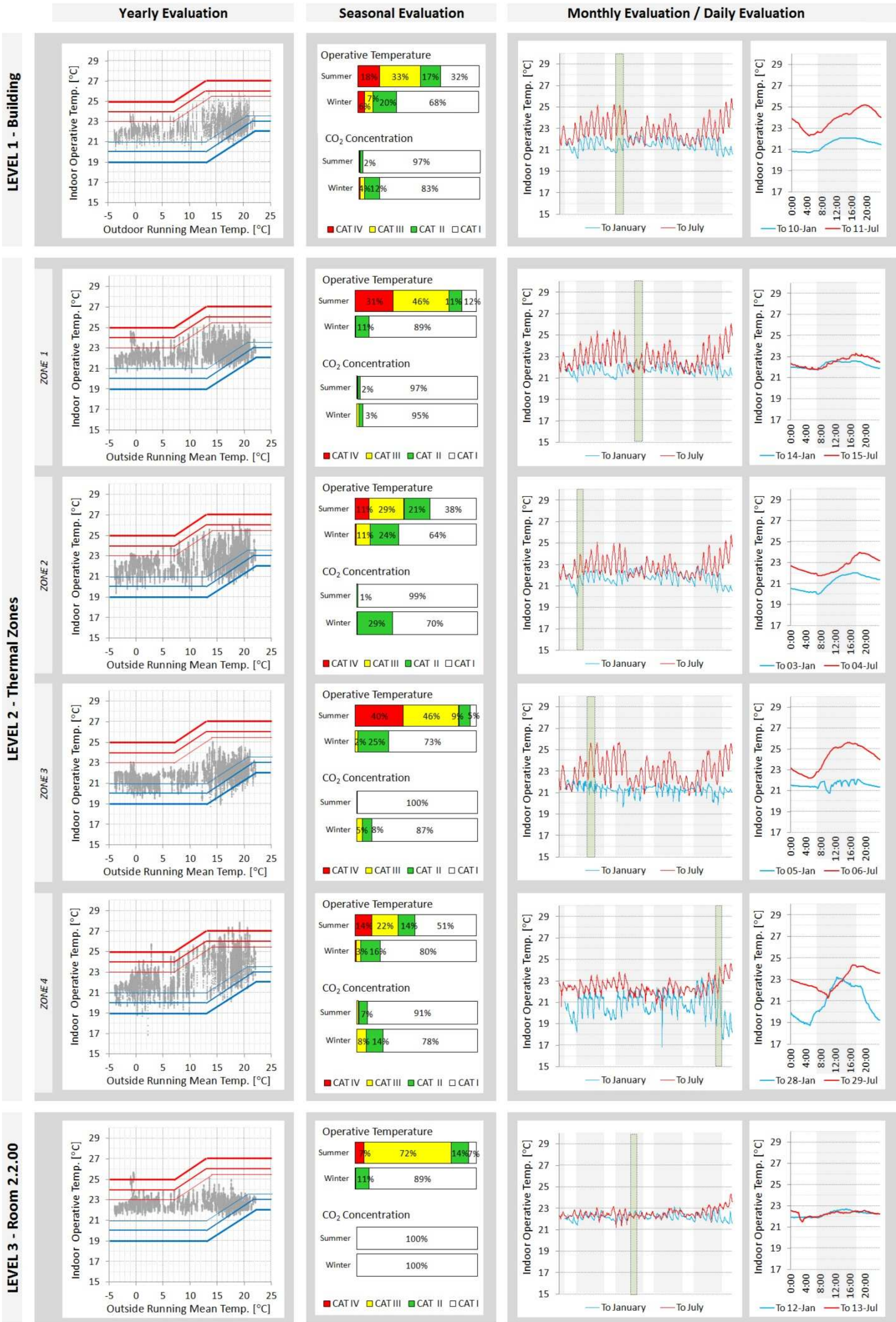

Figure 18. Building climate quality evaluation for different levels of detail and for different periods of time.

Representing elaborations through histograms allow to illustrate the energy consumption distribution, during the monitored time, expressed in terms of absolute consumption (MWh) and specific consumption (kWh/m^2), referring at the floor surfaces area. While the yearly evaluation indicates the total amount of energy required by the entire building, or part of it according with the detail of the analysis, the seasonal distribution splits the same value between winter, summer, and mid-season. From the example of figure 17, in which data from the previously case study are presented, it is interesting to note that during the mid-season the energy consumptions were higher than during the cooling season. For this reason is preferable to don't limit the seasonal energy evaluation at the heating and cooling time.

At Level 1 the energy performance of a building can be expressed through a single value, i.e. the Primary Energy (PE). PE is calculated by multiplying the delivered energy by the primary energy conversion factors. Standard EN 15603:2008 [34] indicates, in the Annex E, the European primary energy factors for renewable or not renewable delivered energy. Primary energy factors, to use in case of lack of more accurate values, are however always determined at national level by national standards. The second level of detail allows to separate the delivered energies carriers that provide heating, cooling, ventilation, lighting and domestic hot water in the building. In the case study, for example, the two delivered energies were district heating and electricity. In level 3, first of all, the delivered energies are separated distinguishing thermal energy from electricity. Then, energy required by the single system, or part of its, is spelled out. In figure 17 shows, the graphs related to the thermal energy show the amount of it used for heat and cool the building, respectively through floor heating, convectors and ventilation systems in the first case, and through floor cooling and TABS, and ventilation system in the second case; moreover it shows the domestic hot water energy consumption. In the graph related to the electricity, consumptions about different section of the system are shown. Finally, the last level of detail, Level 4, investigates on the energy consumption of a single room. In this analysis, since can happen that not all the energy flows are monitored, in some cases the energy consumptions should be estimated according with the floor surface, or the volume, served by the specific system.

A more detailed analysis of the results obtained in the energy evaluation of the case study building is reported in Paper III.

Differently from the energy evaluation, in which has been chosen to express results through histograms, in the indoor climate quality assessment, for diverse periods of analysis (year, months, etc.), the suggestion is to represent elaborated data with different meanings.

In the yearly evaluation, monitored operative temperature can be put in relation with the outdoor running mean temperature. Thermal comfort ranges for an entire year can be defined crossing the categories suggested by the standard EN 15251 [4] for the adaptive model (annex A.2 – "Acceptable indoor temperatures for design of buildings without mechanical cooling systems"), at which to refer for the mid-season period, with the categories suggested by the same standard for the mechanically controlled buildings (annex A.3 – "Recommended indoor temperatures for energy calculations"). Through this analysis it is possible to evaluate if the monitored operative temperature respects the limits prescript by the standard, giving an overall evaluation of the thermal comfort in the building in relation to the boundary conditions. Seasonal evaluation can be performed according with standard EN 15251 too, referring to the annex A.3 for the comfort ranges, but assessing the environment as complying with annex F ("Long term evaluation of the general thermal comfort conditions"), method A, "Percentage outside the range". The last evaluation, indicated as monthly/daily evaluation, is a focus referring to a specific period of time. Purpose of this deepening, performed developing operative temperature profiles during the 24 hours, is the building thermal behaviour gauging in extreme boundary conditions. An additional focus, on particular days or weeks, it helps in the building-plant system proper operation auditing, underlining, if there are any, problems to be solved. In figure 9, for example, referring again to the same case study building, profiles of operative temperature about two months, one representative of the winter time and the other one of the summer period, are shown. For each month, then, daily profiles are analysed too. With the same criteria, different intervals of time could be examined (for instance weeks).

Levels of detail in the indoor climate quality evaluation are those indicated from figure 16. Analyses can therefore be performed for the entire building, for the selected indoor climate zones, and for the single rooms. In Figure 18, for example, the evaluation is shown for the four identified climate zones at Level 2 and for the same room already regarded in the energy evaluation (room 2.2.00) at Level 3. Assessment of indoor climate in the entire building (Level 1) gives an average evaluation of several rooms, that can be characterized by different heating/cooling and ventilation systems, different intended use and solar exposure. For that reason specific thermal dynamics of the building are difficult to understand at this level. At Level 2 important remarks can be done. Different microclimate conditions among the zones can emerge. In the example comparison between Climate zone 1 and 2, allows understanding how much the natural ventilation influence the indoor operative temperature profiles. On the other hand comparing Climate zone 4 and 1, though mechanical systems is the same for both the zones, temperature distribution is very different due to the different intended use: in the commercial activities, because of the frequent opening of the doors for the customers access, the number of air changes pour hour is really high. For this reason, in the yearly evaluation, climate zone 4 looks more dependent by the outdoor climate influence.

It is important to highlight that the yearly evaluation is based in part on the adaptive approach: for that reason results of the seasonal evaluation, based on the Fangers' method, could do not match with those represented in the graphs of the yearly evaluation.

3.2.3 Indoor climate quality VS Energy Consumption assessment

In the previous paragraphs energy and indoor climate quality in the building have been evaluated and represented separately one from each other. Rare are in literature the studies in which energy and indoor air quality of a building are compared, and correlation between them is parsed [40, 41], and only a few times both the evaluations are taken into account in the same building analysis [42-46]. Often procedures for comfort and energy performance of a building with different intended uses are dealt separately [47].

Aimed to put in relation indoor climate quality with the related energy consumptions, graphical representations of monitored parameters are investigated.

First issue to be solved is the research of a unit at which both energy and indoor air quality can be referred to. While different energy carriers (electricity, fuel, etc.) can be converted in primary energy or CO_2 emissions, for the individual indoor environmental factors is even not available any standardized method for estimation of a yearly performance value [48]. As early described in the previous paragraphs, also if does not exist a unique value for to describe indoor climate quality, for all the environmental parameters standards suggest specific ranges for the comfort classification. In order to use categories as yardstick for both energy and comfort evaluation, four intervals of energy consumption can be introduced. These intervals are:

- Category I - < 20 kWh/m^2y
- Category II - > 20, <40 kWh/m^2y
- Category III - > 40, <60 kWh/m^2y
- Category IV - > 60 kWh/m^2y

By means of a radar chart indoor climate and energy data can be represented separately or together on the same graph. Moreover, the same graphical support can be used for showing a seasonal and yearly performance of the building. In order to define a single indicator for to describe the belonging category of the environment object of the study, it has been determined that a building belongs to a certain category if for the 95% of the occupancy time the analysed parameters respect the limits indicated for a certain range.

The radar chart can moreover be used for representing the real values of the monitored data. While using categories it is possible to put in evidence a representative area of the best obtainable situation, i.e. when all the parameters respect category I, the same thing cannot be done when on the axis are indicated values (for example average values for the environmental parameters and total amount for the energy consumptions). In this case important information about the building behaviour can be expressed, but it is not immediately understandable which is the global performance of the building and which are the causes that led to certain conclusions.

In figure 19 examples of data from the case study building are illustrated in accordance with the explained approaches. The figure is divided in two parts: the upper part allows to describe the performance of a building through the use of categories, while the lower part shows the real measured values. The energy data are representative of the third level of analysis (indicated in figure 15), while the comfort parameters are related to the entire building (Level 1 of figure 16). Similar evaluations could be done for different climate zones and for single rooms.

From the example some considerations, extensively investigated in Paper III, can be mentioned. First of all differences in results among seasonal and yearly evaluation using categories depend by the fact that that the seasonal evaluation includes in the analysis only some months of the year. Then, the average values referred to the environmental parameters sometimes can seem good, if only dwelling on the single values, but comparing the results with the one ones obtained with the categories evaluation, outcomes could be no more acceptable. This can be explained by the fact that the average values do not point out that the variables fluctuate, being often greater or lower than the acceptable values. For these reasons a good description about the performance of a building could include these synthetic representation of the results, but just a more detailed analysis permit to better know the dynamics of the building at the boundary condition variation, allowing to make a diagnosis of the building too.

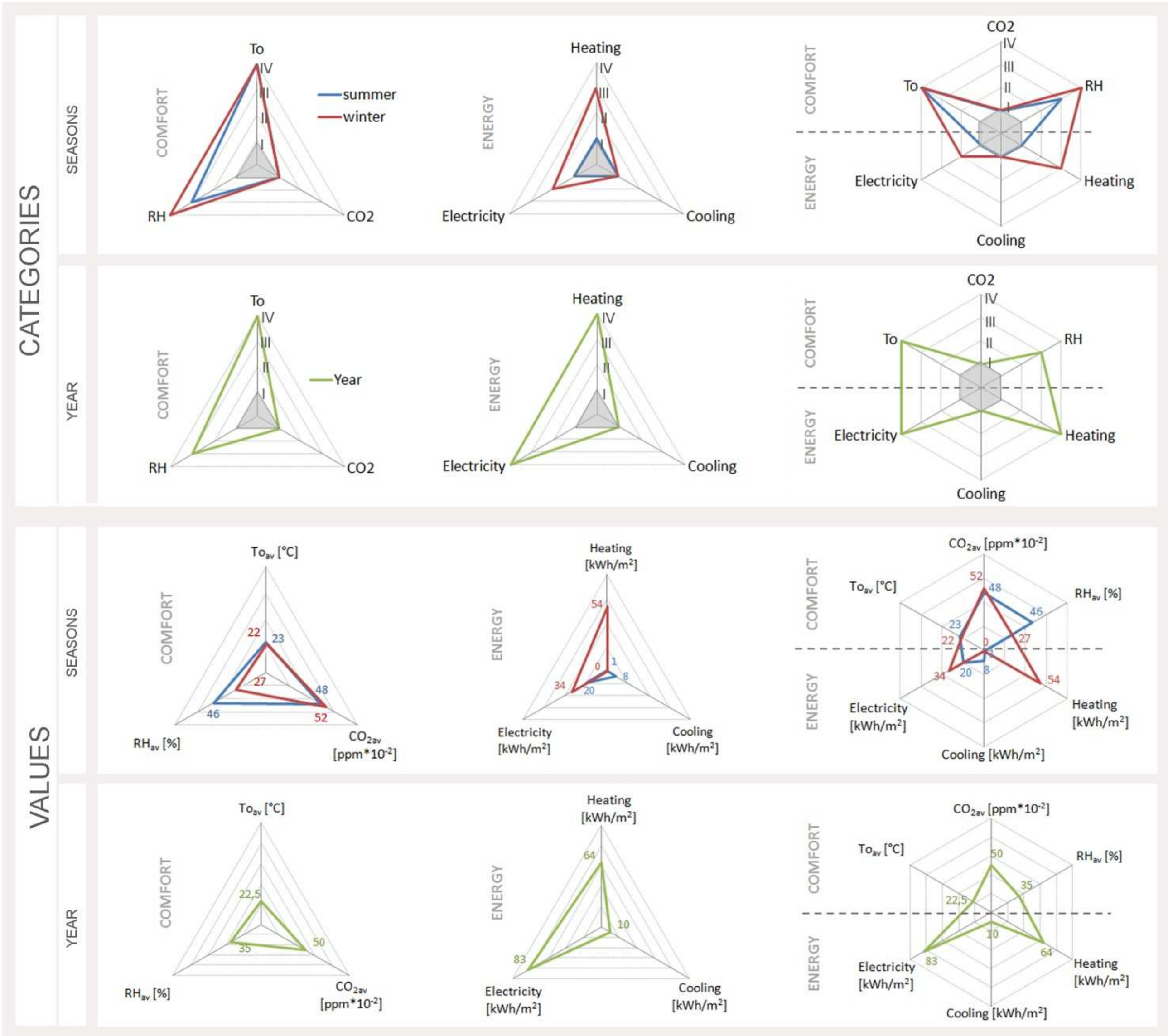

Figure 19. Seasonal/yearly ICQ and energy evaluation.

4. Performance of radiant systems, energy consumptions and thermal comfort evaluations

As it has been earlier pointed out, the simultaneous assessment of energy performances and indoor environmental quality in buildings is a topic of huge interest. Aimed to this attention, research on heating/cooling system that can provide high levels of thermal comfort in buildings, demanding a restricted quantity of energy, is increasing. In this context, radiant panels deserve particular attention because they exchange heat with the surroundings, both by radiation and by convection. In particular they exchange heat directly with occupants by radiation, and humans are mostly sensible to this kind of heat transfer: almost 60% of human body sensible heat transfer is through radiant heat exchange [49]. Furthermore radiant panels don't affect the acoustic quality of the environment and of the indoor air quality, because they generate low air and dust movement in the rooms. They can nevertheless be combined with ventilation systems to guarantee a complete control of latent load and IAQ in the indoor environment.

Several kinds of radiant system can be adopted in buildings. In the specific, according with the used energy carrier, they can be divided in hydronic, electrical or gas systems. They can then be arranged on ceilings, floors or walls.

In order to demonstrate properties and applicability of radiant systems, two different strategies are presented below. These mentioned systems are radiant electrical plates and thermal active building systems (TABS). Characteristics of the experiments are listed in table 5 and analyses are widely developed in Papers VI and V.

Table 5. Characteristics of the experiments of the two kinds of radiant systems.

	Radiant Electrical Plates	TABS (Thermal Active Building System)
Thermal control	High temperature heating	High temperature cooling
Inertia of the system	Low inertia	High inertia
Intended use	Residential	Office building
Tested environment	Test room	In field (existing building)
Measured parameters	Energy and comfort parameters	Energy and comfort parameters
Number of tested systems	3	1
Number of tests for each system	3	3
Test boundary conditions	Steady state condition	Not steady state conditions

Both the strategies have been tested through in field measurements and with the support of simulation tools, but the methodologies approached during the tests have been very different. In both cases the introduction of innovative instruments or methods of analysis in the experiments allowed to obtain original results.

First of all the two radiant systems were tested with different boundary conditions: while radiant plates experiments took place in a test room, with outside fixed and controlled air temperature, the TABS have been evaluated in a building during the system operating time. In this last case the boundary condition were not controlled, and in literature in field tests for evaluating the performance of TABS are not available: studies on this kind of hydronic system are usually carried out only through the use of dynamic simulations.

Then while radiant plates are thought to be used for heat single family houses in winter, TABS found applications in multi-storey buildings for removing cooling loads during the summer period.

Innovative contributions and results of the performed experiments are shown in the next paragraphs.

4.1 Radiant Electrical Plates

Electrical systems application in dwellings is not as common as it is for the hydronic systems, because the use of electricity for the heating purpose could cause energy wasting and, in many countries, it could also be the cause of extremely high heating costs for the users. Nevertheless in new low-energy houses heating is required few days or hours per year, and when it is required the system must react quickly to the thermal demand, to reinstate the proper thermal conditions [50-53]. Due to the very little amount of heating energy required by these low-energy houses, the use of cheap electrical systems could be suitable, and to balance the energy required by the system photovoltaic panels may be integrated. Radiant plates can be easily mounted on a wall when the building is already finished and can be shaped following many different styles. They have a reduced exchanged area and thus they must reach higher temperature if compared with electrical floor or ceiling panels [54], the maximum radiant asymmetries due to warm surfaces have to respect the prescriptions fixed by thermal comfort standards.

4.1.1 Test facilities and experimental apparatus

The test facility arranged to experimentally characterize the radiant electrical plates, of which characteristics are listed in Paper IV, was made up of an insulated chamber (3.57 m x 3.49 m x 2.55 m). The air temperature of the environment around the test chamber could be controlled by means of an air-conditioning system, in order to simulate different heat loss conditions.

The characterization of the radiant plates under test required several quantities to be measured, which are summarized below and explained in Paper IV:

- air and wall temperatures inside the chamber;
- plate surface temperature and corresponding heat flux;
- temperature and relative humidity outside the chamber;
- electric energy consumption (of the plates).

Microclimatic station was also used in the test room during experiments to measure air velocity and difference of radiant temperature between the walls. The aim of these measurements was to verify the absence of local discomfort.

The innovation in these tests is in particular represented by the technologies developed for to assess the experiments. In particular, the sensors used from measure the surfaces temperatures and the air temperature in the center of the test room, presents an innovative technology. Measuring nodes, each one embedding three thermocouples T-type, were in fact studied and here applied. Each node could communicate through a wireless system to a base station, sending measured data that could in this way be logged. Moreover, the realization cost of each node was really little (about 10 Euros). Further information are given in Paper IV.

During the study three different electrical plates with different dimensions and controls have been analyzed:

1 - white metal surface (1.55 m x 0.44 m)
2 - white metal surface whit forced ventilation (1.50 m x 0.53 m)
3 - white perforated surface (0.82 m x 0.54 m)

In figure 20 architecture of the test room, position of the probes for air and surface temperature measurements and position of the radiant plates on a wall are illustrated.

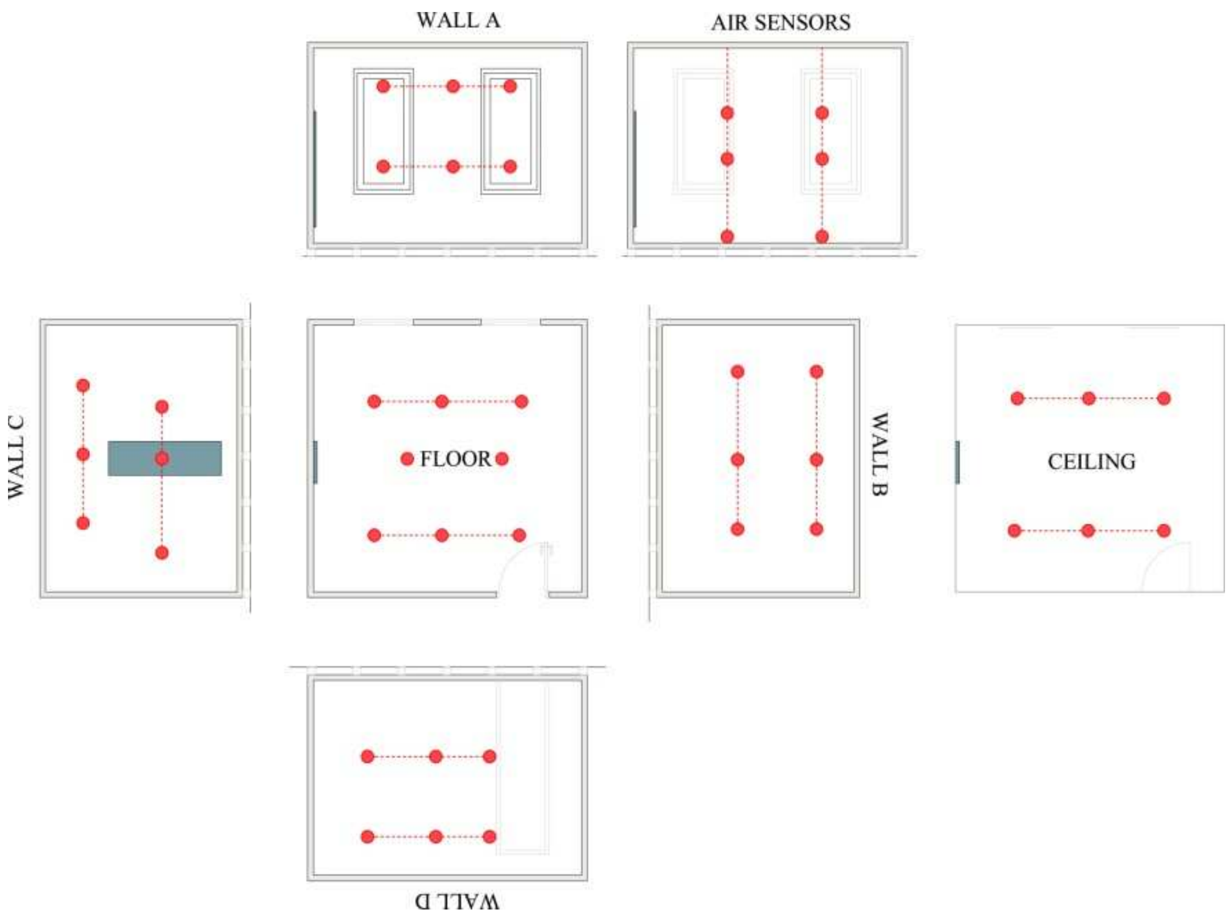

Figure 20. Test room architecture and air and surface temperature sensors position.

4.1.2 Methods

The objective of the measurements was to evaluate the thermal power output of the radiant plates as function of the temperature difference between the plates surface and the room reference temperature. In fact a good performance of the heating equipment can be assumed only when the temperature of the plate surface is not too high, in order to do not create local thermal discomfort to the occupants. Three different test conditions were carried out for each plates: high heat loss, moderate heat loss, low heat loss. All the test were preformed under steady state conditions. The thermal power output was derived from the plate electrical energy consumptions during the test time and it was checked with values obtained by means of heat flux meters. The power output of the electrical plate was finally evaluated by mean of a characteristic equation, as in the case of common radiators, based on the experimental data:

$$\Phi = K_M \cdot \Delta T^n \quad [W]$$

where K_M and n are constant for the plate.

Comfort simulations were conducted with the software Hypercomfort®, an hypertextual tool for the evaluation of the thermal, visual, acoustic and olfactory comfort, developed by the Energey Department of Politecnico di Torino. Top, PMV and PPD were the output of the analysis. In accordance with previous researches [49, 55, 56] the operative temperature in the centre of the chamber at 110 cm above the floor level was considered as the reference temperature. The thermal comfort evaluations have been performed according to the ranges of categories indicated for the standard EN 15251 for residential intend use. The final objective was to assess how the three different plates could alter the thermal environment in which they appear, having analogous average thermal power end energy consumptions and time intervals of monitoring. More information about environmental condition and variables used for the PMV and PPD evaluation are expressed in Paper IV.

4.1.3 Results

Results of the activity demonstrate that all the plates could keep a good level of thermal comfort in the environment, in particular at distances higher than 1,5 m from the radiant surface. Moreover already at the distance of 0,50 m the temperature could be considered acceptable.

The monitored heat flux and the absorbed electricity demonstrate that the use of radiant plates is suitable in dwellings in which the heat losses are very low, as well as the energy demand for heating. With this aim further evaluation about the applicability of these systems in low-energy houses has been performed.

Part of results is presented below, through figure 21 and tables 6 and 7. More accurate outputs of the analysis are shown in Paper IV.

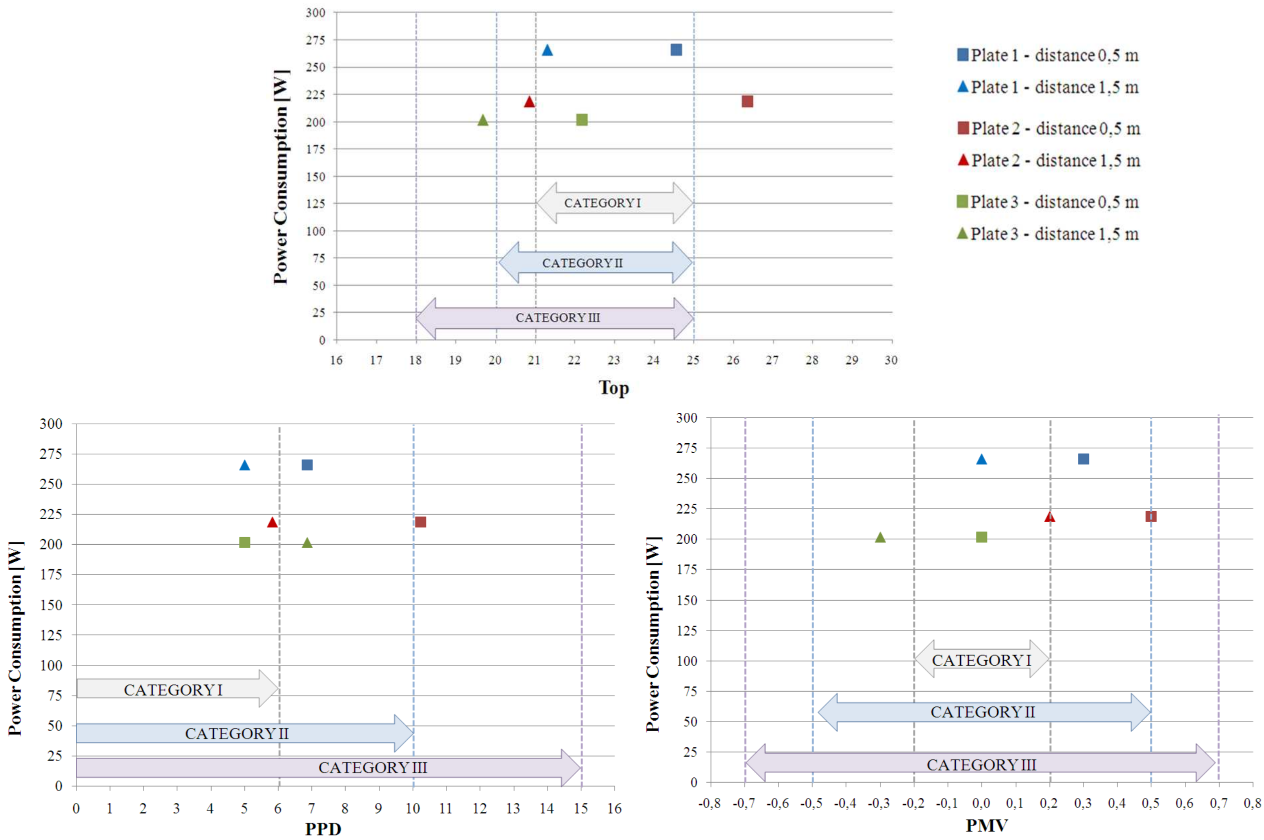

Figure 21. Top, PMV and PPD indexes at 0.5 m and at 1.5 m far from the plates.

Table 6. Thermal conditions during the tests and power output of the electrical plates.

		time [h]	E_{el} [kWh]	T_{out} [°C]	T_p [°C]	$T_{a,110}$ [°C]	T_{mr} [°C]	T_{op} [°C]	$\Delta T_{p\text{-}op}$ [°C]	Φ [W]	$Φ_1$ [W/m$^2_{pan}$]
Plate 1	Test 1	8	2.13	16	55.0	20.6	21.1	20.9	34.1	266	403
	Test 2	24	3.95	18	41.8	20.9	21.2	21.0	20.8	165	250
	Test 3	20.3	1.34	20	31.1	21.2	21.4	21.3	9.8	66	100
Plate 2	Test 1	69	20.05	18.3	57.5	21.2	21.9	21.5	36.0	291	366
	Test 2	19.97	4.37	16.6	49.0	21.9	22.2	22.0	27.0	219	275
	Test 3	14.77	0.27	16	69.7	22.0	23.2	22.6	47.1	18	23
Plate 3	Test 1	6.87	1.26	13.9	60.8	18.7	19.5	19.1	41.7	183	413
	Test 2	5.18	0.75	16.9	51.0	20.1	20.8	20.4	30.6	146	329
	Test 3	8.75	0.40	19.5	32.4	21.0	21.3	10.5	21.9	46	103

As previously enounced, the use of electrical radiant plates can be considered suitable only in houses with low-energy demand for heating. In order to demonstrate this fact, a case study of a single family house (122m^2) was introduced for to evaluate the possible use of the tested plates in low-energy houses at different latitudes and with suitable photovoltaic system to provide electrical energy.

Thermo-physic characteristic of the envelope have been changed in order to satisfy the building energy performance requirements of the Italian legislation for heating and domestic hot water, at different climatic areas in the North of Italy (Bolzano, Torino, Firenze). The climatic data used in the simulations derived from the weather data archive of the Italian Energy Agency (ENEA). An assumption of an efficiency of 13.7% of the photovoltaic modules have been made, which corresponds to polycrystalline silicon commercial modules. Results of the calculations are shown in table 7.

Table 7. Number of radiant plates (type: P1, P2, P3) required to heat the house, heating demand calculated for the standard house in order to fit the different energy levels and photovoltaic area required to balance the heating energy consumptions for the three Italian cities considered.

Heating demand		Required number of radiant plates (type: P1,			Required delivered energy for heating	Required photovoltaic area to balance heating requirements	
		P1	P2	P3	kWh/m^{2}y	m^2	kWp
Bolzano	Very low	8	4	4	10	9.3	1.3
	Low	12	6	6	24	23.1	3.3
	Standard	17	9	8	49	46.8	6.7
	Slightly high	26	14	13	82	78.1	11.2
Torino	Very low	7	4	3	12	10.7	1.7
	Low	9	5	4	24	21.5	3.1
	Standard	14	8	7	59	52.3	7.5
	Slightly high	19	11	9	77	68.9	9.8
Firenze	Very low	5	3	3	8	6.5	0.9
	Low	7	4	3	17	14.9	2.1
	Standard	11	6	6	48	41.3	5.9
	Slightly high	15	8	7	62	53.1	7.6

As confirmed by the results, the use of the tested electrical radiant plates can be considered suitable only in houses with low heating demand, where the number of elements is low and the area required for photovoltaic modules too.

4.2 TABS – Thermal Active Building System

Low temperature heating, called TABS (Thermo-Active Building System) [57], are characterized by embedded pipes in the structural concrete slabs of multi storey buildings [58], in order to get more mass and thermal capacity [59]. Slabs are thermally activated by water or air [60, 61], which operate with small difference between room air and HVAC system temperature allowing the use of low temperature heat sources [62]. In general TABS design is based on the same parameters characterizing other radiant systems (spacing and diameter of the pipes, thickness of concrete layer, water temperature, water mass flow rate) [63, 64]. The high water temperature for cooling shows an overall energy consumption lower than conventional air conditioning systems and it offers the possibility of using renewable or recovery sources of energy, or technologies not usable in traditional systems [65]. Moreover this kind of system allows to remove the daytime peaks loads during the night time, when the prices of electricity are lower [66], and to use water temperature in the pipes close to desired room temperature. It is important to highlight that operative temperature drifts in the room can be expected, because it cannot be controlled as a fixed level [62].

4.2.1 Test facilities and experimental apparatus

As early introduced, this thesis proposes a methodology for to evaluate the performance of a TABS system through in field measurement in an office room. In literature TABS are usually studied through dynamic simulation tools, and just a few examples show measurements in situ. Also in these last cases, however, just a few environment and energy parameters are monitored and systems are not evaluated under particular condition.

The investigation has been performed in the room 2.2.00 of the office building already introduced in chapters 3 and 4. This room had a South-East exposure, and a floor surface of 268 m^2. In winter time it was heated by convectors balanced with mechanical ventilation. In summer TABS integrated in the ceiling, combined with mechanical ventilation, provided to cool the environment. On the concrete slabs a raised floor with acoustic insulation was located, while the pipes were embedded in the lower part of the concrete slab. The lighting level in the room was controlled by sensors of presence and the intensity of the artificial lights was balanced with the natural light. There were automatic and manually curtains for the solar radiation control and the employees had the possibility to open/close the windows.

During the tests, physical parameters were collected through the use of a stand positioned in the center of the room, on which probes were located at different heights. Operative temperature and surfaces temperature were collected through a thermo camera. At the same time a weather station was measuring data about the outdoor environment, and other sensors were measuring temperature of the fluids in the systems. All the monitored parameters, the typology of sensor used, their position, and the frequency of acquisition are listed in Paper V.

4.2.2 Methods

In order to evaluate the TABS performance in summer through field test in an existing office building, the assessment of the hydronic system has been tested at different levels of internal loads. With this aim heated dummies were positioned at the same workstations used by employees during the workdays, and located homogeneously in other empty areas of the room, simulating internal heat gains from people, computers and other sources. During the experiments, dynamic simulations performed through energy simulation tools were conducted simultaneously with physical measurements. The entire investigation process can be divided in four different phases:

- *Phase 1: Determination by dynamic simulations of the room internal loads to be used in the field measurements.* In order to determine the level of internal loads to install in the examined room, dynamics simulations were performed with the support of the energy simulation tool TRNSYS (16.1.0003). The use of simulations in the first phase of the process allowed to solve the energy balance of the room in cooling mode, giving as outputs the total heat loads and the operative temperature in the room. The TABS system was originally designed to maintain thermal comfort conditions at the work places until 40 W/m^2 of cooling loads. Through the simulation model, it was possible to test different levels of internal gains in the room to reach 40 W/m^2 by adding people and computers in the office. The objective was to estimate how many dummies (1 dummy = 1 person + 1 computer = 170 W) had to be placed in the room to reach the designed value.

- *Phase2: In field measurements.* Measurements were carried out in summer 2011. During experiments different levels of internal loads were inserted in the office, according with outside weather condition and based on the results from the simulations. In this way, inserting heated dummies in the room, three different scenarios (S1,S2,S3) were created (Fig. 22). Indoor and outdoor environmental parameters, and supply and return temperature of the air in the ventilation system and of the water in the hydronic system were monitored.

- *Phase 3: Calibrated dynamic simulations and cooling loads calculation:* Through calibrated dynamic simulations, performed with the support of Energy Plus 6.0, internal gains and cooling loads were calculated for the duration of all the experiment.

- *Phase 4: Critical analysis of the results:* see next paragraph.

In this experiment two different simulation tools have been used. Trnsys was used during the first phase, while Energy Plus was employed in the third phase. The decision to change the tool has been dictated by the potentiality of the two instruments in the different steps of analysis. As demonstrated in Paper VI, Trnsys and Energy plus, at the same input data, can give similar results. In the paper four simulation tools were compared (IDA ICE, IES, TRNSYS and Energy Plus). Three rooms of a case study building were simulated for different scenarios, with all the four tools and for one year. Output of the analysis was the operative temperature. From the results emerged how, especially in summer period, from Energy Plus and Trnsys the outputs were comparable (Table 8). In the paper also a TABS system was simulated, and also in that case the difference of temperature obtained in summer from the simulation between the two tools was very little.

Table 8: Calculated degree hours of cooling to 24,5 °C from April through September.

Stage		IDA	IES	Energy+	TRNSYS
		[degree hours in thousand] (cooling)			
1	Basic building	14.2	20.3	36.1	34.9
2a	S1 + Internal Shading	5.7	8.5	26.0	31.0
2b	S1 + External Shading	0.0	0.0	0.0	0.2
3a	S2a + Ventilation (3,5 l/s*person)	0.0	0.0	0.0	0.2
3b	S2a + Ventilation (10 l/s*person)	0.2	0.2	3.3	5.6
4	S3b + Internal Loads	1.4	1.4	3.1	4.7
5	S4 + TABS	0.1	0.1	1.7	1.2

During the work also emerged that in the input data inserting phase, the tools presents little differences. In the creation of stage 5 for example, when also TABS system was included in the model, all the tools, but Energy Plus, could fix the supply temperature in the hydronic circuit as a control strategy. Also in Energy Plus the supply water temperature can be set, but a range in which the temperature can fluctuate is required too, and then the final system control is based on the environment set point temperature. For these reasons, in the start up phase was preferred to use Trnsys, which allowed to evaluate, keeping the supply temperature in the tubes constant at 18 °C, the amount of cooling loads in the room at the level of internal gains variation. Thank to this evaluation was possible to define the three scenarios before mentioned. On the other hands Energy Plus was used making a calibrated simulation. First of all with energy Plus was possible to build an accurate model. Then, since the final control depends by the room temperature set point, a similar state, like it was in reality, was created. The weather file was calibrated with the data monitored from the external weather station, and internal loads from dummies were inserted according with the three scenarios. Tank to this simulation, cooling loads during the experiments were calculated and results are shown in the next paragraph.

4.2.3 Results

During the experiments the systems control was set to keep the air temperature in the room equal to 23°C. In the beginning of S1 both ventilation and TABS systems were not working, so the air temperature increased. During the day just the ventilation system was cooling, and then in the night the ventilation stopped and the TABS started to run. In S2 the cooling was provided only by TABS. In S3 both TABS and ventilation systems were working together. Temperatures profiles are shown in figure 22.

From the graph some consideration about the operating principle of this system can be done. In the beginning of the experiments, when both ventilation and hydronic systems were not working, the slab accumulated a lot of heat, which began to be removed by the TABS when they started to work. Due to the high cooling loads to remove, the supply temperature in the circuit fluctuated between 16°C and 18°C, while during normal working days, over the experiments, supply water temperature in the TABS was around 20°C. During the experiments the heat loads in the room were reduced, the loads removed by the water in the TABS decreased, as well as operative temperature in the room and the difference of temperature between the return and the supply water in the pipes.

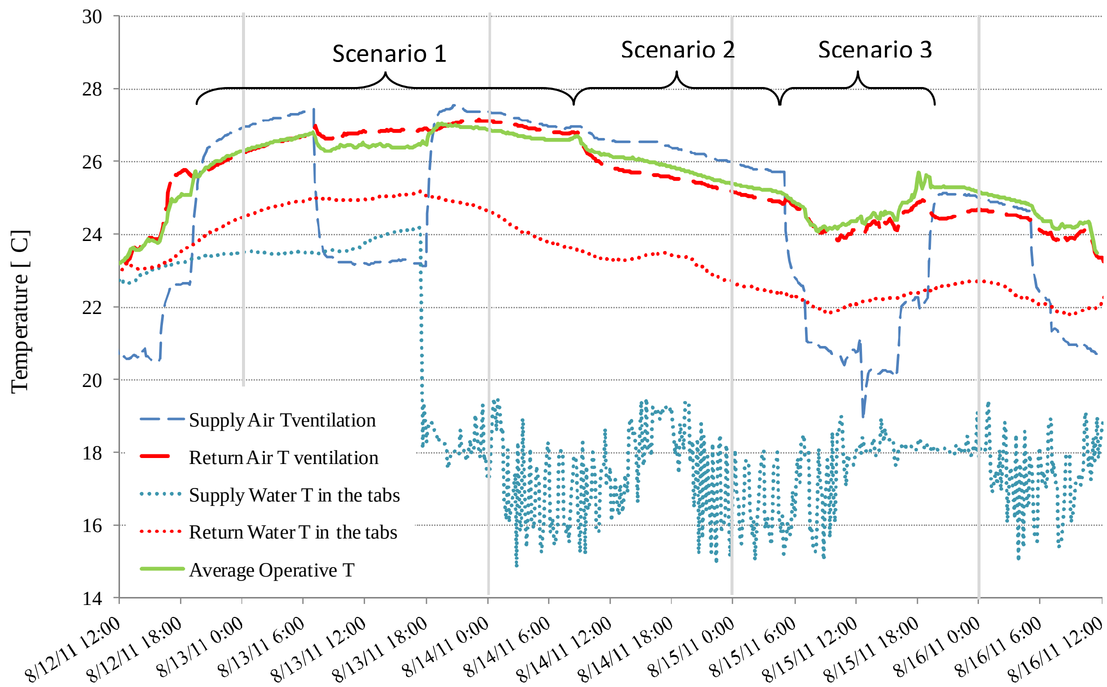

Figure 22- Temperature profiles of average operative temperature in the room, supply and exhaust air temperature in the ventilation system and supply and return water temperature in the pipes.

Surface temperatures (floor, ceiling at 270 cm [suspended ceiling] and ceiling at 330 cm [concrete slab]) were monitored too, and from the graph of figure 23 it can be seen that while floor and suspended ceiling temperatures were in general really close to the air temperature in the room (almost constant at different heights in all the scenarios), ceiling temperature differed at least of 2°C from the air temperature, when the system was operating.

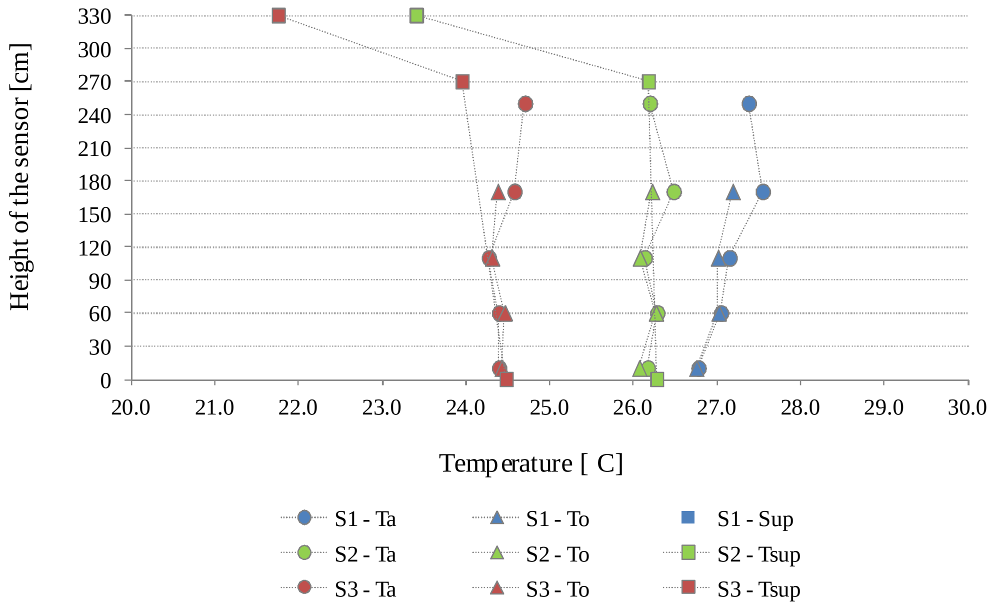

Figure 23 - Average air, operative, and surfaces temperature in the room, for the three scenarios.

For each scenario intervals of 6 hours, in which air temperature in the room and water temperature in the hydronic system were almost constant, were selected. The cooling loads evaluated during these intervals are indicated in table 9. In the table is also possible to read for each scenario heat gains and heat losses.

Table 9- Heat balance of the room in the different scenarios.

		Loads [W/m^2]		
		Int. Scenario 1	Int. Scenario 2	Int. Scenario 3
Heat gains	Dummies	22.2	22.2	22.2
	People	-	-	4.8
	Heaters	13.0	-	-
	Equipements	-	-	3.4
	Lights	3.9	3.9	3.9
	Solar gains	-	8.2	13.5
Heat losses	Infiltrations	-1.3	-0.8	-0.6
	Ventilation	-	-	-6.6
	Walls	-2.5	-1.6	-1.1
	Windows	-3.4	-2.2	-1.5
Cooling loads		31.8	29.6	37.9

In the TABS performance assessment it is important to distinguish between the cooling loads removed from the room by the cool surface, and the loads accumulated in the concrete slab and removed by the cool water in the pipes of the hydronic circuit. In the first case the loads removed from the room can be calculated through the equation:

$$Q/A= (hc+hr)*DT \quad (1)$$

were:

- (hc+hr)floor = 6 W/m^2K,
- (hc+hr)ceiling = 11 W/m^2K and
- DT is the difference among the average air temperature in the room and the surface temperature.

In the second case, knowing supply and return water temperature in the TABS, and flow rate in the pipes, loads removed by the water can be calculated by using the basic equation:

$$Q/A= m*cp*DT \quad (2)$$

where:

- m is the flow rate in the pipes,
- cp is the specific heat of the water and
- DT is the difference between return and supply water temperature in the pipes.

In table 10 al the monitored data useful for to apply the equations (1) and (2) are shown. Results are then illustrated in the schemes of figure 24.

Table 10- Measured temperature in the tabs system, in the ventilation system, in the room and outside.

Scenario	TABS				Ventilation				Average temperatures		
	Supply [°C]	Return [°C]	DT [°C]	Flow rate (kg/s)	Supply [°C]	Return [°C]	DT [°C]	Flow rate (kg/s)	To [°C]	Ta [°C]	Tout [°C]
1	18.1	24.7	6.6	0.42	27.4	27.1	-0.3	-	27.0	27.1	16.1
2	18.1	23.4	5.3	0.42	26.5	25.7	-0.8	-	26.1	26.1	18.8
3	17.9	22.1	4.2	0.42	20.5	24.1	3.6	1.40	24.3	24.2	19.6

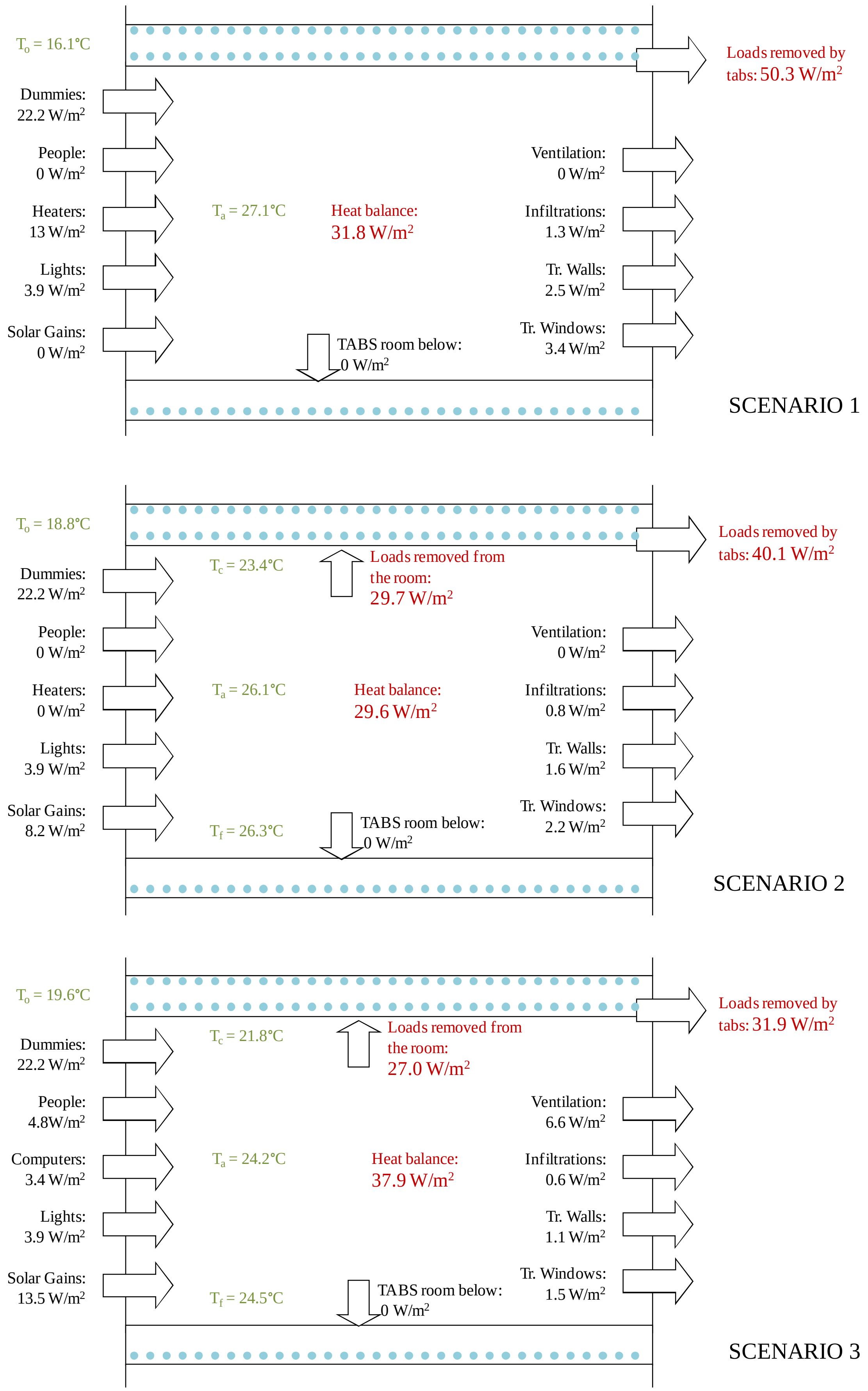

Figure 24 – Total Energy balance - intervals of scenario1, 2 and 3.

From the schemes emerge that:

- During the first day of monitoring the slab accumulated a lot of radiant heat, which was then removed during the following days. The temperature in the room was high, but this is explained by the fact that no systems were working.
- During S2 TABS was still removing part of the loads accumulated in the previous days.
- In S2 cooling loads removed by the room from the cool surface were almost the same than the cooling loads calculated with the heat balance. This means that in that interval of time, the TABS were balancing the cooling needs of the room.
- During the S3 the ventilation was contributing to remove loads from the room. The calculations denote that the system was not removing enough heat as required by the energy balance.

In order to analyze the performance of the system, the loads removed by the TABS for the three scenarios were calculated in relation to the difference between the average water temperature in the pipes and room operative temperature. This is equivalent to the total heat exchange coefficient between water and room:

$$h_{total} = L / [T_o - (T_{supp} + T_{ret}) / 2] \quad (3)$$

where:

- h_{total} = Total heat exchange coefficient i.e. loads removed by the TABS for degree temperature difference between average water temperature in the circuit, pour square meter [W/m²°C]
- L = loads removed by the TABS, calculated with (1) [W/m²]
- T_o = operative temperature [°C]
- T_{supp} = Supply water temperature in the TABS [°C]
- T_{ret} = Return water temperature in the TABS [°C]

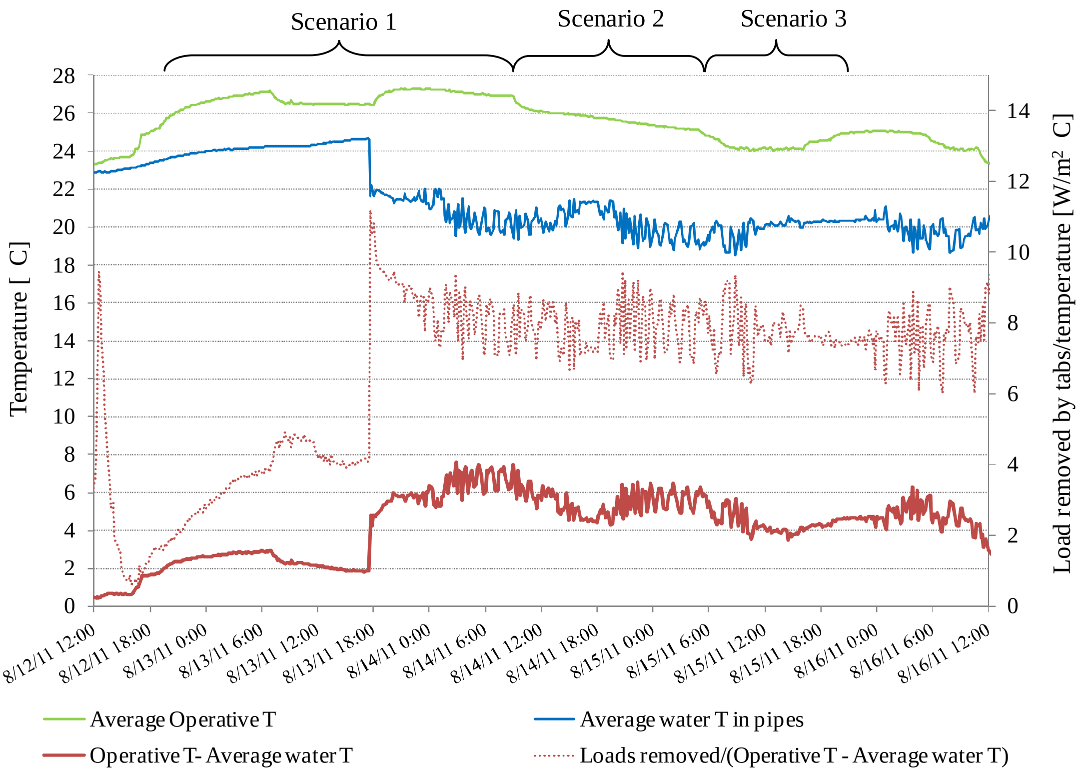

Figure 25 - Loads removed by the system per degree temperature difference between average water temperatures in the pipes.

Figure 25 shows that the system removed averagely about 8 W/m^2 per degree temperature difference between average water temperature (cooling capacity = 8 $W/m^2°C$), during all the scenarios. This means that also in case of different heat loads in the room, the system control allowed to maintain a good performance. From the graph the average water temperature in the pipes was always around 20°C, while the operative temperature decreased from S1 to S3. When for example the operative temperature was 26°C (S2), and consequently the temperature difference was 8°C, the system could remove about 48 W/m^2. Wanting to evaluate how much loads could be removed by the system at lower water temperature, if the average water temperature in the pipes in that case was 18°C, it could be said that the system could then remove about 64 W/m^2, but in that case the supply temperature would be too low (< 18°C), which could increase the risk for condensation on the supply pipes and it would be more difficult to control. So a cooling capacity of 40-50 W/m^2 can be documented by the present test.

5. Discussions and Conclusions

This thesis deals with indoor environmental quality evaluation and energy assessment in buildings, with a focus on radiant systems performance.

Indoor environmental quality data elaboration and representation have been investigated for both long and short periods of analysis. International standard EN 15251 defines three different methods (A,B,C) at which to refer in the thermal quality assessment, and that evaluate the thermal environment on the basis of the "thermal comfort indexes", i.e. operative temperature, PMV and PPD. These three methods have been critically analyzed in this work through a case study. Collected data from a monitoring campaign in an office building were used to compare these three methods, highlighting their potentiality and limits. From the study emerged how the three approaches give different information in terms of thermal comfort, in particular method A ("Percentage outside the ranges") respect to methods B and C. In order to gather in a single output several information a variation of method A is proposed in this work. Thank to this new approach a more detailed analysis of the thermal behavior of the building can be done. The study also highlighted the differences in the evaluations considering as thermal comfort index operative temperature or PMV. PMV calculation depends by four physical parameters and two subjective parameters: this fact can highlights significant problems in the accuracy of the prediction. Different is for the operative temperature, because in this case the parameter is only one, and the errors that could be encountered just depend by the accuracy of the measurement of mean radiant temperature. The work also dealt with the spot measurements, describing them as useful for giving a detailed picture of the IEQ in particular configurations, like in specific critical locations and periods of time. Spot measurements can be useful also in the startup phase of a long term monitoring, giving a rapid overview of the homogeneity of the indoor environment and helping in the long term monitoring design. Moreover can be used in the local discomfort assessment. Through a case study in which physical parameters and subjective evaluation were performed and elaborated, spot measurements and indications referred to data elaboration and representation are illustrated. From the study it resulted that occupants thermal sensation and PMV calculation do not always match.

In addition to deal with the indoor climate evaluation, part of the work focuses on the energy demand required by the systems for to maintain a good thermal quality in the building. Due to the fact energy demand can vary depending not only from the envelope characteristics and quality, but also and from the system control and the outdoor climate conditions, a study about the heating and cooling energy demand variation at the thermal and air quality changes (comfort categories variation from I to III), for different climate zones (Moscow, Turin and Athens), has been performed. Result of that analysis, conducted through energy simulations, underlined how, in cold climate, the energy requirements for heating are prevalent and the influence of expected indoor air quality level prevails on primary energy demand. Due to this reason, in cold climate it is always desirable use a the thermal recovery in order to save energy. The study showed how:

- in the coldest climate and without heat recovery the range of primary energy demand for heating could go up to 70 kWh/m^2 for a variation in the ventilation rate rage, while it varied only of about 17 kWh/m^2 for a variation in the operative temperatures; in the warmest climate, both the variations (ventilation and operative temperature) are negligible and equal to 2-3 kWh/m^2;
- in hot climate the energy requirements for cooling were prevalent and the influence of expected indoor thermal quality level prevailed on primary energy demand. With reference to the this aspect, in all the analyzed locations, the range of variation of the primary energy demand for cooling due to a change in the ventilation rates is similar to the one due to a change in the operative temperatures and is equal to 19-24 kWh/m^2 for the warmest location, while it decreases to around 5 kWh/m^2 for the coldest location.

The same study also demonstrated than for an increase of heating/cooling degree-days, more primary energy must be consumed for cooling than for heating purposes.

In order to assess climate quality and energy consumptions in buildings, this thesis is presented a procedure at which referring in long term monitoring analysis. The correlation between energy and indoor environment measurements carried out simultaneously allows to give, as output of the analysis, a complete building energy and environment evaluation. The approach here proposed permits to go to the monitoring plans design till the data elaboration and results representation. Through the application on a case study the following considerations, representing the mains aspects of the study, have been made:

- Comfort and energy monitoring plans can be developed starting from diagrams representing, in a schematically way, architecture and integrated systems.
- Both total energy use and indoor environment can be expressed with different levels of detail, in terms of kind and grade of information, deepening the analysis from the entire building to the single rooms. Levels of detail in energy evaluation are: Delivered primary energy, Delivered energy, Net energy needed by the technical systems and Space net energy needed. In IEQ evaluation levels are: Whole building indoor climate analysis, Single Indoor climate zone evaluation and Indoor climate quality evaluation in specific rooms.
- Analysis of energy and climate quality can be performed for different intervals of time, like year, seasons, months, days, etc., giving different kind of information for each interval. The length of the interval of analysis to choose depends by the objective of the monitoring.
- Representing the comfort performance of a building with a single value is still an issue to be solved, but comfort parameters can be put in relation to each other through the use of categories suggested by the standard EN 15251. Introducing also categories for the energy consumption classification, energy performance of a building can be put in relation to the correspondent comfort assessment. In this way a good description about the performance of a building could include a synthetic representation of the results, but more detailed analysis consent to better know the dynamics of the building at boundary condition variation, allowing to make a diagnosis of the building.

The connecting element between IEQ and the related energy consumptions, beyond boundary conditions and envelope thermo physical properties, is the installed plant system. In literature many studies about thermal comfort treated the topic of low energy radiant systems for to reach the indoor environmental quality objective. For this reason, and in accordance with the topic of this thesis, two kinds of radiant systems have been object of analysis and experimentation: the first is represented by vertical electric radiant plates for heating, and the second by TABS (Thermal Active Building System) for cooling. In both cases energy and environmental parameters were measured. In the first case the experiments took place in a test rooms, in the second experiments were performed in situ (office room).

The analysis conducted showed that electrical radiant plates may be a good heating system, but due to their high electricity demand, the results show that their use can be considered suitable only in houses with low-energy demand, where the yearly heating consumption can be balanced by the production of photovoltaic energy on site. Low cost equipments can, under these conditions, be competitive with other systems: in fact, for economical sustainability, low energy requirements have to be faced by low cost technologies in order to give suitable payback time. In terms of indoor environment results of the activity demonstrated that the plates can keep a good level of thermal comfort in the environment at distances higher than 1,5 m from the radiant surface, but already at the distance of 0,50 m the temperature can be considered acceptable.

Field tests conducted in an office building, in order to evaluate the performance of a TABS system (embedded in the ceiling slab), given different kind of results, demonstrating the ability of the relatively high temperature water to remove heat accumulated in the slab. During the tests, at high levels of cooling loads in the room, the hydronic system could keep the total heat exchange coefficient between the average water temperature in the pipes and the operative temperature in the room almost constant about 8 W/m^2 per degree temperature. The analyzed system could remove from the room a cooling load of 30 W/m^2 using an average supply water temperature in the pipes of 18 °C. Higher cooling loads could be removed with lower supply temperature.

From the experiments emerged the possibility to install a suspended ceiling also in case of TABS integrated in the ceiling slab. The important thing is to use a suspended ceiling well designed for to be combined with this kind of radiant system. In the case study the false ceiling was made by steel bars that allowed the indoor air to circulate, without interfere with the ability of the system to keep comfort in the room.

Answering at the objectives of the thesis it can be said that:

- In the long term climate quality assessment a new evaluation method, that summarize the information given by the three methods presented in the standard EN 15251, has been proposed. This new approach allows to give more accurate information about the indoor climate.
- Building energy demand depends by the level of indoor climate quality in a different way as a function of the outside climate. In cold climate, in fact, the energy demand is more affected by the indoor air quality level (expressed in terms of air change rates) than in warm climate. Moreover, air quality is more influencing than thermal quality, independently by the climate zone.
- A method for the ICQ and energy assessment in buildings, from the monitoring plan to the data elaboration and representation is introduced. Both ICQ and energy consumptions can be elaborated for different levels of detail, proposed in the thesis. As a function of the length of the period of analysis different representations are proposed too, with the aim to give an overall evaluation of the energy and indoor climate performance of the building.
- A representation method that put in relation energy consumption and indoor air quality, for seasonal and yearly evaluation is presented. This method can give different kind of information if

indicating comfort and energy categories, or comfort and energy values. Using categories a reference “area” delimiting the best obtainable performance of the building is indicated. Since a European labeling for energy certification has not yet been defined, the energy categories proposed in the thesis only indicate ranges of energy values; for this reason the method could be adapted in different countries according with different national energy certifications.

- In relation at the two radiant system tested and described in the thesis it emerged that:
  - Electrical radiant panels could be a suitable system just if installed in low energy buildings, in which electricity is integrated by photovoltaic system. They are able to produce a good thermal comfort, but their high electricity demand represents a limit.
  - The experimental apparatus adopted for the measurements during the experiments, due to the new technology and the limited production cost, could find a wide application in many different experimental studies.
  - Tabs system can remove radiant loads accumulated in the slabs using high temperature water. In the thesis have been demonstrated the total heat exchange coefficient between the average water temperature in the pipes and the operative temperature in the analyzed room was almost constant at different levels of cooling loads in the room, highlighting the good performance of the system. However, higher cooling loads could be removed with lower supply temperature. Further test like the one here illustrated could be repeated in different building and for longer periods of time, with the aim to improve the test methodology and the results.
  - Performance of TABS systems can be evaluated in situ and during the operating systems. This means that steady state conditions cannot be created, but is possible to find intervals of time in which environmental parameters are almost constant.

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8. PAPERS

8.1. PAPER I

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Evaluation methods for indoor environmental quality assessment according with the comfort European standards.

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Evaluation methods for indoor environmental quality assessment according with the comfort European standards.

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SUMMARY
In existing and future buildings there will be an increasing focus on energy uses and indoor environmental quality. Even if buildings are using several different kinds of energy sources, the yearly energy performance is expressed in one format either as primary energy or CO_2 emission. As a consequence, in order to compare energy performance with the corresponding indoor environmental performance, there is a need to express also the indoor environmental performance on a yearly basis, referring both to each separate environmental factor (thermal comfort, air quality, light and noise) and to a combination of these factors. If the indoor environmental criteria in existing standards have to be met 100% of the occupancy time, the amount of heating, cooling and/or ventilation capacity of any HVAC installation would be prohibitive in terms of energy consumptions. Economic and/or environmental considerations lead to a more pragmatic position of allowing the indoor environmental conditions to exceed the recommended ranges for a limited period of time: this can be verified both by computer simulations (design stage) and by the field monitoring (post-occupancy phase).

The present paper will present some concepts to carry out a whole year performance evaluation of the indoor environment, inspired by ISO EN 7730 (thermal environment) or EN15251 (thermal, indoor air quality, light and noise). Besides, some new suggested concepts about indoor environmental quality are tested. Based on data from indoor environmental measurements in an existing building, methods for long term evaluations will be presented and discussed. The results show that the different concepts to a great extend will bring the same relative results. The results also show that today we still do not have enough knowledge to be able to combine the indoor environmental parameters into one synthetic indicator.

KEYWORDS

Indoor environment, criteria, measurements, thermal comfort, air quality.

INTRODUCTION

The environmental factors that define the indoor environmental quality (IEQ) are: thermal comfort, indoor air quality, acoustic comfort and visual comfort. This makes it almost impossible to describe the indoor environment in a building on a yearly basis with only one indicator. This is much easier with energy, where the different energy carriers (electricity, fuel, etc.) can be converted to primary energy or CO_2 emission. For the individual indoor environmental factors, there is even not any standardized method for the estimation of a yearly performance descriptor.

Criteria for acceptable thermal conditions are specified as requirements for global thermal comfort (PMV- Predicted Mean Vote, PPD- Predicted Percentage of Dissatisfied, or operative temperature, air velocity and relative humidity) and local thermal discomfort (draught, vertical air temperature differences, radiant temperature asymmetry, surface temperature of the floor). Such requirements can be found in existing standards and guidelines like EN ISO 7730 (2007) [1], CR 1752 (1998) [2], EN15251 (2007) [3] and ASHRAE 55 (2007) [4]. Moreover for free running or natural ventilated office buildings, the criteria for an acceptable operative temperature are given as a function of the mean outdoor temperature [3] [4].

Different categories of criteria, according to [1] and [3], may be used for IEQ assessment depending on type of building, type of occupants, type of climate and national differences (Table 1). Some of the standards specify different categories of indoor environment which could be selected as a reference for the space to be conditioned. These different categories may also be used to give an overall, yearly evaluation of the indoor environment by estimating (through measurements or dynamic building simulations) the percentage of time in each category of the analyzed room or building [5].EN 15251, for example, specifies how criteria about IEQ can be established and used at the design stage; moreover it defines the main parameters to be used as input for building energy calculation and long-term evaluation of the indoor environment [6].

But, if thermal comfort criteria have to be met 100% of the time of occupancy, including extreme weather conditions, the heating and/or cooling capacity of any HVAC installation would be prohibitive [7]. Economic and/or environmental considerations lead to a more pragmatic position of allowing the thermal conditions to exceed the recommended ranges for a limited period time. There is a need to quantify through some suitable index long term comfort conditions to compare alternative design solutions and long term measurements during the post-occupancy phase in existing buildings.

Table 1. Example criteria for PMV-PPD, operative temperature, relative humidity and ventilation (CO_2 concentration) for typical spaces with sedentary activity. [3]

Category	Thermal Comfort indexes		Operative Temperature range		Relative Humidity	Ventilation
	PPD	PMV	Winter 1.0clo/1.2met	Summer 0.5clo/1.2 met		CO_2 Above outdoor
	[%]	[/]	[°C]	[°C]	[%]	[ppm]
I	< 6	-0.2< PMV<+0.2	21.0-23.0	23.5-25.5	30-50	> 350
II	< 10	-0.5< PMV<+0.5	20.0-24.0	23.0-26.0	25-60	350 - 500
III	< 15	-0.7<PMV<+0.7	19.0-25.0	22.0-27.0	20-70	500 - 800
IV	> 15	PMV >±0.7	< 19.0-25.0<	<22.0-27.0<	<20-70<	> 800

Note: In standards like EN ISO 7730, EN15251 and EN 13779 (2007) [8] categories or classes are also used; but they may be named differently (A, B, C or 1, 2, 3 etc.).

The use of categories during the design stage to evaluate different design options can be done by yearly building energy simulations. In these calculations, the categories may be clearly adopted and performance indicators can be expressed as percentage of time where the indoor environment falls into the different categories. The use of categories to express the quality of the indoor environment during building operation can be based on measurements of the physical parameters. . Focusing on the thermal environment assessed by in-field measurements, the use of PMV can highlight significant problems in the accuracy of the prediction (for example, the accuracy by evaluation of the clothing and activity is not good enough to estimate the difference between classes of PMV). If it is decided that the evaluation is simplified by assuming a given value for clothing and activity the criteria can be expressed as operative temperature. The major problem is the accuracy of the measurement of mean radiant temperature, which often is higher than 0.5 -1.0 K. For many buildings the difference between air and mean radiant temperature is however less than 2 K, and then this accuracy will not be so important. Also as shown in the present paper it is possible to measure the operative temperature directly

The present paper deals with thermal environment and indoor air quality assessment. Based on data from measurements in an existing office building, different methods for long and short term indoor climate investigations are presented and discussed.

METHOD

The building
In order to carry out a critical analysis of the use of the comfort categories as introduced in EN 15251[4], a case study is presented and discussed.
The case study is an office building located in Denmark (Lat: 55.5°, Lon: 9.75°). The building has a complex shape (see Figure 1.). From the architectural point of view a key elements is the roof shape, accommodating multiple functions. 83 prism-like skylights compose the roof surface defining the geometry of the building. The total volume is mainly occupied by bank offices, but also a bookshop, a café and a real estate agent office is located at the ground floor level, around a central plaza. The working areas (basically open space offices) are mainly located on three open terraces, called “plateaus”, internally connected by broad staircases. On each floor also single offices, meeting rooms and other rooms for dedicated services are placed. The building envelope is made mainly by structural glass (U=1.1 W/m2K), with the transmission coefficient (visible light/solar energy) equal to [0.64/0.35]. The office is normally occupied from 8:00 to 18:00, from Monday to Friday.

The indoor environmental control of the building is divided into two main strategies:

- Type 1: Convectors and balanced mechanical ventilation for heating and ventilation control during the winter period, TABS (Thermo active building system) and HVAC system for cooling and ventilation control during summer. This kind of system is mainly applied in single offices and meeting rooms.
- Type 2: Embedded water based radiant system, and convectors for thermal control. Natural ventilation by controlled window openings to provide acceptable indoor air quality. This kind of strategy is applied in all the large spaces, like in the offices situated on the terraces (plateaus), in the canteen and in the central square at the ground floor.

The monitoring campaign started in July 2010.. In this paper, the data collected during winter 2010/2011 and summer 2011 are presented. During that period, measurements of air temperature, operative temperature, relative humidity and CO_2 concentration were collected every 10 minutes in 12 different rooms. Meanwhile, an external weather station collected data of the outdoor air temperature, relative humidity, wind velocity/directions and solar irradiance. The average monthly outdoor climatic data during the occupancy hours are shown in Table 1.

Table 1. Average monthly outdoor climatic data monitored during the occupancy hours.

Month	Solar radiation [W/m²]	Outside Temperature [°C]	Relative Humidity [%]	Wind Velocity [m/s]	Mean direction [deg]
December	216	-3.8	84.1	1.72	45.2
January	226	1.7	83.1	1.79	52.8
February	154	1.4	76.6	2.87	75.5
March	205	4.1	74.0	2.53	161.3
May	203	16.2	62.1	2.69	415.2
June	208	19.3	62.5	2.22	424.0
July	216	19.4	69.8	2.32	328.7
August	170	19.3	71.7	2.68	295.2

Energy consumptions for heating, cooling, ventilation, lighting and appliances were also collected from November 2010, but results will not be showed in this paper which focus is the indoor environment..

In this paper the investigation of IEQ focuses on two spaces. The first (ROOM A) is an open space office located at the first floor and characterized by control strategy Type 1. The second space (ROOM B) is another open space also located on the first floor, but characterized by control strategy Type 2 (Figure1).

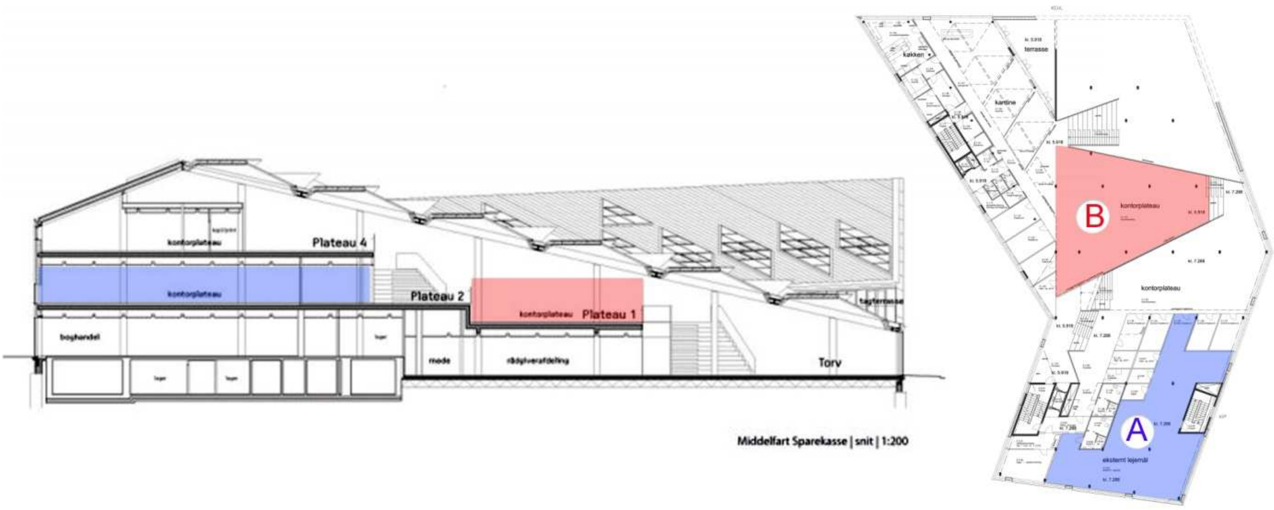

Figure 1. Case study building (vertical and horizontal sections).In evidence the two analyzed rooms located at the first floor (ROOM A and ROOM B).

Measurements

In the present study a grey globe sensor with a diameter of 4 cm was used to measure the combined influence of air and mean radiant temperature. This sensor represent in 0,6 m height the operative temperature for a sedentary person and in 1,1 m for a standing person. In the spot measurements the globe sensor was also used at 0,1m and 1,7m.

RESULTS

Long term evaluation methods

Standard EN 15251 [3], in annex F ("Long term evaluation of the general thermal comfort conditions"), suggests three different methods (A,B,C) to evaluate and represent the comfort conditions over time (season, year), based on data from measurements in real buildings or obtained by dynamic computer simulations.

Method A, "Percentage outside the range", is based on the calculated number (or %) of hours in occupied period when the PMV or the Operative Temperature are outside a specified range.

Method B, "Degree hours criteria", represents the time during which the actual operative temperature exceeds the specified range, during the occupied hours, weighted by a factor depending on how many degrees the range has been exceeded.

Method C, "PPD weighted criteria", represents the time during which the actual PMV exceeds the comfort boundaries, weighted by a factor which is a function of the PPD. This weighting factor, wf, is equal to 0 if the calculated PMV falls within a comfort ranges described in Table 1. If the value is over the upper/lower limit of the range, the wf is the ratio between the PPD calculated on the actual PMV and the PPD calculated on the PMV limit.

Method A: "Percentage outside the range"

Application of this method is shown in Figure 2. Here the thermal performance of the two analyzed rooms, in terms of percentage of time according to the four categories of operative temperature and PMV suggested by the standard (Table 1), was evaluated both for winter *(a)* and summer *(b)* periods.

The aim of this investigation is to show and compare different method for describing thermal comfort and indoor air quality. In this paper long and short term evaluation applied to the two analyzed office rooms are addressed and discussed.

Also if Method A describes just an evaluation based on operative temperature or PMV, other physical parameters, monitored or deriving by dynamical simulations, can be represented with the same approach. Figure 2 also shows the percentage of time when the CO_2 concentration and the Relative Humidity exceed the respective ranges indicated in Table 1.

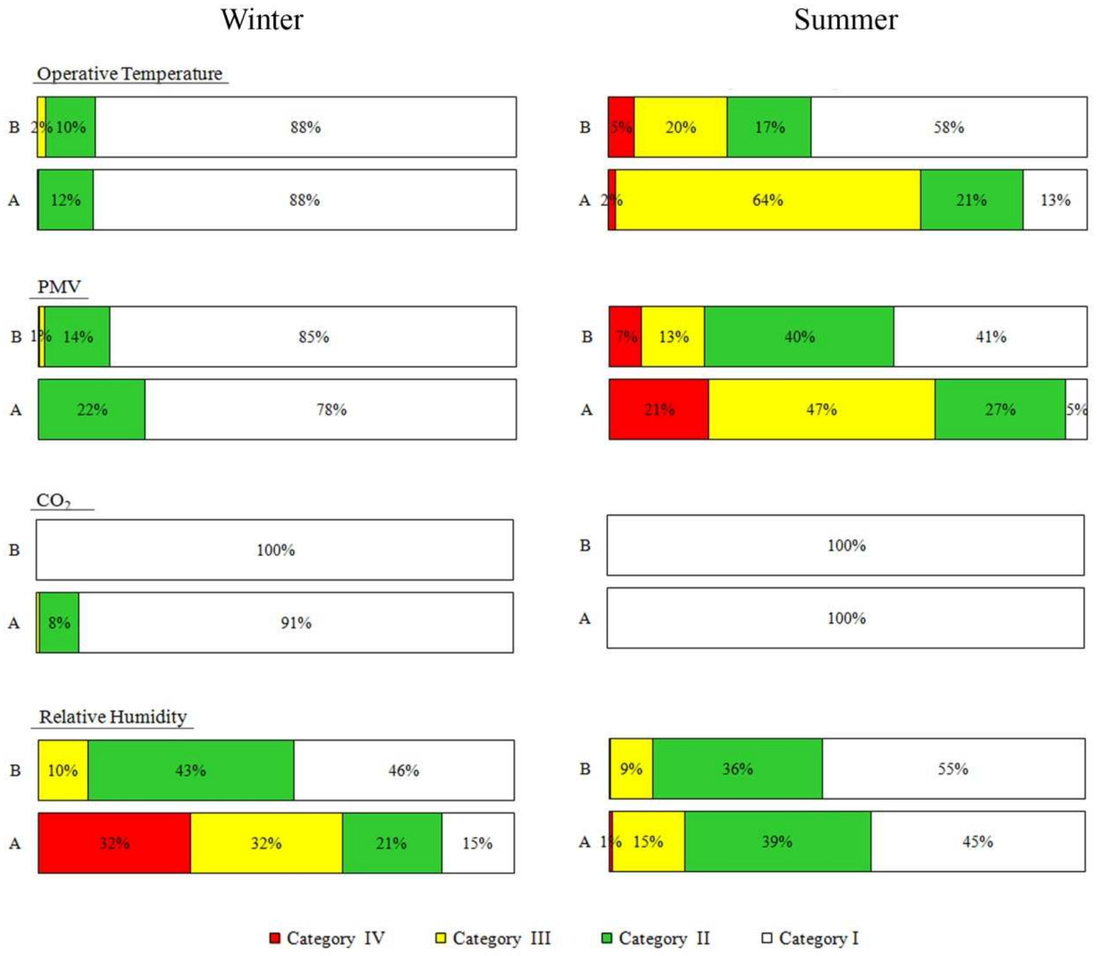

Figure 2. Indoor Operative temperature, PMV, Air quality (CO_2 concentration) and Relative humidity measurements, expressed as percentage of time in four categories, for winter and summer periods.

Operative temperature and PMV evaluations, even if both represent the application of Method A, show some differences in the results: the operative temperature evaluation gives slightly better results compare to the PMV evaluation. While the first considers just the operative temperature, the PMV calculation depends by physical parameters (air temperature, relative humidity, air velocity, mean radiant temperature) and subjective parameters (thermal resistance of the clothes and metabolic rate). In this case study the physical parameters, except to air velocity, were monitored in continuous. Trough spot measurements performed in different periods of the year, it was however possible to establish that the air velocity was averagely around 0.10 [m/s]. For the PMV calculation the air velocity value was then kept constant as 0.10 [m/s]. Regarding the subjective parameters, the metabolic rate used in the analysis was the one indicated by standard ASHRAE 55/2004 for "Office activity-Filing, seated", 1.2 [met]. Also the clothing insulation value was kept constant: 0.5 [clo] in summer period and 1 [clo] in winter period. Due to these assumptions, the PMV calculation does not represent the real PMV of a specific occupant in the room during the monitored time, but it represents the average evaluation of the thermal environment according to the comfort standards for office buildings.

From Figure 2 it is possible to note that, during the heating period, both the two control strategies, Type 1 and 2 (Room A and B) were able to provide a very good thermal quality in the analyzed rooms. Only a little percentage of time (less than 2%) was in Category III, while for the 88% of time operative temperature felled in Category I. The situation was different in summer period. As shown in the figure during the warm season the thermal quality in both the rooms presents a large percentage of time when the temperature felled in Category III and also a little in Category IV.

This method is a fine way to present the yearly results, but it is not possible to see if the problem is a too warm or too cold environment.. If we analyze Category IV, splitting it in two parts, Category $IV^{(-)}$ when T<22°C and Category $VI^{(+)}$ when T>27°C in summer, it is possible to see that the percentage of time when the temperatures in room B exceed the upper range is negligible. This fact is better shown in the operative temperature profiles of Figure 3. According to this analysis the performance in summer is not acceptable because temperatures are too low for a big percentage of time for both cases, A and B. With an optimized control setting under cooling can be avoided and energy saved

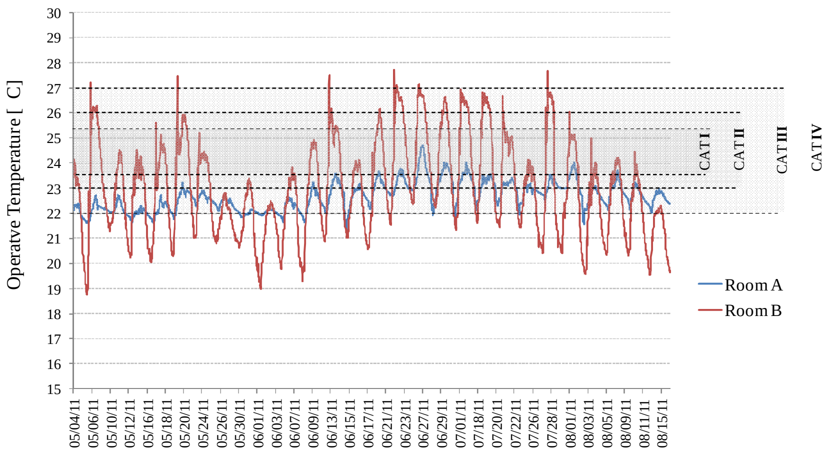

Figure 3. Operative temperature profiles during the occupied hours for Rooms A and B in summer period.

Figure 3 also shows the bigger fluctuation of operative temperature of Room B respect to Room A during the working day. The mechanical ventilation in room A contributes to reach the temperature of 23°C with very small fluctuations (< 2-3 K). .While in the natural ventilated Room B, the variations of the operative temperature is larger (> 9K). The control of the natural ventilation was based on controlled window openings according to indoor temperature and CO2 concentration.. Looking at this graph, and at the values of Table 1, it can be observed that most of the time the outside temperature was lower than the indoor temperature, so natural ventilation could be a useful and economic way to remove and control the heating loads during summer; but to avoid undercooling and the large variations in operative temperature the control of the window openings must be improved.

Similar considerations can be done also for the winter period (Figure 4). In this case the little percentage of data out of Category I is due to temperatures below the lower limit of the range.

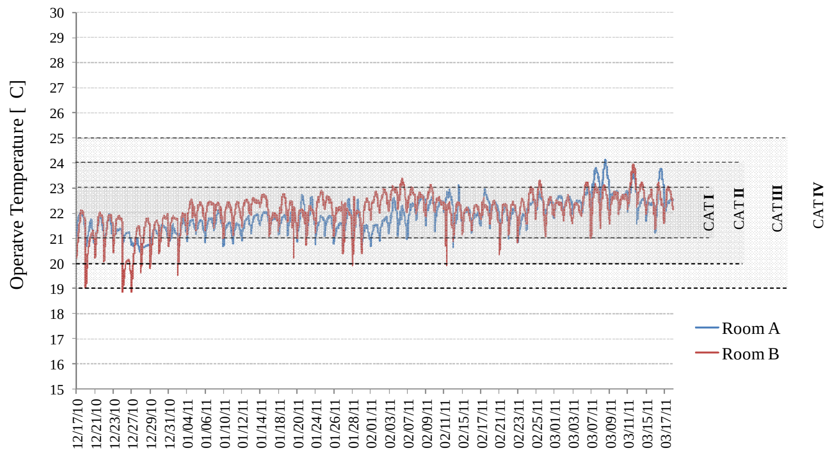

Figure 4. Operative temperature profiles during the occupied hours for Rooms A and B in winter period.

From Figure 2 it is also possible to see that for both the rooms, and for both seasons, the CO_2 concentration was very good: the percentage of time when the air quality was in Category I was always greater than 91% in winter period and equal to 100% in summer. The same figure also shows the relative humidity evaluation: in that case emerges that for both seasons, the best results are in Room B but, as already highlighted before, from this representation is not possible to see that the values falling from Category II to Category IV are lower/higher (winter/summer) than the lower/upper limit of Category I.

Looking at the ranges of values indicated in Table 1, and splitting these ranges in two parts, e lower or higher than the values indicated for Category I, it is possible to translate Table 1 in Table 3.

Table 3. PMV, PPD, operative temperature, relative humidity and ventilation (CO_2 concentration) comfort ranges for typical spaces with sedentary activity, dividing the categories indicated by [3] in lowers and uppers categories respect to Category I.

Category	Thermal Comfort indexes		Operative Temperature range		Relative Humidity	Ventilation
	PPD	PMV	Winter 1.0clo/1.2met	Summer 0.5clo/1.2 met		CO_2 Above outdoor
	[%]	[/]	[°C]	[°C]	[%]	[ppm]
IV -	> 15	PMV < - 0.7	< 19.0	< 22.0	< 20	> 800
III -	< 15	- 0.7 <PMV< - 0.5	19.0-20.0	22.0-23.0	20-25	500-800
II -	< 10	- 0.5 < PMV< - 0.2	20.0-21.0	23.0-23.5.0	25-30	350-500
I	< 6	- 0.2 < PMV< +0.2	21.0-23.0	23.5-25.5	30-50	> 350
II +	< 10	+ 0.2 < PMV<+0.5	23.0-24.0	25.5-26.0	50-60	350-500
III +	< 15	+ 0.5 <PMV< +0.7	24.0-25.0	26.0-27.0	60-70	500-800
IV +	> 15	PMV > + 0.7	> 25.0	> 27.0	> 70	> 800

Elaborating the monitored data once again with Method A, but referring this time at the ranges of categories described in Table 3 instead of Table 1, the results obtained are shown in figure 5.

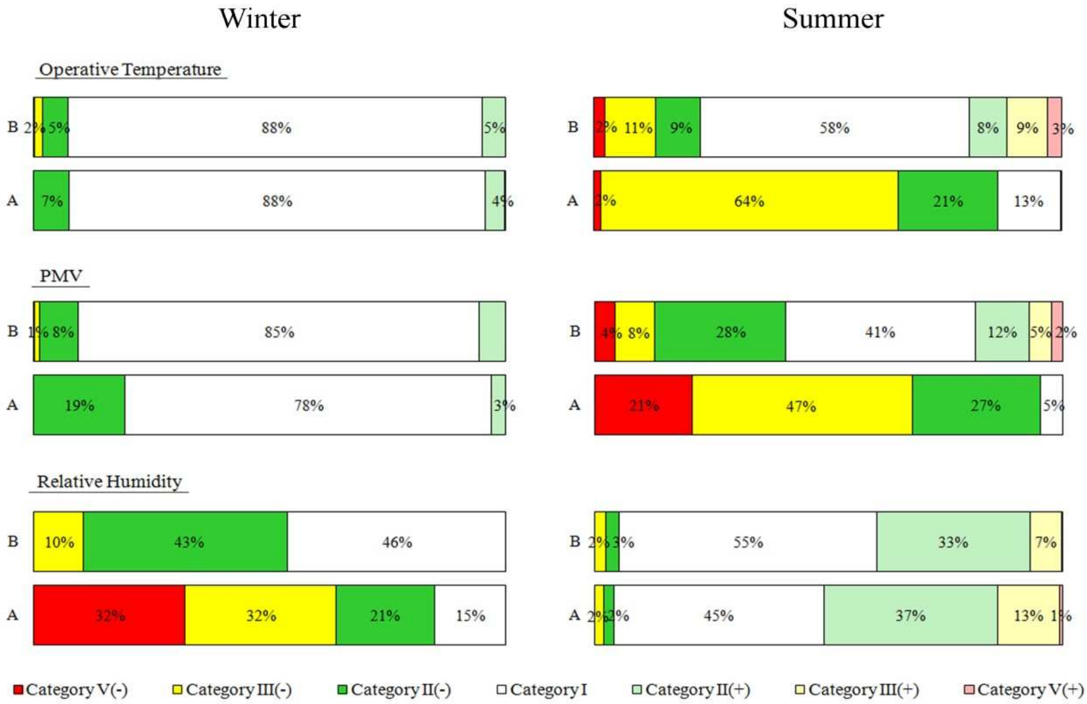

Figure 5. Indoor Operative temperature, PMV, and Relative humidity evaluation, in percentage of time in categories, for winter and summer periods, according with the values ranges of Table3.

From this kind of representation it is possible to get a more informative presentation of the yearly evaluation. For example figure 5 now show, what could be seen from figure 3 and 4, that that the operative temperature in summer for Room A was always lower than the limit of Category I. Room B presents, on the other hand, values falling in categories both lowers and higher than Category I. . Same considerations can be done for the PMV evaluation. More interested is the relative humidity analysis. Here is clear that the values, for both rooms, were low in winter season and at the contrary they were high in summer season. Focusing on Room A during the heating season, the results can be justified by the fact that until the beginning of February, just a few employees were occupying the office.

Method B: "Degree hours criteria"

This method allows to quantify the amount of degree hours of overheating or overcooling respect to the selected category. Figure 6 and Figure 7 show, respectively for winter and summer period, this amount of degree hours over category I, II and III for both rooms A and B. As already highlighted before, also from this kind of representation it emerges the good thermal environment in winter period. Respect to Method A, here it is evident the very little deviation from category I in both rooms

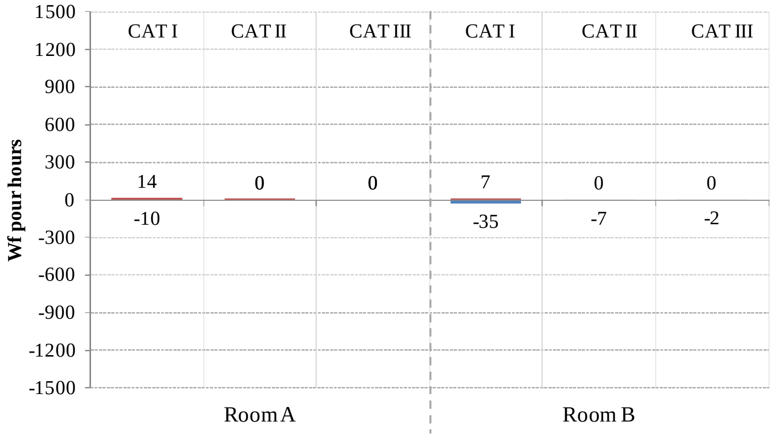

Figure 6. Degree hours criteria applied to Rooms A and B for the winter period.

The situation is different is in summer period. In Figure 7 it is visible that the problem of room A was the overcooling, while in room B there was both overcooling and overheating, but less significant. In Figure 2, where the same operative temperatures were represented in a different way, this kind of information was not shown, but it was evident in Figure 5.

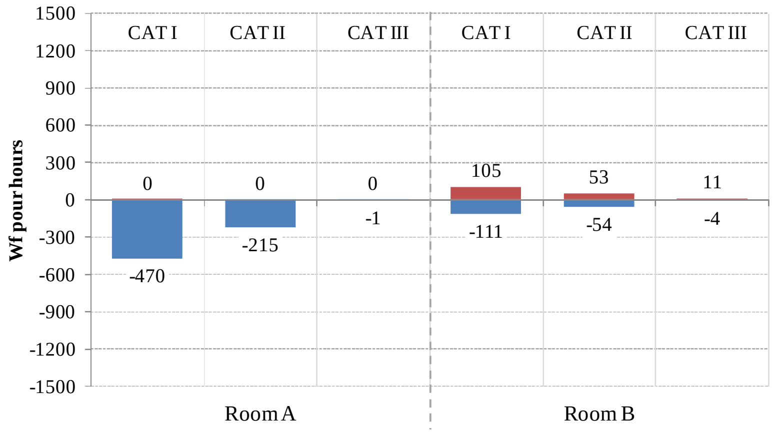

Figure 7. Degree hours criteria applied to Rooms A and B for the summer period.

As already shown for the Method A (Fig. 2), Method B could also be applied for the evaluations of other parameters.

Method C: "PPD weighted criteria"

The sum of the weighted factors function of the PPD, multiplied for the number of hours when the PMV exceeds the category range is shown in Figure 8 and Figure 9. As it was for method B, the graphs represent for winter and summer period the amount of wf *hours over Category I, II and III for both room A and B.

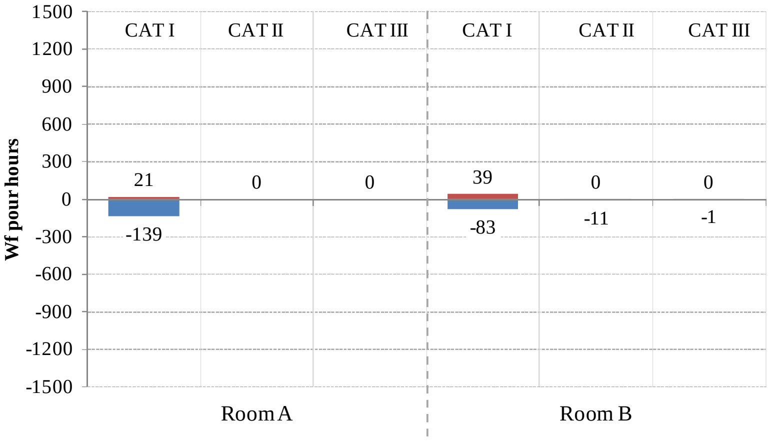

Figure 8. PMV- hours criteria applied to Rooms A and B for the winter period.

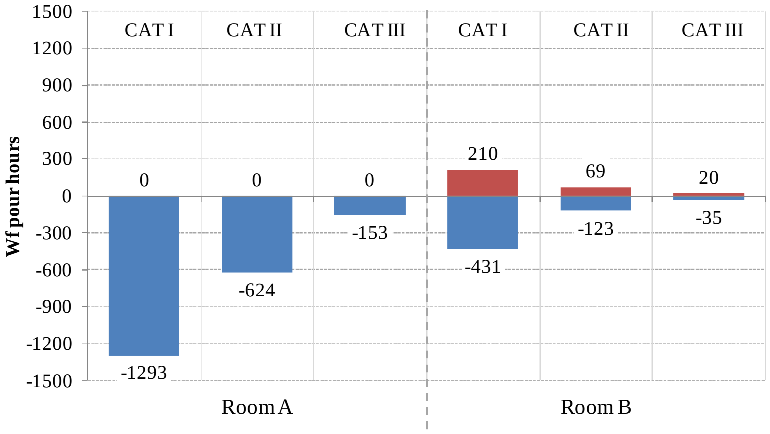

Figure 9. PMV- hours criteria applied to Rooms A and B for the summer period.

Method B and Method C, even though based on different parameters evaluation, describe the weighted deviation between the monitored parameter and the limit range of the comfort category. What emerge by the comparison of the two methods is that the trend of the data is really similar in both cases, but the values of wf*hours of Method C are greater than Method B.

Short term evaluation

The use of spot/short term measurements is useful for give a detailed picture of the IEQ (Indoor Environmental Quality) in given examined configurations, in specific critical locations and times [8]. In the present case study in parallel to the long term monitoring, also spot measurements were carried out.

Measurements were performed during the working hours on March, 22-2011 (winter period) and August, 10-2011 (summer period) through physical measurements and subjective evaluation. The monitored physical parameters were air temperature, operative temperature, air velocity, relative humidity and lighting level. Sensors and loggers for the data collection were fixed on a portable stand. The luminance was measured only with one sensor at the height of 0.6 [m] (work plane position), while all the other parameters were monitored at four different heights: 0.10 [m] (height of the ankles), 0.60 [m] (height of the body for a seated person), 1.10 [m] (height of the body of a stand person) and 1.70 [m] (height of the head of a stand person). The interval of monitoring was 1[s] for the air velocity and 10 [s] for the other parameters. In each room at least 5 points were tested for 15 minutes each.

During the physical measurements people were asked to fill subjective questionnaire about the comfort sensation, in terms of thermal quality, air quality, light, noise and about the symptoms perceived in the room. People were furthermore asked to give information about the clothes that they were wearing, the position of their desk in the room, sex, age, height and weight. With the collected data and with the physical measurements, it was possible to calculate the PMV and the PPD indexes in the rooms.

Results from the physical measurements are shown in Figure 10 (winter) and Figure 11 (summer).

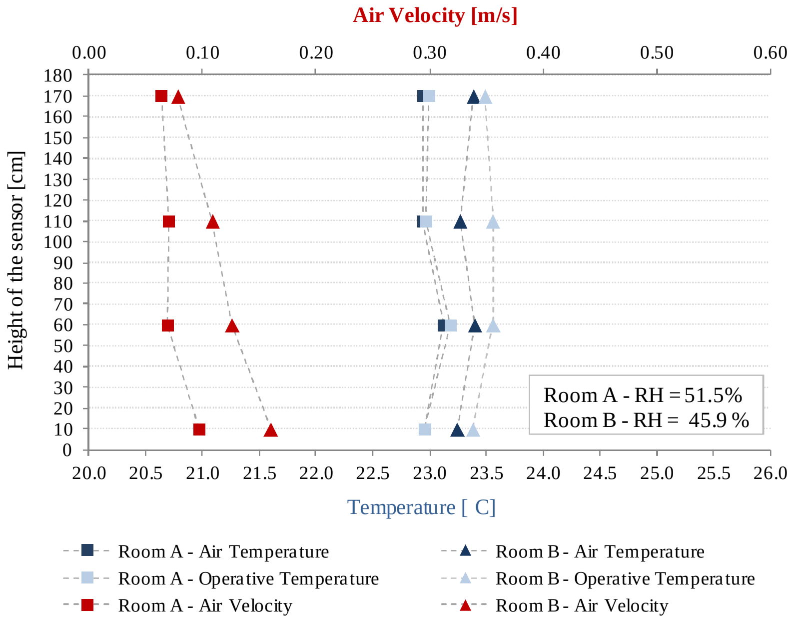

Figure 10.Winter spot measurements. Average value of air temperature, operative temperature and air velocity at different heights for Room A and B.

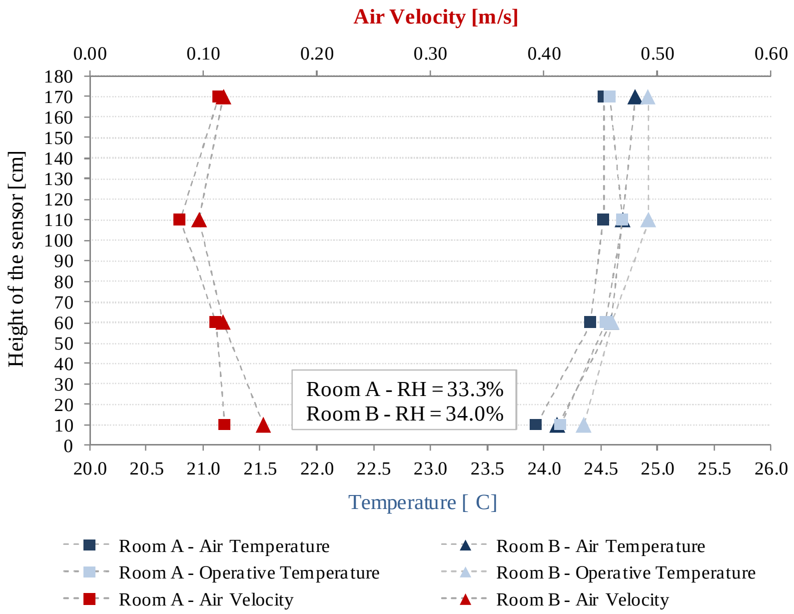

Figure 11. Summer spot measurements. Average value of air temperature, operative temperature and air velocity at different heights for Room A and B.

It is important to highlight that the spot measurements represent just a particular situation in a precise moment, and they are not representative of the seasonal indoor environmental quality. For example, in both the cases here illustrated, the outside weather conditions were different by the average values described in Table 2. On March, 22 the outside temperature was 9.4 [°C] greater than the average value of the month. The same was for the summer: on the 10 of August the outside temperature was 4.3 [°C] lower than the Augusts' average (Table 2).

Table 4. Average outdoor climatic data, monitored during the occupancy hours, for the two days in which spot measurements were performed.

Month	Solar radiation [W/m²]	Outside Temperature [°C]	Relative Humidity [%]	Wind Velocity [m/s]	Mean degree direction
March, 22	246	13.5	70.2	2.72	303
August, 10	241	15.0	71.8	2.54	248

Through these reasons, it is possible to explain why during the winter spot monitoring the operative temperature in both the rooms was slightly greater than 23 [°C] (upper limit of Category I). In contrast to the long term evaluations showing that the temperatures in winter were on averagely lower than 23 [°C] (easy to see from Figure 4).

In the spot monitoring also air velocity was evaluated. By air temperature and relative humidity it was possible to verify that in the two analyzed rooms the percentage of dissatisfied for draught was always below the limit suggested by standard ISO 7730 [1] for Category I.

The subjective evaluation of the thermal environment was obtained with questionnaires. This evaluation has been performed using the ASHRAE thermal sensation scale, where: +3 corresponds hot , +2 warm, +1 slightly warm, 0 neutral, -1 slightly cool, -2 cool, -3 cold. Figure 11 shows the average evaluation given by the occupants of the thermal sensation perceived in the two rooms .

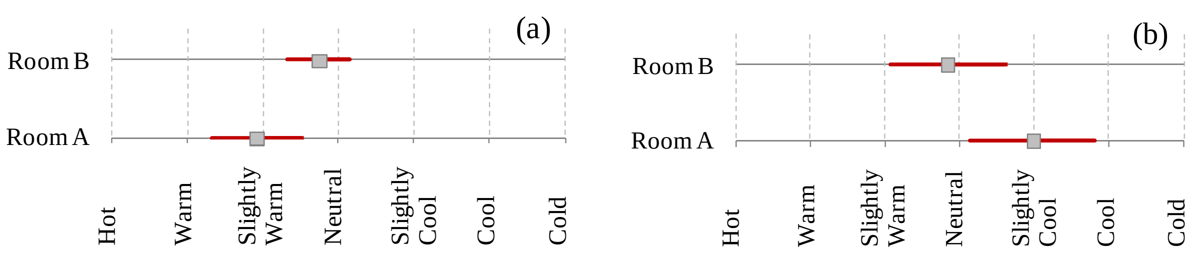

Figure 11. Subjective evaluation of the thermal environment on winter (a), and on summer (b).

The graphs show that the occupants perceived the environment from neutral to slightly warm during the winter spots. This sensation can be explained by the higher operative temperature in the rooms (23-23.5 C) with respect to the average for winter period. Regarding the summer thermal sensation emerge that in Room A, mechanically ventilated, the people perceived the environment slightly cool. In both cases, winter and summer in the mechanically ventilated room (A), the occupants felt more warmer (+1) in winter and colder (-1) in summer than in the naturally ventilated room (B), where the occupants in both seasons felt close to neutral. Looking at the calculated PMV indexes reported in Table 5, the difference between the PMV and PPD values obtained for Room A and Room B, in summer or winter period, is really small,. The difference between the average thermal sensation value(TSV) and the PMV-index larger in the mechanical ventilated Room A than in the natural ventilated room B.

Table 5. Average outdoor climatic data, monitored during the occupancy hours, for the two days in which spot measurements were performed.

Floor	Room	Number of People	Icl [clo]	Average Subjective response	Calculated PMV (0.6 m)	Calculated PPD (0.6 m)
Winter	Room A	7	0.79	1.09	0.11	5.25
	Room B	9	0.83	0.26	0.18	5.65
Summer	Room A	3	0.77	- 0.98	-0.10	5.19
	Room B	5	0.71	0.26	-0.24	6.22

The differences between subjective responses and calculated PMV values can be furthermore justify by the difference of outdoor temperature during the spot monitoring days compared to the outside temperatures in the previous days. The subjective response depends by a combination of factors, including the expectations of the indoor environment deriving by previous experiences.

DISCUSSIONS AND CONCLUSIONS

The main idea behind the categories for IEQ assessment is to use them from the design up to the post-occupancy phase for buildings and HVAC systems analysis, in order to provide evaluations about the indoor environment over a longer period like a year. The intention is not to force the operation of a building within one class the whole year, but to critically analyse the possible change of classes over the year. In fact, even if a building is designed for a lower category, it will still be possible to operate the building the majority of the year in a higher category. For building with HVAC systems the categories are based on different levels of the PMV-PPD index and/or operative temperature. If the long term evaluation also will be used to analyse a problem and find solutions it is important to evaluate the deviations outside the categories on the warm and cold side separately. In practice, very often, operative temperature is the reference parameter used in field investigations. It is, however, questionable if fixed temperature ranges should be used for a long term evaluation. In fact, people often adapt their clothing according to the outside climate: this is true for both mechanical and naturally ventilated buildings. This aspect needs to be deeper studied in future researches, in order to take this into account for category range definition.

In this paper the use of categories for the thermal environment and indoor air quality assessment in an office building is performed. Two different environment (naturally ventilated and mechanically ventilated), part of the same office building, are compared. Results and elaboration about long term monitoring and spot monitoring in the selected rooms are shown.

Different methods of classification for the long term evaluation suggested by the standards are analysed, and critical aspects are highlighted. A variation of application of one of the method suggested by the standard EN ISO 15251 is presented. Representation and elaboration of data from spot measurements, and importance of this analysis, are also shown in this paper.

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8.2. PAPER II

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Categories of indoor environmental quality and building energy demand for heating and cooling.

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Categories of indoor environmental quality and building energy demand for heating and cooling

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Research Article

Abstract

Maintaining suitable indoor climate conditions is a need for the occupants' well being, while requiring very strictly thermal comfort conditions and very high levels of indoor air quality in buildings represents also a high expense of energy, with its consequence in terms of environmental impact and cost. In fact, it is well known that the indoor environmental quality (IEQ), considering both thermal and indoor air quality aspects, has a primary impact not only on the perceived human comfort, but also on the building energy consumption. This issue is clearly expressed by the European Energy Performance of Buildings Directive 2002/92/EC, together with the most recent 2010/31/EU, which underlines that the expression of a judgment about the energy consumption of a building should be always joint with the corresponding indoor environmental quality level required by occupants. To this aim, the concept of indoor environment categories has been introduced in the EN 15251 standard. These categories range from I to III, where category I refers to the highest level of indoor climate requirement. In the challenge of reducing the environmental impact for air conditioning in buildings, it is essential that IEQ requirements are relaxed in order to widen the variations of the temperature ranges and ventilation air flow rates. In this paper, by means of building energy simulation, the heating and cooling energy demand are calculated for a mechanically controlled office building where different indoor environmental quality levels are required, ranging from category I to category III of EN 15251. The building is located in different European cities (Moscow, Torino and Athens), characterized by significantly different wheatear conditions. The mutual relation between heating and cooling energy demand and the required levels of IEQ is highlighted. The simulations are performed on a typical office room which is adopted as a reference in validation tests of the European Standard EN 15256 to validate calculation procedures of energy use for space heating and cooling.

Keywords

indoor environmental quality,
categories,
energy demand,
building energy simulation

Article History

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Building Thermal, Lighting, and Acoustics Modeling

1 Introduction

In the recent years, the topic of the level of the indoor environmental quality in buildings has become more and more important, due to its direct correlation with operating energy consumptions in buildings (Fabrizio et al. 2010). This concept was explicitly introduced by the European Directive 2002/91/CE about the energy performance of building: the level of the indoor environmental quality have to be clearly defined before expressing the building energy consumption. In fact, the building energy performance rating must be shown together with the indoor environmental quality rating.

This specific topic is faced by European Standard EN 15251(2008) "Criteria for the Indoor Environment including thermal, indoor air quality, light and noise.", which introduces the concept of category of indoor environmental quality (IEQ), according to definition shown in Table 1. Standard EN 15251 analyses all the aspects of IEQ: thermal, indoor air, acoustic and visual quality.

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Table 1 Definition of IEQ categories according to EN 15251

Category	Explanation
I	High level of expectation and is recommended for space occupied by very sensitive and fragile persons with special requirements like handicapped, sick, very young children and elderly persons.
II	Normal level of expectation and should be used for new buildings and renovations.
III	An acceptable, moderate level of expectation and may be used for existing buildings.
IV	Values outside the criteria for the above categories. This category should only be accepted for a limited part of the year.

NOTE: In other standard like EN 13779 and ISO 7730 categories are also used; but may be named different (A, B, C or 1, 2, 3 etc.).

In general Standard EN 15251 specifies how criteria about IEQ can be established and used at the design stage; moreover it defines the main parameters to be used as input for building energy calculation and long-term evaluation of the indoor environment (Ansaldi et al. 2009). In particular, the standard proposes different types of classification of the indoor environment, which can be based on:

(1) criteria used for energy calculations (new buildings);
(2) whole year computer simulations of the indoor environment and energy performance (new and existing buildings);
(3) long-term measurement of selected parameters for the indoor environment (existing buildings);
(4) subjective responses from occupants (existing buildings).

In this paper, the analysis will focus on the above mentioned point (2) of standard EN 15251, applied to an office building with mechanical heating and cooling where different IEQ categories are required.

It is evident that high levels of IEQ, that is for example keeping relatively constant all over the year the set-point temperature in heating, ventilation, and air conditioning (HVAC) systems, produces high energy demand for space conditioning and, as a consequence, high environmental impacts due to air conditioning (Karlsson and Moshfeg 2006). To extreme the concept, high comfort level requirements means high CO_2 emissions and this is unacceptable in the modern "low-carbon economy". Therefore, educating and teaching people to a sustainable and environmental friendly behaviour in air conditioning can lead to high energy saving potentialities without high investment costs (Ouyang and Hokao 2009).

Now, the key question is: what is the effect in terms of energy consumption of a variation of recommended indoor temperature ranges and air change rates as it is expressed in EN 15251 Standard?

First of all, it is important to highlight that EN 15251 introduces two separated thermal environment recommended criteria, distinguishing between buildings with and without mechanical cooling.

In buildings with mechanical cooling, which are the focus of the present paper, the indoor thermal conditions are fixed according to the static model of thermal comfort, belonging to Fanger's theory based on the predicted mean vote (PMV) index (Fanger 1970). In particular, the recommended values of indoor temperature acceptable ranges in categories I, II and III are expressed for heating and cooling operating modes: when dynamic energy simulations are performed to evaluate building energy requirements, the indoor temperature is maintained within the defined ranges in order to keep the room in the desired IEQ category (Olesen 2007).

In buildings without mechanical cooling, the recommended ranges of operative temperature are expressed as a function of an index related to the outdoor climate (running mean outdoor temperature). This approach, widely described in the research activities carried out by De Dear and Brager (1998) and presented in ASHRAE RP-884, is also adopted by ASHARE Standard 55-2005. This approach is based on the adaptive comfort theory, highlighting that the people thermal perception can be modified by adaptive adjustment mechanisms (physiological, psychological or behavioural adjustment) which are emphasised in "naturally ventilated buildings" (Brager and de Dear 2000). In such buildings, the recommended ranges are not used to evaluate the cooling energy demand (without mechanical cooling there is no energy consumption for this purpose) but they are very useful to verify possible situation of overheating in the analyzed rooms. It is interesting to notice that some authors introduced some preliminary proposals about a sort of adaptive HVAC control strategy to fully exploit the potentialities of a shift from a static to an adaptive control (van der Linden et al. 2006).

In this scenario, it is fundamental to highlight the relationships among indoor environmental quality, energy consumption and environmental cost which are deeply influenced by the "indoor climatic control" strategies adopted for the HVAC systems (Corgnati et al. 2008; Fabrizio et al. 2010). The study here presented deals with the relationship between building energy consumptions and indoor environmental quality categories expressed by EN15251: the aim is to exploit the energy saving potential that is due to the relaxation of the IEQ requirements (moving from category I to III) but maintaining acceptable the thermal comfort and indoor air quality (IAQ) levels.

For a case study consisting in a typical mechanically controlled office room, the heating and cooling energy consumptions related to the different thermal and indoor air quality categories, according to Standard EN 15251 definitions, are calculated by means of energy dynamic simulations and compared in terms of both heating/cooling (delivered) energy and primary energy requirements. Three different European cities, characterised by significantly different wheatear condition along the year, are investigated: Moscow, Torino and Athens.

2 The simulation tool

The building simulation program used is Energy Plus version 4.0.0, a modular structure code developed by the US Department of Energy since 2001 (Crawley et al. 2001) that combines the best capabilities and features of BLAST and DOE-2. The building thermal zone calculation method of Energy Plus is a heat balance model (Energy Plus Manual). This model is based on the assumptions that the air temperature of the thermal zone, by default, is well stirred (complete mixing model), the temperature of each surface is uniform, the long- and short-wave irradiation is uniform, the surface irradiation is diffusive and the heat conduction through surfaces is one-dimensional. Non uniform air temperature distribution can be accounted for by alternative room air models.

The most common thermal comfort indicators (Operative temperature, PMV, predicted percentage of dissatisfied (PPD), etc.) are also calculated by the engine at the centre of the thermal zone by an area weighted surface temperature or in some other position in the zone once that the angle factors for each surface are defined. These factors should be calculated off-line.

3 Description of the case study

A typical room of an office building was adopted as a reference to evaluate the impact of the thermal comfort on heating and cooling energy demands. The reference room is drawn from validation tests of the European Standard EN 15256 on general criteria and validation procedures of calculations of energy use for space heating and cooling. The dimensions of the room are: length = 3.6 m; depth = 5.5 m; height = 2.8 m. The external wall including window is facing west. The area of the window is 2.6 m^2.

The thermophysical properties of the opaque components are resumed in Table 2: the thermal resistance varies as a function of the location, according to the national *U*-value

Table 2 Thermophysical properties of the opaque components

Material		d (m)	λ (W/(m·K))	ρ (kg/m^3)	c_p (kJ/(kg·K))
External wall	Outer layer	0.115	0.990	1800	0.85
	Insulating layer Athens	0.035	0.040	30	0.85
	Insulating layer Torino	0.095	0.040	30	0.85
	Insulating layer Moscow	0.210	0.040	30	0.85
	Masonry	0.175	0.790	1600	0.85
	Internal plastering	0.015	0.700	1400	0.85
Internal wall	Gypsum plaster	0.012	0.210	900	0.85
	Mineral wool	0.100	0.040	30	0.85
	Gypsum plaster	0.012	0.210	900	0.85
Internal ceiling	Plastic covering	0.004	0.230	1500	1.50
	Cement floor	0.060	1.400	2000	0.85
	Mineral wool	0.040	0.040	50	0.85
	Concrete	0.180	2.100	2400	0.85
Internal floor	Concrete	0.180	2.100	2400	0.85
	Mineral wool	0.040	0.040	50	0.85
	Cement floor	0.060	1.400	2000	0.85
	Plastic covering	0.004	0.230	1500	1.50
External ceiling	Plastic covering	0.004	0.23	1500	1.50
	Cement floor	0.060	1.400	2000	0.85
	Mineral wool Athens	0.025	0.040	50	0.85
	Mineral wool Torino	0.050	0.040	50	0.85
	Mineral wool Moscow	0.160	0.035	50	0.85
	Concrete	0.180	2.100	2400	0.85
	Mineral wool Athens	0.030	0.040	50	0.85
	Mineral wool Torino	0.060	0.040	50	0.85
	Mineral wool Moscow	0.200	0.035	50	0.85
	Acoustic board	0.020	0.060	400	0.84
External floor	Acoustic board	0.020	0.060	400	0.84
	Mineral wool Athens	—	—	—	—
	Mineral wool Torino	0.080	0.040	50	0.85
	Mineral wool Moscow	0.15	0.040	50	0.85
	Concrete	0.180	2.100	2400	0.85
	Mineral wool Athens	—	—	—	—
	Mineral wool Torino	0.020	0.040	50	0.85
	Mineral wool Moscow	0.060	0.040	50	0.85
	Cement floor	0.060	1.400	2000	0.85
	Plastic covering	0.004	0.23	1500	1.50

requirements in European countries (Seppänen 2010). The solar and thermal characteristics of the windows are given in Table 3.

As to the internal sources, there are two people (occupancy = 10 $m^2_{floor\ area/person}$) at an activity level of 126 W/person, with a fraction radiant of the sensible heat equal to 0.4 and a work efficiency equal to 0.0 (all of the energy produced in the body is converted into heat). Heat gains are assumed equal to 15 W/m^2 (with a radiant fraction of 0.5). The occupancy schedule plans the presence of the people (100%) from Monday to Friday, from 8:00 to 18:00.

During the night time, on Saturday and on Sunday no people is inside the room. The HVAC plant availability schedule is equal to the schedule of the people presence.

Torino (45°N, 7°E) is the location where the first set of simulations are carried out. Then the simulations are extended to the location of Moscow (55°N, 37°E) and Athens (37°N, 23°E). The climate of Torino is temperate and subtropical, with hot and humid summers and cold and dry winters. The climate of Moscow is cold continental, with extremely cold and long winters and short summers, seldom hot. On the opposite, the climate of Athens is Mediterranean with hot and dry summers and mild winters.

In this paper, the heating and cooling energy demands are calculated for different indoor environmental quality levels—thermal and indoor air quality—required and expected by occupants. To select the indoor environment requirements, the comfort categories presented in Table 1 of the EN 15251 standard are adopted. These are

- Category Ⅰ—high level of expectation
- Category Ⅱ—normal level of expectation
- Category Ⅲ—acceptable, moderate level of expectation

In Table 4, the indoor air quality expressed in terms of ventilation flow rates for a low polluted single office and the indoor thermal quality expressed in terms of operative temperatures recommended for office room are shown for the described three comfort categories. Nine different combinations of the categories expresses in Table 4 can be selected ranging from category Ⅰ-Ⅰ (IAQ in category Ⅰ and thermal quality in category I) to category Ⅲ-Ⅲ.

In order to evaluate the differences in the energy demand among rooms situated in various positions in the building (Fig. 1), with different heat loss surfaces and with different solar expositions, nine different room configurations are considered in the simulations. As shown in the figure, two extreme situations are considered. The first analysis (Case A) considers a room located in an intermediate floor with only one external wall including the window (west exposed); all other surfaces, ceiling and floor are adiabatic. The second analysis (Case B) considers the test room located at the corner of the uppermost floor of the building with one external wall including the window (west exposed); ceiling and the wall south exposed are opaque external surfaces; all the other surfaces and the floor are adiabatic.

Table 3 Thermophysical properties of the windows

Component		Transmittance	Reflectance	Absorptance
Shading		0.20	0.50	0.30
Pane		0.84	0.08	0.08
Thermal resistences including convection and long wave radiation (m^2·K/W)				
External				0.0435
Between external blind and external pane				0.0800
Between external pane and internal pane				0.1730
Internal				0.1250
City	Layers	Visible light transmission (%)	Solar energy transmission (%)	U-value (W/(m^2·K))
	Glass (4)	89	96	5.60
Athens	4-12-4 (air)	80	76	3.00
Torino	4-12-4-12-4 (argon)	72	67	1.90
Moscow	4-12-4-12-4 (krypton)	67	55	0.75

Table 4 Indoor air quality and thermal quality levels according to EN 15251

Comfort category	Recommended ventilation flow rates for a low-polluted single office (L/(s·m^2))			Recommended indoor operative temperature ranges (℃)	
	q_P (for occupancy)	q_B (for the building)	q_{tot} ($q_P + q_B$)	Heating (clothing 1.0 clo)	Cooling (clothing 0.5 clo)
Ⅰ	1.0	1.0	2.0	21.0–23.0	23.5–25.5
Ⅱ	0.7	0.7	1.4	20.0–24.0	23.0–26.0
Ⅲ	0.4	0.4	0.8	19.0–25.0	22.0–27.0

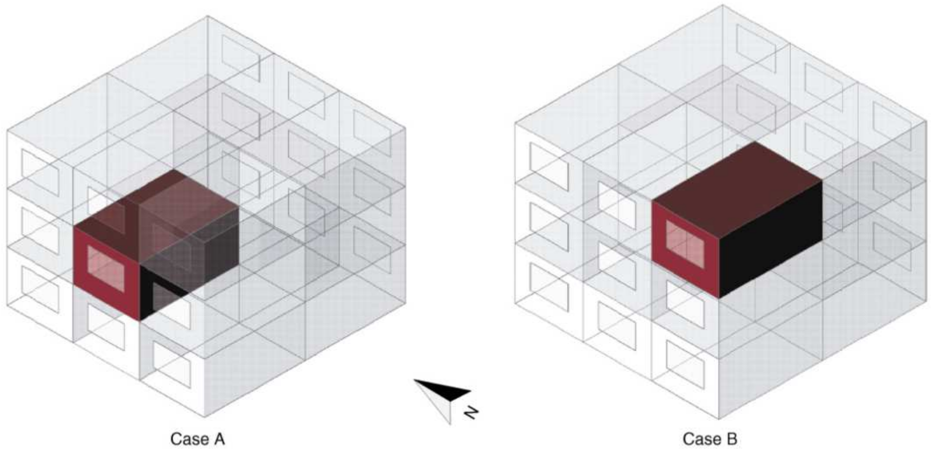

Fig. 1 Analysed rooms in the case study building

The heating and cooling periods were determined by means of two preliminary simulations over the complete year: first, the operative temperature was set to 20℃ (lower limit for heating) in order to determine, from the ideal heating load profiles the heating period, then in the second simulation it was set to 26℃ (upper limit for the cooling), in order to determine, from the ideal cooling load profile, the cooling period. The values of 20℃ and 26℃ correspond respectively to the lower and upper category Ⅱ operative temperature limits. Also for the ventilation rate, the comfort category was set equal to Ⅱ (1.4 L/(s·m^2)). Figure 2 shows the sensible heating/cooling rate (Case A) for the city of Torino and, based upon those curves, the heating and cooling periods of time. These are interspersed with periods (spring and autumn) where the environment is considered as free running (no air conditioning).

With the same comfort categories, similar simulations were carried out for the Athens and Moscow locations. The heating and cooling periods that were chosen, for the three locations, are reported in Fig. 3.

The case studies are analyzed both in terms of space heating and cooling energy demand and in terms of primary energy for heating and cooling. The conversion of space energy demand to primary energy was carried out firstly by calculating the delivered energy demand to the building considering an ideal HVAC system and an heat generator with mean efficiency $\eta = 0.8$ and a chiller with COP = 3.5. Then, the delivered energy was converted into primary energy by applying the conversion factors for natural gas and electricity that are reported in the EN 15603 standard ($fp_{gas} = 3.36$, $fp_{electricity\ mixUCPTE} = 3.14$). These conversion factors were preferred to the national conversion factors in order to maintain an uniformity between the results and to make possible the comparison among the various locations.

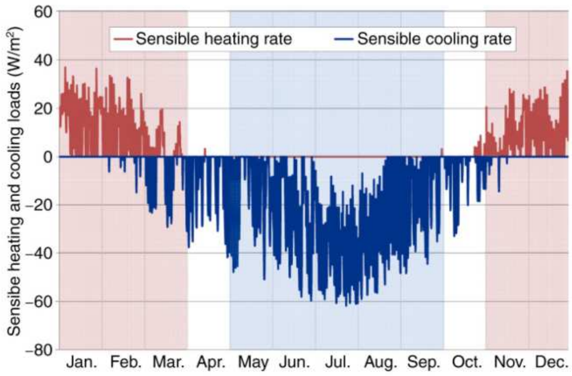

Fig. 2 Sensible heating and cooling loads and heating and cooling periods of time for the Torino location and test Case A

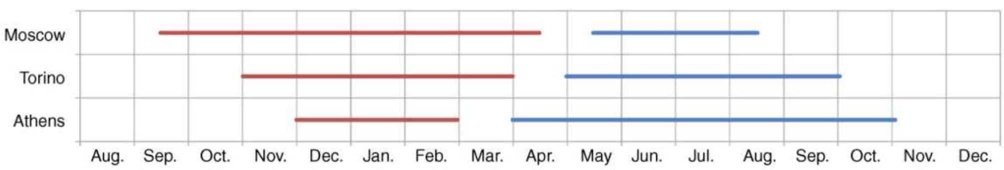

Fig. 3 Heating and cooling periods for the three locations

4 Results and discussions

Space heating and cooling energy demands for different categories of indoor air quality and thermal quality are evaluated for Cases A and B of Fig. 1 located in Torino and presented in Tables 5 and 6. Below each result, the percentage reduction with reference to the value assumed for the comfort category Ⅲ-Ⅲ is indicated.

From the data reported in Table 5, the fact that the variation in the primary energy demand is much affected by heating than cooling can be appreciated. In the case of heating, in fact, moving from Class Ⅲ-Ⅲ to Class Ⅰ-Ⅰ, it can be seen that the energy demand is more than doubled. Energy costs increase both when the indoor air quality and the thermal quality increase.

This is unlike the cooling, where the energy costs rise for an increase in the operative temperature category, but fall for an increase of the ventilation rates category. This is because, for the Torino climate, where the outside air temperature is often below the internal air temperature, an increase in the natural ventilation flow rates in summer allows a free cooling of the indoor environment. Conversely, the less ventilation is made, the more the energy costs for cooling increase, as a result of an increase in the internal temperature. During the heating season, however, the outside air is always at a temperature lower than the preferred temperature; in this case an increase in the ventilation rates helps to lower the indoor temperature, thus requiring the mechanical heating.

The same considerations can be made for the results of Case B that are summarized in Table 6. Compared to the previous case, the total primary energy demand has increased. Due to an increase in the heat loss surface of the test room, the energy consumption for heating sees a significant percentage increase. As for cooling, however, the change in energy demand follows the same trend but the percentage change are always small.

The frequency distribution curves reported in Fig. 4 were made assuming different categories of operative temperature (from Ⅰ to Ⅲ) and maintaining a constant ventilation category equal to Ⅱ. The operative temperature range in the definition of these curves is equal to 0.2℃. It can be seen from Fig. 4 how the operative temperature fall between, for most of the time, the lower and higher values set by the EN 15251 standard for respectively heating and cooling modes (Table 4). This frequency distribution is justified by the fact that the system assumed in these simulations is an ideal type of plant. This, having the characteristic of an immediate supply to the energy needs from building, does not consider the gradual change of temperature that always occurs in real cases and depends on the type of system that is used.

Table 5 Case A (Torino): primary energy for space heating and space cooling for different comfort categories (operative temperatures and ventilation rates)

			Heating (kWh/m²)			Cooling (kWh/m²)		
			Comfort category			Comfort category		
			Ⅲ	Ⅱ	Ⅰ	Ⅲ	Ⅱ	Ⅰ
Comfort category	Ventilation rate (L/(s·m²))	Operative temperature (℃)	19–25	20–24	21–23	22–27	23–26	23.5–25.5
Ⅲ	0.8		16.06	17.06	18.10	21.59	23.39	24.34
		Difference	Ref.	6%	13%	ref	8%	13%
Ⅱ	1.4		19.20	21.74	24.63	19.56	21.82	22.58
		Difference	20%	35%	53%	−9%	−1%	5%
Ⅰ	2.0		28.58	32.95	37.78	18.01	20.64	21.99
		Difference	78%	105%	135%	−17%	−4%	2%

Table 6 Case B (Torino): primary energy for space heating and space cooling for different comfort categories (operative temperatures and ventilation rates)

			Heating (kWh/m²)			Cooling (kWh/m²)		
			Comfort category			Comfort category		
			Ⅲ	Ⅱ	Ⅰ	Ⅲ	Ⅱ	Ⅰ
Comfort category	Ventilation rate (L/(s·m²))	Operative temperature (℃)	19–25	20–24	21–23	22–27	23–26	23.5–25.5
Ⅲ	0.8		16.63	15.19	16.97	29.17	31.54	32.80
		Difference	Ref.	11%	25%	Ref.	8%	12%
Ⅱ	1.4		20.28	23.46	26.95	27.69	30.43	31.77
		Difference	43%	72%	98%	−5%	4%	9%
Ⅰ	2.0		31.23	36.13	41.46	26.27	29.45	31.06
		Difference	123%	165%	204%	−10%	1%	6%

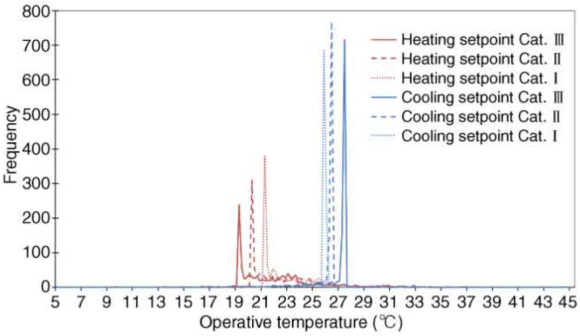

Fig. 4 Case A (Torino): frequency distribution curves of the operative temperature for various operative temperature categories and a ventilation rate category Ⅱ

Similarly to the Torino location, simulations were performed for the cities of Moscow and Athens. Due to cold winter weather conditions, the simulations for Moscow were performed both without and with a ventilation air heat recovery, which is characterized by a mean seasonal efficiency of 75%. In Figs. 5 – 8, the comparison of the main results obtained in the three cities with reference to Case A are presented: the results for Moscow with heat recovery are labeled as $\text{Moscow}_{\text{rec}}$.

As can be seen from the Figs. 5 and 6, Athens has a primary energy demand for cooling that is much higher than the primary energy demand for heating, regardless of the cases analyzed (A and B) and independently by the operating temperature categories. Contrarily, the city of Moscow without heat recovery. In the case of Torino, both primary energy demand for heating and cooling have a significant contribution. In all the cases that were simulated, the energy demand is bigger in Case B respect to the Case A, and it grows for an improvement (Ⅲ to Ⅱ and Ⅰ) in the operative temperature category. From Fig. 5, the influence of the variation of the operative temperature category can be appreciated: the ratio between the primary energy demand for heating and cooling (PE_h/PE_c), in the various cases, is equal to about 5.0 for Moscow without heat recovery, 1.45 for Moscow with heat recovery, 0.63 for Torino and 0.12 for Athens. Results for Moscow show a significant reduction of heating energy demand when the ventilation air heat recovery is used.

The rectangles in Figs. 5 and 6 also highlight the amplitude of the variation in the primary energy for heating and cooling. When the climate becomes more cold, the longest side of the rectangle is the vertical one. Again, it is evident that the variation of the ventilation rate category has an effect greater for a change in the ventilation rate category than for a change in the operative temperature category; the absolute values of the variations are reported in the same figures.

From the graph that is reported in Fig. 6, it can be seen that in cold climates, a change in the ventilation rate category affects the heating energy much more than a change in the operative temperature category (Fig. 5). The ratio PE_h/PE_c equals 14.4 for Moscow without heat recovery, 2.2 for Moscow with heat recovery, 1.9 for Torino and 0.24 for Athens.

The analysis of the office cases A and B, which are located in two different position in the building (Fig. 1) shows that there is not a significant influence on the energy demand for heating, while there is an increase from 10 to 15 kWh/m^2 on the energy demand for cooling.

In Fig. 7 the primary energy is plotted as a function of the degree days (determined from the IEWC weather file statistics); this is done for both heating and cooling, and it can be seen that the slope of an hypothetical tendency curve

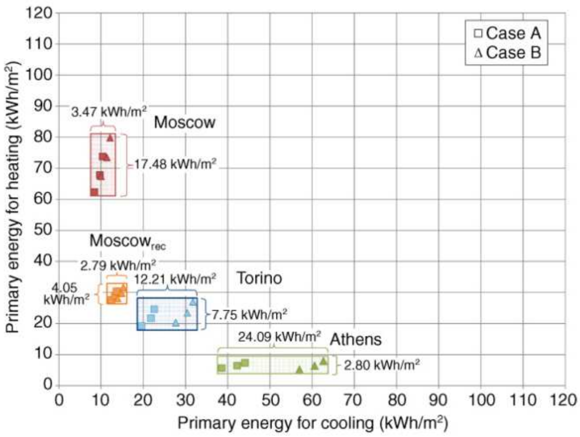

Fig. 5 Primary energy for heating vs. primary energy for cooling, Cases A and B for the Athens, Torino and Moscow locations, at the variation of the operative temperature category (ventilation rate category set to Ⅱ)

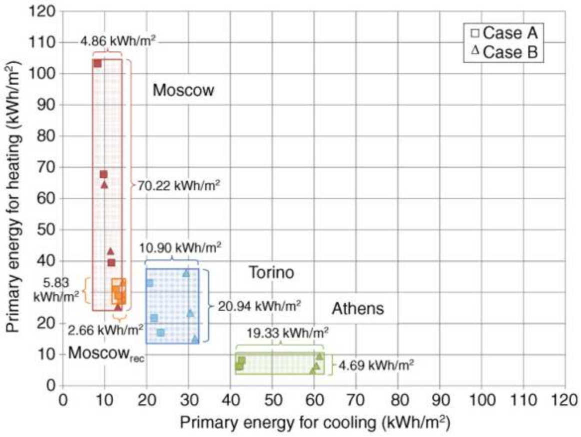

Fig. 6 Primary energy for heating vs. primary energy for cooling, Cases A and B for the Athens, Torino and Moscow locations, at the variation of the ventilation rate category (operative temperature category set to Ⅱ)

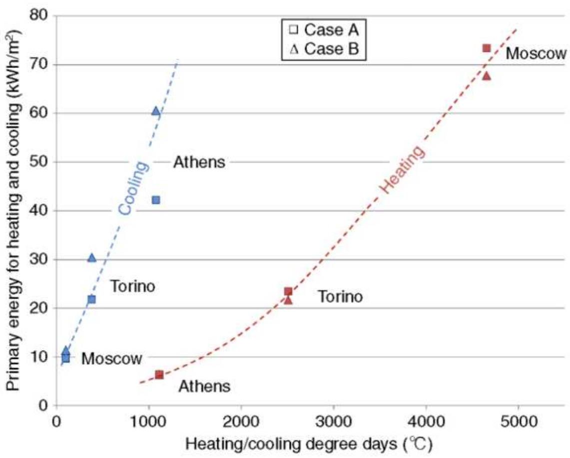

Fig. 7 Primary energy for heating/cooling as a function of the heating/cooling degree days for operative temperature category Ⅱ and ventilation rate category Ⅱ

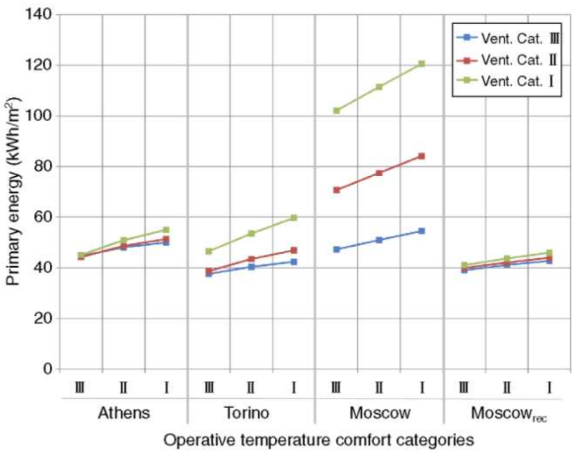

Fig. 8 Primary energy demand for heating and cooling vs. operative temperature categories as a function of the ventilation rate categories

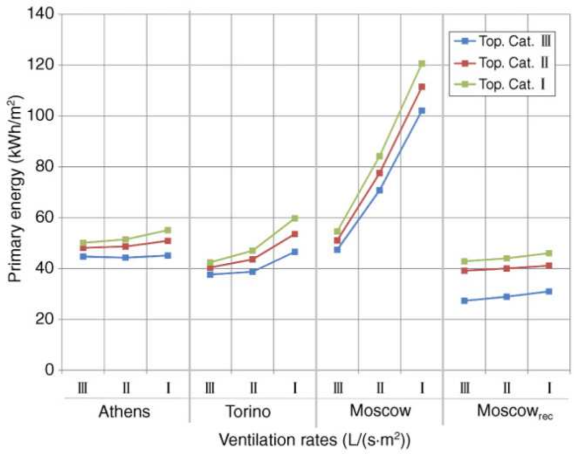

Fig. 9 Primary energy demand for heating and cooling vs. ventilation rate categories as a function of the operative temperature comfort categories

(the dashed ones in Fig. 7) is higher in the cooling mode than the one of the heating mode. This also points out the fact that for an increase of degree-days, more primary energy must be consumed for cooling than for heating purposes. In order to compare homogeneous results, the case of Moscow with heat recovery is not considered in this graph.

In Fig. 8, the primary energy demand for heating and cooling is represented, for the three analyzed locations (Moscow with and without heat recovery), at three different operative temperature comfort categories as a function of the ventilation rates categories. In all the three locations, it can be seen that for a change in the ventilation category (Ⅲ to Ⅰ) the primary energy demand increases if the climatic conditions are more stringent. This factor is due to the fact that in winter the temperature difference between indoor and outdoor (ΔT) in Moscow is very high and therefore, increasing the category of indoor air quality, automatically increase the ventilation losses: this is the reason why the ventilation air heat recovery was applied to the Moscow case. The same thing happens in the other two cities under consideration, but energy costs are lower proportionally to the decrease of ΔT. The variations between the upper and the lower ventilation rate categories are of the order of the 1%—10% for Athens, 24%—41% for Torino and 116%—121% for Moscow (without heat recovery).

From Fig. 9, it can be seen that the operative temperature variation is less important than the ventilation rate variation. The curves for Athens, Torino and Moscow are closer than the ones in Fig. 8; on the contrary for Moscow$_{rec}$ the effect of operative temperature category variation is greater than the effect of ventilation rate category variation. The variations between the upper and the lower operative temperature categories are of the order of the 12%—22% for Athens, 13%—28% for Torino and 15%—18% for Moscow (without heat recovery).

5 Conclusions

In the present paper, the topic of the relationship between indoor environmental quality categories and building energy demands was investigated. The IEQ categories introduced by standard EN 15251 were taken as a reference, considering both indoor thermal and air quality requirements: variations of operative temperature and air ventilation rate were considered. Three European locations, characterised by different climate conditions, were considered: Moscow (coldest), Torino and Athens (warmest).

The main results are here summarised.

In general, in cold climate the energy requirements for heating are prevalent and the influence of expected indoor air quality level prevails on primary energy demand: due to this reason, it is always desirable to the thermal recovery from ventilation air. With reference to this aspect, in the analyzed locations, the range of variation of the primary energy demand for heating can go up to 70 kWh/m^2 for a variation in the ventilation rates in the coldest climate without heat recovery, while the same quantity varies only of about 17 kWh/m^2 for a variation in the operative temperatures; in the warmest climate, both the variation are negligible and equal to 2 – 3 kWh/m^2.

In hot climate the energy requirements for cooling are prevalent and the influence of expected indoor thermal quality level prevails on primary energy demand. With reference to the this aspect, in all the analyzed locations, the range of variation of the primary energy demand for cooling due to a change in the ventilation rates is similar to the one due to a change in the operative temperatures and is equal to 19 – 24 kWh/m^2 for the warmest location, while it decreases to around 5 kWh/m^2 for the coldest location.

A significant difference between Case A and Case B can only be appreciated in case of the cooling energy demand.

These aspects should be taken carefully into account when designing and operating an HVAC system in each one of those climates: in fact, the developed study highlights significant influences of IEQ selected categories on the building energy demand.

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8.3. PAPER III

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Detection and representation of total energy use and indoor climate quality in buildings: application to an office building through in field monitoring.

Manuscript, under internal reviewing.

Detection and representation of total energy use and indoor climate quality in buildings: application to an office building through in field monitoring

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ABSTRACT

The study on the buildings energy performance has been increasingly addressed in recent years on real energy consumptions evaluation. What it is essential to clarify is that building energy consumptions are strictly correlated with the indoor climate quality required by the occupants. In this regard when real consumptions are examined is essential to consider the contextual analysis of the indoor climate quality levels maintained in the spaces.

Both total energy use and climate quality can be expressed with different levels of detail, in terms of kind and grade of information, deepening the analysis from the entire building to the single rooms. For example consumptions can be assessed starting from the primary energy, till the energy consumptions of the end-uses.

In order to make an evaluation of the total performance of a building in this paper different levels of information for the energy analysis are introduced, and methods for presenting the results, including both energy performance and indoor climate quality are presented too. Moreover, this paper proposes a methodological approach for the analysis of energy and indoor climate quality in buildings, conducted through long-term in field monitoring.

Keywords: Energy consumptions, Indoor Climate quality, Energy evaluation, Indoor climate evaluation, Data representation

1. Introduction

In recent years, attention toward to the buildings energy performance study has been increasingly addressed on real energy consumptions. When real consumptions are examined is essential to consider the contextual analysis of the indoor climate quality levels maintained in the spaces, at which consumptions are connected.

Furthermore, it is essential to clearly define which is the control surface to investigate for the consumption evaluation: starting from the consumed energy sources up to energy the end-uses.

It is obvious that to fully explore this issue is necessary to have a measurement system, which is appropriately positioned by mean a dedicated monitoring plan. Moreover this system have to be able to provide all the useful information about the real behaviour of the building, from the consumptions, till the values of the thermo-hygrometric parameters.

Once measured, the variables need to be elaborated and analyzed to provide an overview of the building-plant system energy metabolism: the process can be presented at gradually increasing levels of detail. Investigations may relate the energy consumption and the associated end-uses subdivision, or the relationship between energy consumption and obtained environmental quality.

The next step concerns the results representation ability. This aspect is essential because requires to identify synthetic indicators, capable to clearly express the energetic quality of the building, moreover the building energy systems quality. Synthetic indicators both respect to the space and to the time variables.

This article proposes a methodological approach for the analysis of energy and indoor climate quality in buildings, conducted through long-term in field monitoring. The approach is then tested and shown through a case study, consisting of an office building with the bank intended use.

In particular are introduced different levels of information for the energy analysis, and methods for presenting the results, taking into account both the energy performance and indoor climate quality.

2. Levels of detail in energy and indoor climate quality detection

Both total energy use and comfort quality can be expressed with different levels of detail, in terms of kind and grade of information, deepening the analysis from the entire building to the single rooms. In the next paragraphs these levels of detail are investigated.

2.1 Total energy use

Total energy use of a building can be described according to the approach proposed by the standard EN 15603:2008 [4], and subsequently revised and integrated in the system boundary for net delivered energy scheme introduced by [1,13] and adopted by REHVA task force "Nearly Zero Energy Buildings" (nZEB) [3,15]. That diagram is a schematic drawing in which energy carriers are illustrated and where all energy uses of a building, or part of its, can be taken into account. Similar schemes to the one here proposed, in which energy carriers in buildings and system networks are part of the dealt study, are available in literature [16-18, 21] In this paper, the description of the energy uses is proposed to be performed with different levels of detail and, a way to represent these, is also suggested in order to provide a clear picture of the building as an organism fed by energy. As figure 1 shows, this action helps in clarifying the energy required by the entire building, by its systems or by single zones or rooms. The proposed levels of detail are four:

- *Level 1: Delivered primary energy* – It indicates the total primary energy delivered to the building, at the net of the exported energy (if presents), obtained by multiplying the delivered energy (Level 2) by a primary energy factor that takes into account the extraction of the energy carrier, its transport to the utilization site, as well as for processing, storage, generation, transmission, distribution and delivery [2]. Standard EN 15603:2008 [4] indicates, in the Annex E, the European primary energy factors for renewable or not renewable delivered energy. Primary energy factors, to use in case of lack of more accurate values, are however always determined at national level by national standards.

- *Level 2: Delivered energy* – It is the energy needed from a building for heating, cooling, ventilation, domestic hot water, lighting and appliances. Represents the energy delivered to the building (electricity, fuel, district heating, etc.), but also the renewable energy produced on site (solar energy, geothermal energy, etc.).
- *Level 3: Net energy needed by the technical systems* – It represents the thermal or electrical energy required by the building technical systems (heating system, cooling system, ventilation system, etc.). This energy is from the delivered energy to the building or from on site renewable energy (Level 2).
- *Level 4: Space net energy needed* – It is the net energy required for a single room or zone of the building. It is the energy supplied by the technical systems (Level 3) to the rooms' terminal devices (radiant systems, radiators, convectors, diffusers of the ventilation systems, lighting equipments, appliances, etc.).

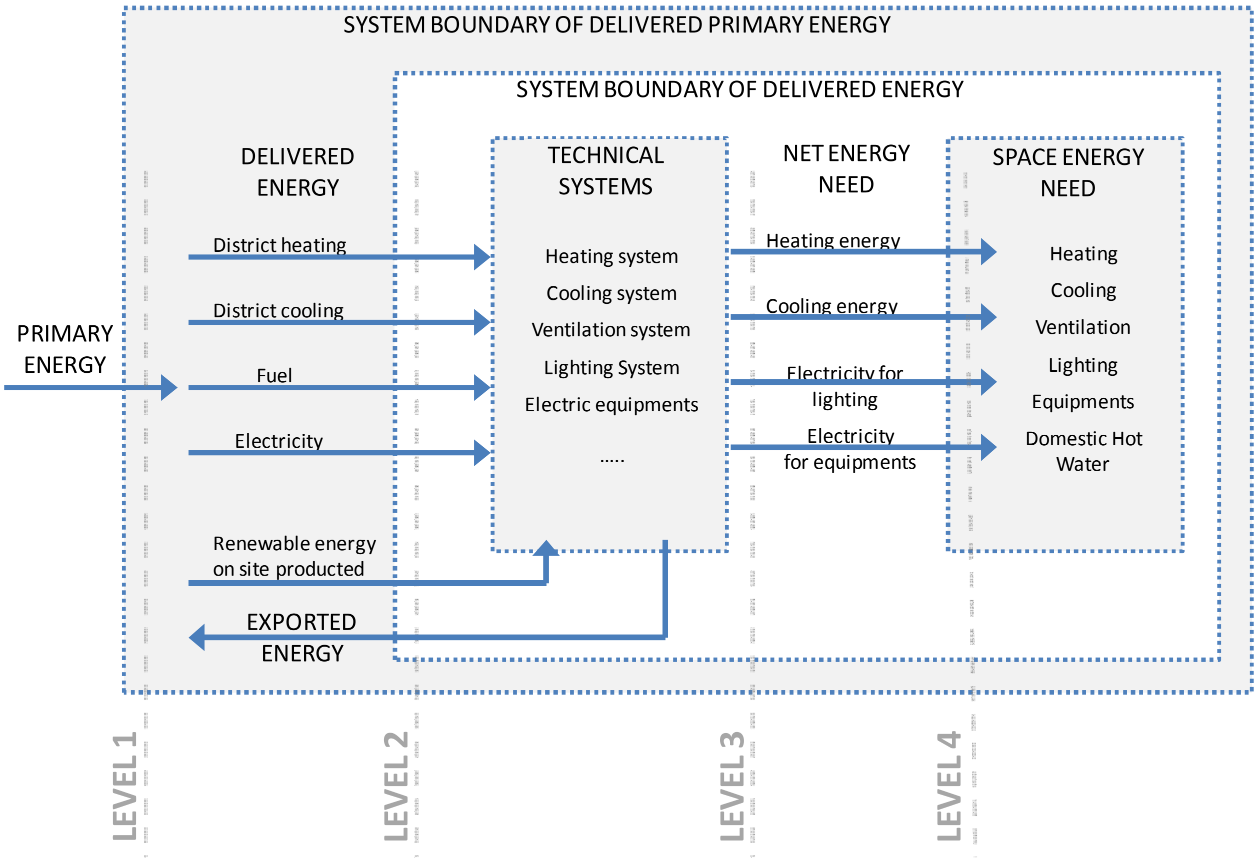

Figure 1. Energy flow scheme and levels of detail in the analysis of building total energy use.

2.2 Indoor Climate Quality (ICQ)

Similar approach to the one used for the total energy use analysis can be adopted for the climate quality assessment. Also in this case different levels of detail can be introduced in the indoor comfort evaluation. This time, the three levels are proposed as it follows, and illustrated in figure 2:

- *Level 1: Whole building indoor climate analysis* – It describes the indoor climate quality of an entire building considering, in a single evaluation, the performance of different thermal zones and of all the single rooms of which the building is composed.
- *Level 2: Single Indoor climate zone evaluation* –It is the ICQ evaluation related to a group of rooms characterized by similar kind of installed systems, exposure and intended use. In these rooms the environmental parameters are almost the same, and in the comfort analysis a single room can be representative of the entire thermal zone.
- *Level 3:* Indoor climate quality *evaluation in specific rooms* – Represents the ICQ assessment in a specific room, in which particular environmental conditions need to be respected.

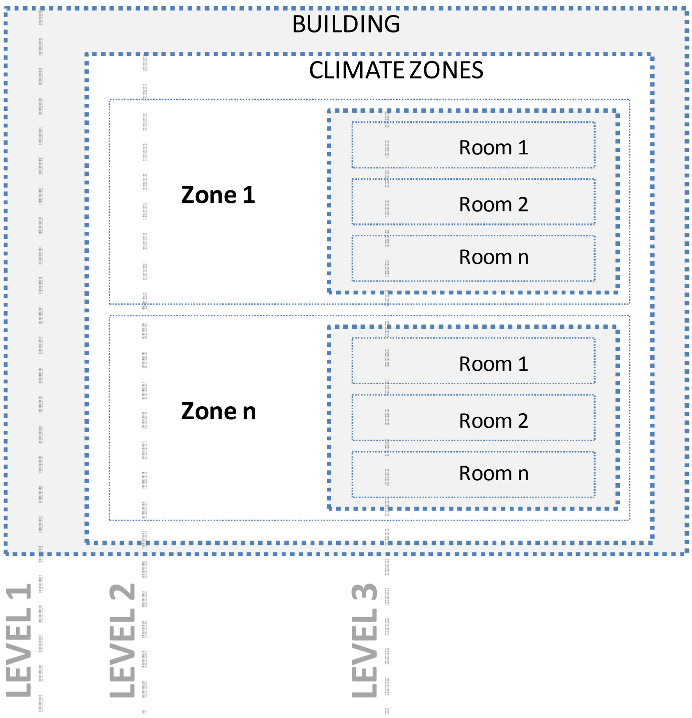

Figure 2. Levels of detail in the analysis of indoor climate quality.

Indoor climate quality in the building, thermal zones and single rooms can be assessed with long term or spot evaluations (through calculations or measurements) of the environment. In both cases the respect of the indoor environment conditions is due according with the suggestions given by the European standards 15251:2007 [6] (Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics), 7730:2005 [7] (Ergonomics of the thermal environment - Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria), and ASHRAE Standard 55:2007 [8] (Thermal environment conditions for human occupancy).

3. Long term evaluation: yearly, seasonal, monthly, weekly or daily.

Both energy and indoor climate quality can be assessed for long or short periods of time. Energy and comfort data, from on site monitoring or from calculations (obtained through the use of suitable energy simulation tools) can be elaborated for different periods of time, like years or seasons, otherwise it can be useful to focus on specific periods of time, like months, weeks or days. Independently by the length of these intervals, the analysis can be due for all the levels of detail listed before, allowing to evaluate in this way the performance of the entire building, of an indoor climate zone, or of a single space.

Examples of energy and comfort analyses, treated for different levels of detail and for different periods of time, are shown and examined in the next paragraphs through an office case study building.

4. Case study

4.1 Building architecture and envelope thermophysical properties.

The case study is a 5380 m^2 building located in the city of Middelfart, Denmark (Lat: 55.5°, Lon: 9.75°). The 80% of the floor surface is occupied by bank offices, while the other 20% hosts external activities: a bookshop, a cafè, a dress shop and a real estate agent. The building has a complex shape, characterized by the particular geometry of the roof (see figure 3). Commercial activities are situated at the ground floor, while bank offices are placed on three different floors, and changing and technical rooms are located on the basement. The main open plain offices are placed on four open terraces, called plateaus, situated at different levels and connected to each other by broad staircases. On each floor also single offices, meeting rooms and other rooms for dedicated services are placed. The building envelope is mainly made by structural glass, with thermal transmittance U=1.1 [W/m^2K], and with transmission coefficient (visible light/solar energy) equal to [0.64/0.35]. Bank offices are normally occupied during daily time from 8:00 to 18:00, from Monday to Friday.

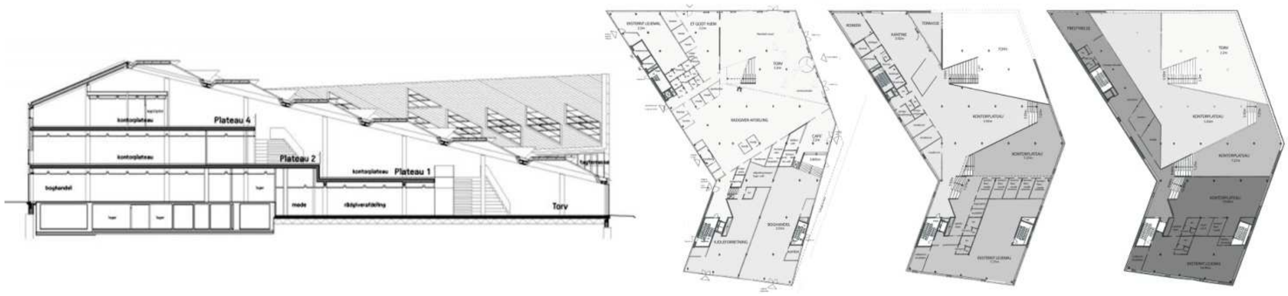

Figure 3. Case study building (vertical and horizontal sections).

4.2 Building systems and controls.

Thermal and air quality are guaranteed in the building by different combinations of systems. Heating loads in winter are provided in part by convectors, located on the floor along the perimeter of the building, and in part by hydronic systems (floor heating). Cooling loads in summer are removed in part by the hydronic system (floor cooling) and in part by TABS (Thermal Active Building System). Also the ventilation systems, in addition to air quality control, contribute to add or extract loads respectively in winter and summer period, in some part of the building. The building is partially mechanically and partially naturally ventilated. The mechanical ventilation is divided in five different systems. The natural ventilation is made by vents whose opening is controlled on the basis of indoor and outdoor temperature, indoor CO_2 concentration and outdoor wind velocity. The natural ventilation is also used in summer period for the night ventilation of the building.

The indoor climate control of the building is divided in two main strategies:

1- Embedded, water based radiant system (floor heating), and convectors for thermal control. Natural ventilation by controlled vents openings to provide acceptable indoor air quality. This kind of strategy is applied in all the large spaces, like in the offices situated on the terraces (plateaus), in the canteen and in the central plaza at the ground floor.
2- Convectors and balanced mechanical ventilation for heating and air quality control during the winter period, TABS and ventilation system for cooling and air quality control during summer. This kind of system is for example applied in the single offices and meeting rooms at the first floor and in the shops situated at the ground floor.

The systems control is based on the rooms' thermal and air quality: air temperature and CO_2 sensors are installed in all the building in strategically positions and collect data every 10 minutes. Also a weather station collects data about air temperature, relative humidity and velocity, wind direction, and solar radiation each 10 minutes. In the ventilation systems, flow rate and supply and return air temperature in the ducts are monitored, as well as the supply and return water temperature in the pipes of the hydronic systems. Operative temperature sensors have been inserted in 10 rooms too (at the height of 110 cm), aiming at evaluating the thermal quality in the building.

Artificial light system is controlled on the basis of the light intensity in the rooms, measured by dedicated sensors, and its operation is controlled by an occupancy sensor. An automated system regulates the opening/closing of internal curtains for the solar radiation control.

4.3 Levels of detail in energy and indoor climate quality detection

4.3.1 Energy

Building systems scheme and energy carriers are shown in the single line diagram of figure 4. On the diagram, designed according with the general representation described in 2.1 and showed in figure 1, the use of energy is represented in four levels of detail:

- Level 1: delivered primary energy to the building
- Level 2: delivered energy to the building (electricity and district heating)
- Level 3: energy needed by the main technical systems; 3a) energy needed by the single divisions of the technical systems.
- Level 4: energy needed by a single zone (a 268 m^2 office room, in this specific case study).

The red dots drawn on the scheme of figure 4, distributed for the different levels of detail, indicate the points where the energy is monitored and consequently assumed for the building energy evaluation.

As it can be seen from the diagram, the two delivered energies of the building are district heating and electricity. The first one allows the building heating, through floor heating and convectors systems, it is used to heat the supply air of the ventilation systems in winter, and provides the domestic hot water. On the other hands the electricity allows to power the cooling system (chillers, dry coolers, pumps etc.) for the building cooling, through floor cooling and TABS systems, and for the supply air cooling of the ventilation systems in summer. Moreover electricity is used for lighting, for other building installations, for the kitchen including cold store, for computers and server room, and for all kind of purposes/appliances in the building.

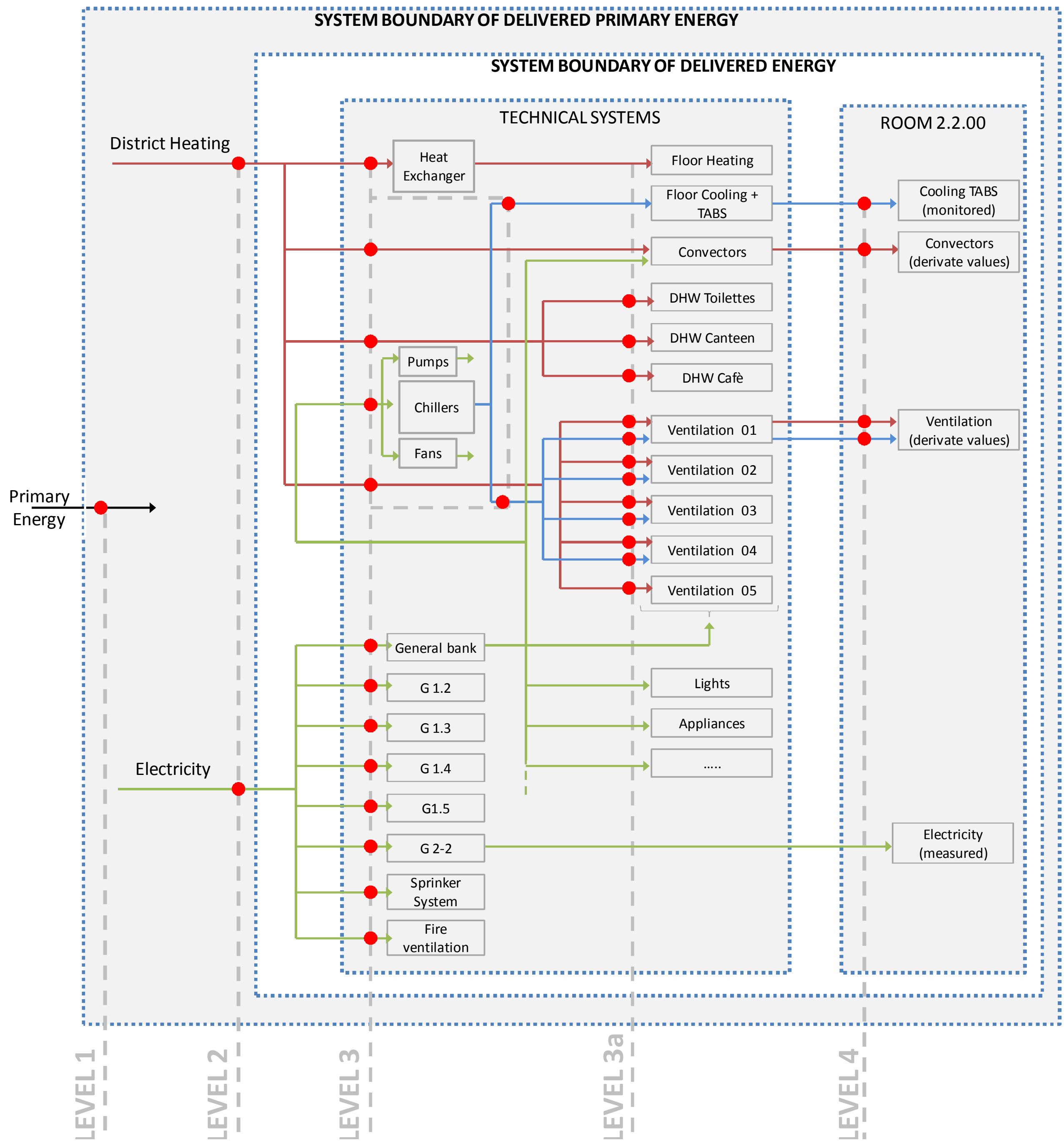

Figure 4. Building systems energy flow scheme, with evidence of the monitoring points and of the detail levels of the analysis. In the diagram different kind of energy flows are indicated with different colors: black - primary energy, red - thermal energy for heating, blue - thermal energy for cooling, green - electricity.

4.3.2 Indoor Climate Quality

The same approach has been used for the ICQ evaluation, by dividing the building in different thermal zones and drawing a diagram on the basis of the one described in figure 2. The indoor climate zones are characterized through the kind of installed systems, the exposure and the intended use. In each selected and representative room, indoor climate parameters were collected. In this case study air temperature, operative temperature, CO_2 concentration and air relative humidity were monitored. Through these parameters indoor climate quality analysis could be performed for each single room, for each single thermal zone or for the entire building. Figure 5 shows the diagram for the indoor climate quality evaluation in which monitored rooms are grouped in indoor climate zones.

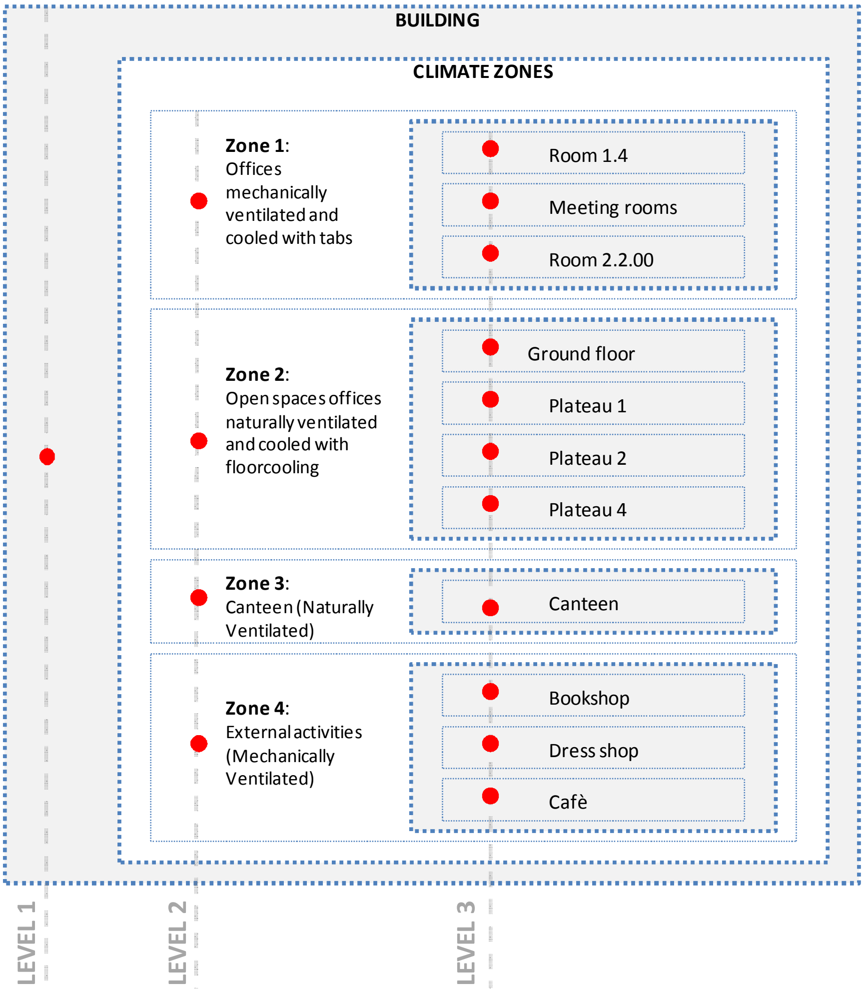

Figure 5. Diagram for the ICQ evaluation, with evidence of the evaluated spaces and of the levels of detail.

4.4 Data representation

As introduced in paragraph 3, data from monitoring or simulations can be elaborated and represented in different ways according with the level of detail, both in terms of building zone or volume analysis, and of length of time in which performing the analyses. Usually the evaluations referred to a year of analysis. In fact, during that period of time it is possible to monitor the energy behavior of a building, focusing, through the energy and indoor climate quality analysis, on the performance of the systems, and allowing to make a diagnosis of the entire building or of a part of it. During a year it is then possible to divide heating and cooling seasons, evaluating the behavior of the building in different periods of time, with different outdoor weather conditions. Having data collected about indoor and outdoor environment, considerations about the systems operating can be done, and elaborations about these data, in the specific of the case study, are showed in figure $6_{a\text{-}b}$.

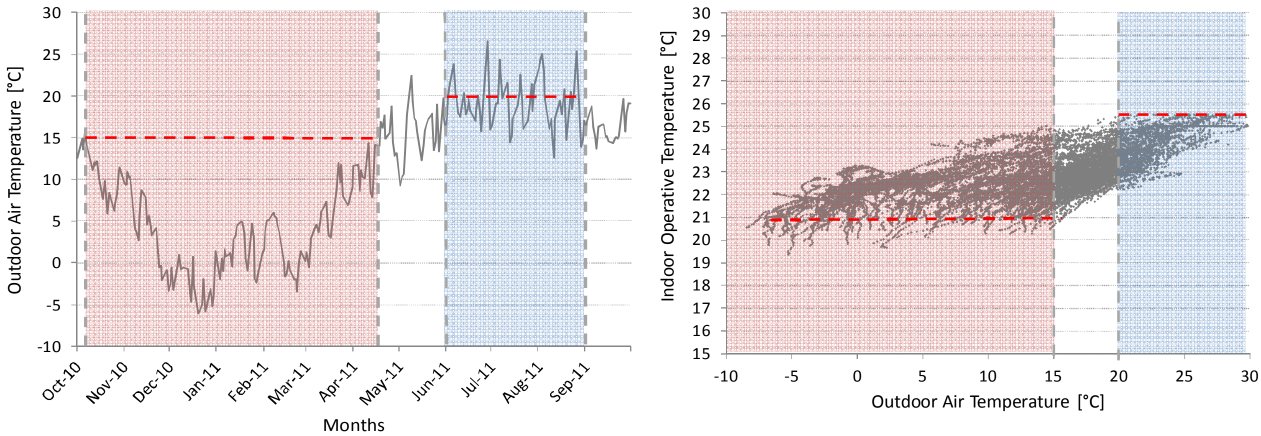

Figure 6 $_{a-b)}$ Representation of outdoor air temperature and indoor operative temperature during the occupancy hours to determine heating and cooling seasons.

In figure 6, two different ways of representing the data are shown. In the left chart outdoor air temperature (Ta_{out}) profile from October 2010 to September 2011 is represented. On the same graph heating and cooling periods are pointed out. Furthermore outdoor air temperature minimum and maximum values for the heating and cooling systems ignition time are evidenced by a dotted line. On the other hand the right chart correlates outdoor air temperature and average indoor operative temperature (To_{in}) monitored in the naturally ventilated plateaus. Also in this case heating and cooling periods are highlighted. Summing up, figure 6 allows to describe the building thermal behavior according with the outdoor climate changes, evidencing the periods in which heating and cooling system were operating, and enabling to determine summer and winter season through few considerations. In figure 6_b To_{in} rose with Ta_{out} increasing, but it was mostly higher than 21°C for outdoor temperatures lower than 15°C, and always lower than 25,5°C for outdoor temperatures higher than 20°C. In the picture these limits are indicated by dotted lines. Considering therefore 15° and 20°C respectively the higher and lower outdoor air temperatures for establish the heating and the cooling periods, and crossing these values with the Ta_{out} profile of figure 6_a, it was possible to determine winter and summer seasons. The first went from the second week of October until the second week of April, i.e. when Ta_{out} was lower than 15°C, while the second went from the beginning of June until the end of August, i.e. when the average Ta_{out} was higher than 20°C. To confirm the analysis, these intervals have been compared with the monitored heating and cooling systems operating periods, finding correspondence. However, during the mid-seasons the heating system, in case of low outdoor temperatures, was running sporadically, and for this reason energy consumptions were registered out of the highlighted heating period and they will be showed in the following paragraph.

4.5 Energy

Energy consumptions in the building during the monitoring time are shown in figure 7. In accordance with what specified in paragraphs 3, elaborations were performed for different periods of time: a) one year, b) heating and cooling seasons, and c) months. In figure 7, results represented through histograms allow to highlight the energy consumption distribution during the long term monitoring, expressed in absolute consumption (MWh) and in specific consumption (kWh/m^2), referred to the floor surfaces 4596 m^2, i.e. the total building area at the net of the basement. While the yearly evaluation indicates the total amount of energy required by the entire building, or part of it according with the detail of the analysis, the seasonal distribution splits the same value between winter and summer time, and mid-season. It is interesting to note that that during the mid-season the energy consumptions were higher than during the cooling season. Only analyzing the data at different levels of detail it is possible to understand why this happens: looking at the Level 3, in fact, energy for heating and for cooling, besides electricity, were required also during this period. If then further focus wants to be carried out, monthly distribution can be a useful tool.

Primary energy represented at Level 1 has been calculated by multiplying the delivered energy by the primary energy conversion factors established in Denmark, i.e. 1 for the district heating, and 2,5 for the electricity. At this level, the performance of a building can be expressed through a single value, equal to 321 kWh/m^2y. As above mentioned, looking at the seasonal analysis, the primary energy in the mid-season was higher than in the cooling season: it was in fact 87 kWh/m^2, while it was 173 kWh/m^2 in winter and 61 kWh/m^2y in summer.

The second level of detail allows to separate the two delivered carriers energies that provide heating, cooling, ventilation, lighting and domestic hot water in the building. From the seasonal and monthly analysis emerges that the biggest amount of district heating was required during the cold months when the heating demand was higher (62 kWh/m^2 of the totals 77 kWh/m^2y), while the electricity consumptions were homogeneously distributed during the year (around 8 kWh/m^2 each month). That electricity was then divided in different components in the third level of analysis.

Level 3 highlights, the total energy required by the building (94 kWh/m^2y) splitted between energy consumption of the bank offices (65 kWh/m^2y), also including the energy required by the building cooling system (chillers, fans, pumps) (12 kWh/m^2y), and the energy consumptions for lighting and appliances of the other rooms with different intended uses (cafè, dress shop, etc) (16 kWh/m^2y). At the same level also the electricity for the sprinklers and the fire ventilation system is explicate (less than 0,5 kWh/m^2y). Level 3 also shows the thermal energy used for heat and cool the building, respectively through floor heating (37 kWh/m^2y), convectors (26 kWh/m^2y) and ventilation systems (6 kWh/m^2y) in the first case, and through floor cooling and TABS (10 kWh/m^2y), and ventilation system (1 kWh/m^2y) in the second case; moreover it shows the domestic hot water energy consumption (4 kWh/m^2y). As the graphs illustrate, the biggest amount of energy was employed to heat the building. The energy for cooling represented just the 13% of the total thermal energy. The percentages of thermal energy required by the system in the building during the yearly evaluation are better explained by figure 8.

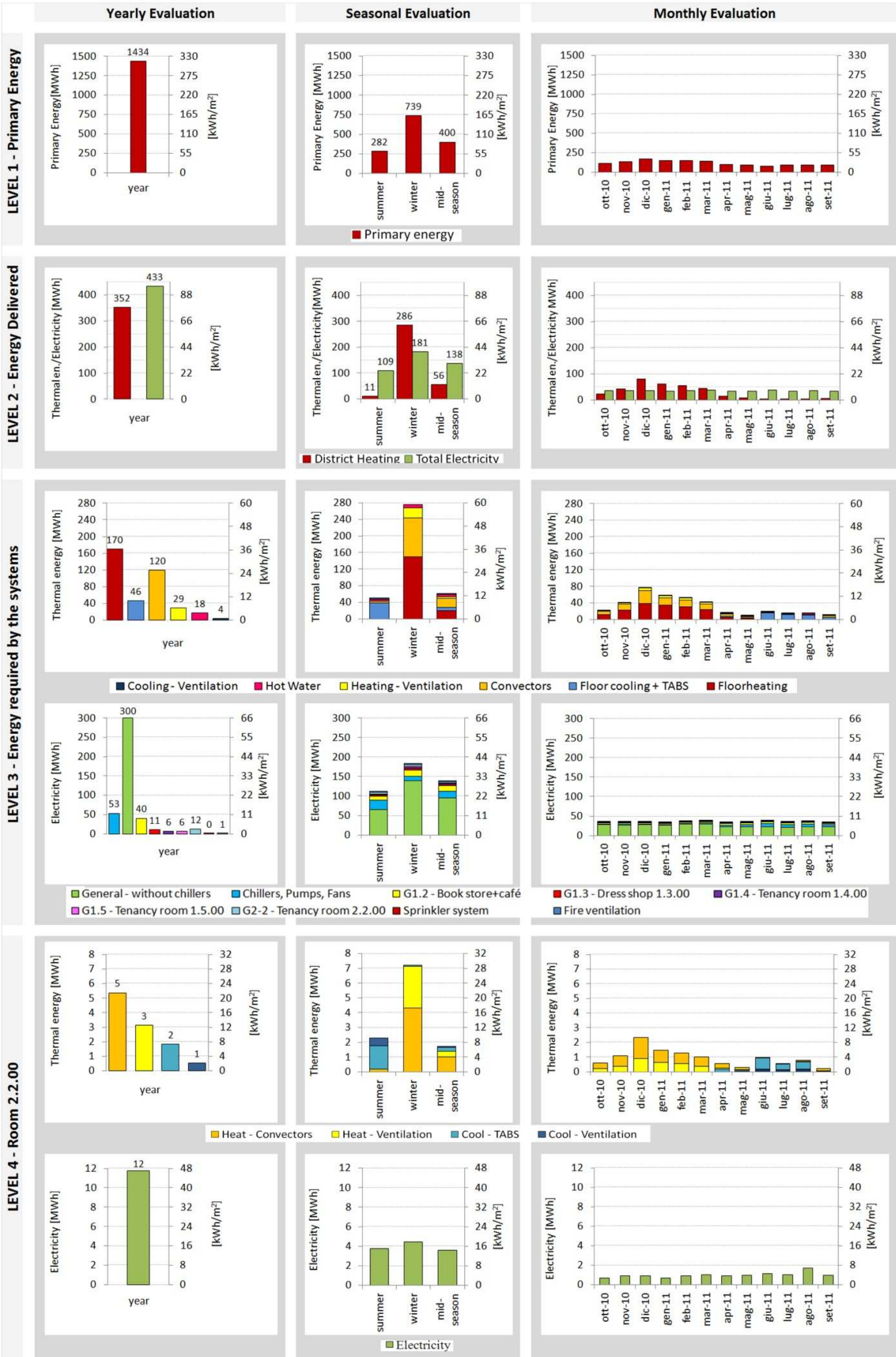

Figure 7. Building energy evaluation for different levels of detail and for different periods of time.

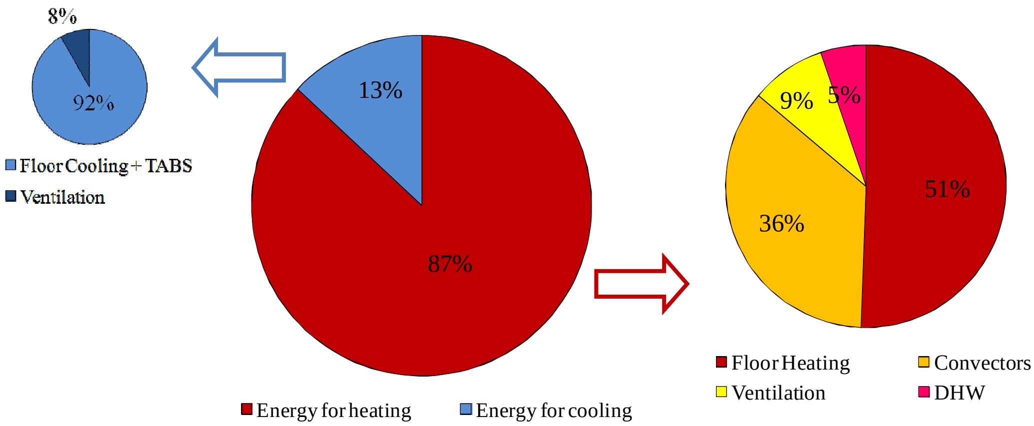

Figure 8 – Percentage of thermal energy required by the systems in the building.

Figure 4 indicates Level 3a too, but for reason of brevity, and because of results from that monitoring do not add important information at the topic, analysis of the different section of the system are not here presented.

Last level of detail investigates the energy consumption of a single room, in this case indicated in the project with the code "2.2.00". This room, mechanically ventilated, heated by convectors and cooled by TABS system, is situated at the first floor and it is west exposed. It is an open plane office born to be rented and then occupied by the bank employees. In this room the electricity consumptions, like in the rest of the building, were almost constant during all the years (46 kWh/m^{2}y). At the same, thermal energy consumptions, for cooling (9 kWh/m^{2}y) and for heating (33 kWh/m^{2}y), had a similar trend for the entire building. In this analysis, since not all the energy flows were monitored, in some cases the energy consumptions were estimated according with the floor surface served by a specific system. In particular total electricity and thermal energy for cooling were monitored, but the energy consumption of the convectors and of the ventilation system have been calculated proportionally to the floor surface of the room.

4.6 Indoor climate quality

Global comfort in a building is determined by air quality, thermal, visual and acoustic comfort. In this paragraph, for brevity, only thermal comfort, and air quality in the seasonal evaluation, are analysed and results are represented in figure 9.

Differently from the energy evaluation described before, in the indoor climate quality assessment, for diverse periods of analysis (year, months, etc.), different kind of data elaboration and representation are here proposed.

In the yearly evaluation, the monitored operative temperature is put in relation with the outdoor running mean temperature. Thermal comfort ranges are here indicated for an entire year, crossing the categories suggested by the standard EN 15251:2007 [6] for the adaptive model (annex A.2 – "Acceptable indoor temperatures for design of buildings without mechanical cooling systems"), at which to refer for the mid-season period, with the categories suggested by the standard for the mechanically controlled buildings (annex A.3 – "Recommended indoor temperatures for energy calculations”). In (table 1), in addition to other information, thermal comfort categories for a mechanically controlled building, for an office with sedentary activity (~ 1,2 met), are expressed in terms of operative temperature. Through this analysis it is possible to evaluate if the monitored operative temperature respects the limits prescript by the standard, giving an overall evaluation of the thermal comfort in the building in relation to the boundary conditions.

Seasonal evaluation has been performed according with standard EN 15251 too, referring to the annex A.3 for the comfort ranges, but assessing the environment as complying with annex F (“Long term evaluation of the general thermal comfort conditions”). Here the standard suggests three different methods (A,B,C) to evaluate and represent the comfort conditions over time (season, year), based on data from measurements in real buildings or obtained by dynamic computer simulations. These three methods prescribe the assessment of the thermal environment through the analysis of operative temperature or PMV (Predicted Mean Vote) evaluation [7730]. The adopted one, applied in this evaluation, is method A, “Percentage outside the range”, which is based on the calculated number (or %) of hours, in occupied period, when the PMV or the operative temperature are outside a specified range.

The last evaluation, indicated as monthly/daily evaluation, is a focus referring to a specific period of time. Purpose of this analysis deepening, represented through operative temperature profiles during the 24 hours, is the building thermal behaviour in extreme boundary conditions. At this aim the additional focus on particular days helps in the building-plant system comprehension, underlining, if there are, problems to be solved. In figure 9, for example, profiles of operative temperature about two months, one representative of the winter time and the other representative of the summer period, are represented. For each month, then, daily profiles were analysed too. At the same way, different intervals of time could be examined (weeks for example).

Levels of detail in the indoor climate quality evaluation are those indicated from figure 5. Analyses were therefore performed for the entire building, for the four selected thermal zones, and for the same room where also energy evaluation was performed (room 2.2.00).

Level 1 describes the thermal performance of the entire building. The represented data show the average values of operative temperature measured in the 12 monitored rooms over one year of analysis. From the yearly assessment emerge that in summer the temperatures were averagely lower than the ones prescribed from the comfort standards. This fact can be attributed at the low air temperature set point fixed for the cooling season, equal to 23°C. The optimal temperature in the rooms, according with the standard categories, should be 24,5°C, i.e. the average value for all the ranges of categories. This low temperature environment in summer is then better illustrated in the seasonal evaluation. Here it is evident that the thermal environment cannot be considered acceptable for the 18% of the occupancy time. From the monthly evaluation is then possible to see as in a summer month (July in this case) the operative temperature thermal excursion between day and night was averagely higher than in winter (~3°C in July, and ~1°C in January).This summer temperature fluctuations can be attributed in a large percentage at the rooms-intended uses, together with the employed ventilation system: as described before, Level 1 gives an average evaluation of several rooms, characterized by different heating/cooling and ventilation systems.

For that reason at this level is difficult to understand determinate thermal dynamics of the building.

Analyzing Level 2, important considerations can be achieved. Here differences in results between indoor climate zones are put in evidence. Comparison between Climate zone 1 and Climate zone 2, for example, allows understanding how much the natural ventilation influence the indoor operative temperature profiles. From the yearly evaluation, in fact, it can be seen the effect of the summer night ventilation cooling strategy used in the naturally ventilated Climate zone 2, where the monitored data distribution varied more than in the case of Climate zone 1 in accordance with the outdoor temperature. Looking at the summer evaluation, the operative temperature of Climate zone 1 was lower than the range of category IV for the 31% of the time (due to the low temperature set point and to the mechanical ventilation), while in Climate zone 2 it was lower of category IV just for the 11% of the time (because of the low temperature set point). Regarding the intended use it is a different matter. According with what above stated, looking Climate zone 4, what would be expected to see, for all the different periods, is a similar evaluation to the one obtained for the Climate zone 1, since the installed systems in both the zones are the same. However, the book shop and the dress shop (part of Climate zone 4), even though mechanically ventilated, presented an higher number of air changes pour hour respect to the offices of Climate zone 1, due to the frequent opening of the doors for the customers access. In Climate zone 4, the operative temperature distribution in the yearly evaluation looks in fact more dependent by the outdoor climate influence.

The comfort assessment at Level 3, where only room 2.2.00 was analyzed, shows the case of a mechanically ventilated office, in which the temperature was kept almost constant during the entire year (∼22,5°C). Here also the temperature fluctuation between day and night was negligible, both is summer and in winter period. Moreover, as the seasonal evaluation highlights, temperatures in winter were really good in room 2.2.00, but being theme almost the same in summer too, the thermal environment during the cooling period was here evaluated too cool.

It is important to highlight that the yearly evaluation is based in part on the adaptive approach: for that reason results of the seasonal evaluation, based on the Fangers' method, could do not match with those represented in the graphs of the yearly evaluation.

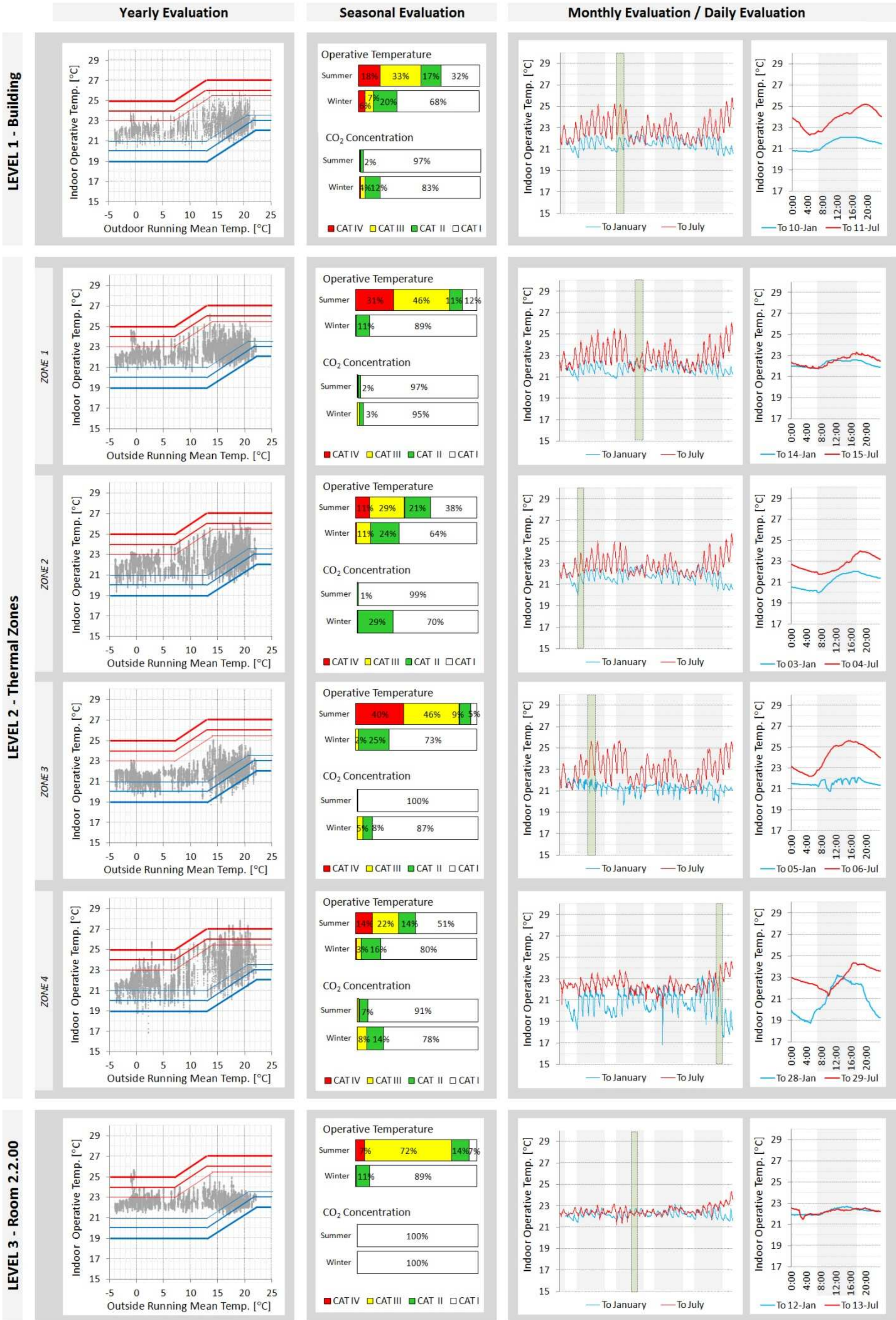

Figure 9. Building thermal comfort evaluation for different levels of detail and for different periods of time.

4.7 Energy VS indoor climate quality

In the previous paragraphs energy and indoor climate quality in the building have been evaluated and represented separately one from each other. Rare are in literature the studies in which energy and indoor air quality of a building are compared and correlation between them is parsed [11, 28], and only a few times both the evaluations are taken into account in the same building analysis [9,20,22,23,27]. Often procedures for comfort [10, 14, 25, 26] and energy performance of a building with different intended uses are dealt separately [19].

Aim of this part of the study is to put in relation indoor climate quality with the energy consumptions required for to keep a certain level of comfort in the buildings. Through graphical representations of monitored parameters, interesting considerations about the buildings energy and comfort behaviour can be expressed.

First issue to be solved is the research of a unit at which both energy and indoor air quality can be referred to. While different energy carriers (electricity, fuel, etc.) can be converted in primary energy or CO_2 emissions, for the individual indoor environmental factors is even not available any standardized method for estimation of a yearly performance value [5]. Also if does not exist a unique value for to describe indoor climate quality, for all the environmental parameters standards suggest, as early describe in the previous paragraphs, categories for the comfort classification. In table 1 operative temperature, relative humidity and CO_2 ranges, indicated from the EN 15251 for the comfort and air quality evaluation, are shown. The same table shows categories for energy classification too. These energy categories, representing ranges of energy consumption, have been included in the study in order to use four categories as ~~the~~ same yardstick for both energy and comfort evaluation.

Table 1. Ranges of categories for operative temperature, relative humidity and ventilation (CO_2 concentration) for typical spaces with sedentary activity, indicated by the standard EN 15251:2007. Ranges of "energy consumption" suggested for the analysis.

Category	Operative Temperature ranges Winter 1.0clo/1.2met [°C]	 Summer 0.5clo/1.2 met [°C]	Relative Humidity [%]	Ventilation CO_2 above outdoor [ppm]	Energy consumption (thermal/electricity) [kWh/m^{2}y]
I	21.0-23.0	23.5-25.5	30-50	> 350	0-20
II	20.0-24.0	23.0-26.0	25-60	350 – 500	20-40
III	19.0-25.0	22.0-27.0	20-70	500 – 800	40-60
IV	< 19.0-25.0<	<22.0-27.0<	<20-70<	> 800	>60

Using a radar chart in the categories representation, indoor climate quality and energy indicators can be depicted with the same tool. As it is shown in figure 10, indoor climate and energy can be represented before separately and then together on the same graph. Moreover, the same graphical support can be used for to describe, seasonal and yearly performance of the building. In both the periods it has been fixed that a building belongs to a certain category if for the 95% of the occupancy time the analysed parameters respect the limits indicated for a certain range.

Figure 10 is divided in two parts. The upper part of the picture allows to describe the performance of a building through the use of categories, while the lower part shows the real measured values (average values for the environmental parameters and total amount for the energy consumptions).The energy data are representative of the third level of analysis showed in figures 4 and 7, while the comfort parameters are related the entire building (Level 1 of figure 5 and 8). Similar evaluations can be done for different climate zones or single rooms.

As the upper part of figure 10 shows, with the radar chart it is possible to put in evidence a representative area of the best situation, i.e. when all the parameters respect category I. That area is in the graphs indicated with a gray coloured shape.

The same thing cannot be done for the evaluation illustrated in the lower part of the figure. Here the graphs gives important information about the building behaviour, but does not allow to understand immediately if that performance is good or not and, in this last case, which are the causes that led to certain conclusions. For example, analyzing the yearly or the seasonal average operative temperature, the values indicated by the graphs in the lower part of the figure denote a good operative temperature in the building. But looking at the charts in the upper part of the figure, the thermal quality in the building seems to be very bad (Category IV). This can be explained by two facts: first of all the indicated value does not point out that in the reality the temperature was always lower or higher than the average. Second, the categories are not representative of an average situation, but as above expressed indicate that for the 95% of the time the temperatures respect the limits of a certain range. For example from figure 7 is visible that during the summer period the operative temperature in the building was only for the 82% of the time in the range of category III (between 22°C and 27°C). For that reason in this kind of representation the building in summer is considered of category IV.

Another thing to highlight is that the yearly evaluation through the use of categories could appear different by the seasonal building assessment. For example, the electricity consumptions that in summer were in category I and in winter in category II, in the yearly evaluation were in category IV. The reason is that electricity consumptions, as illustrated in figure 7, were distributed almost homogeneously during all the months, included during the mid-season. For better understand is necessary to see the monitored values: in summer the energy consumption was 20 kWh/m^2, in winter it was 34 kWh/m^2, while the total electricity during the whole year was about 83 kWh/m^2. This means that during the mid-season about 29 kWh/m^2 of electricity was consumed.

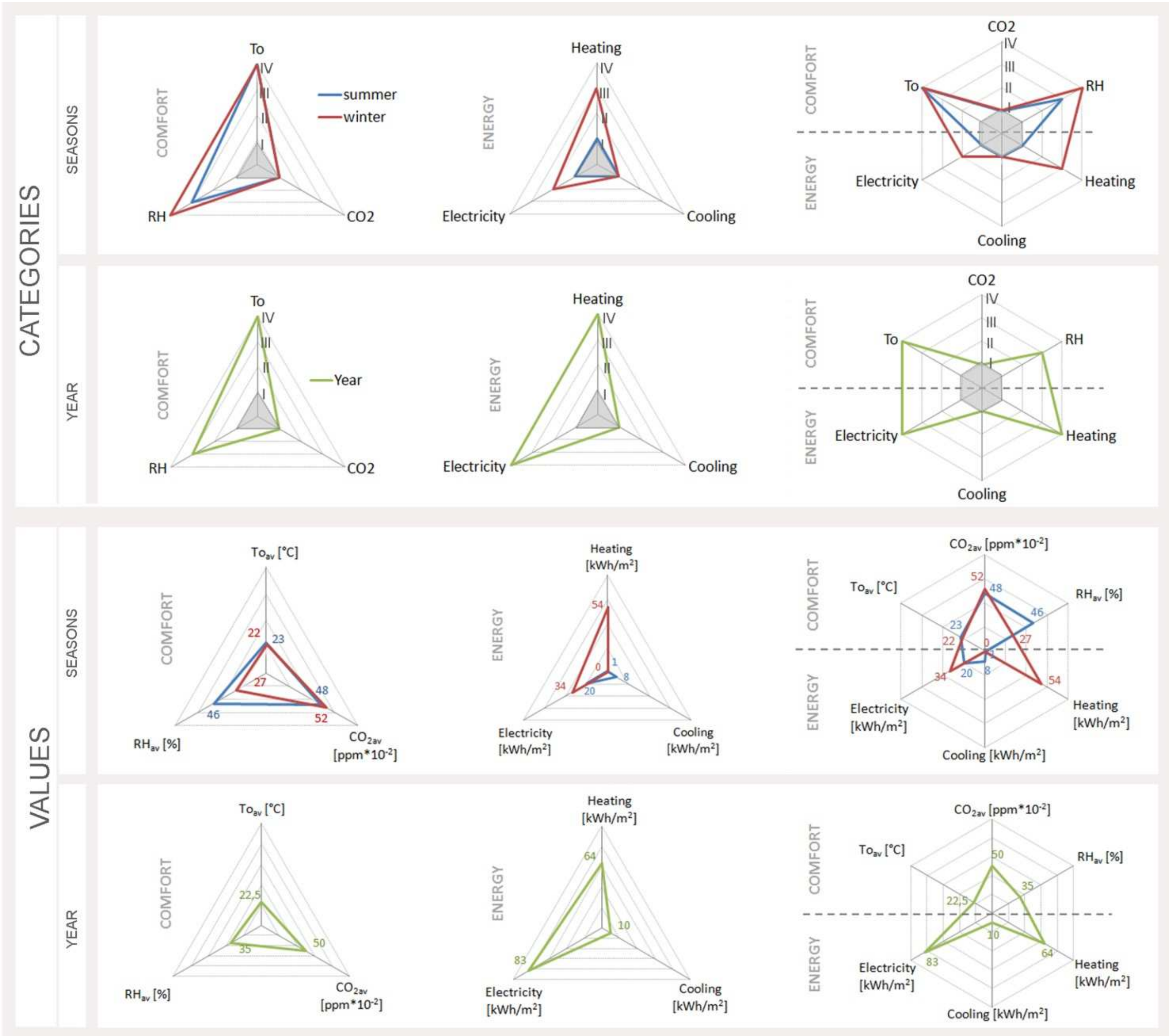

Figure 10. Seasonal/yearly comfort and energy evaluation. Energy data are representative of the third level of analysis described in figures 4 and 7, while comfort parameters are average monitored data for the entire building (Level 1 of figure 5 and 8).

5. Conclusions

Energy performance and indoor climate quality of a building are proposed and discussed in this paper. From the study the following results were obtained:

- Different levels of details in both energy and comfort analysis can give interesting results about the performance of a building.
- Analysis of energy and climate quality can be performed for different intervals of time, like year, seasons, months, days, etc., giving different kind of information.
- Representing the comfort performance of a building with a single value is still an issue to

be solved, but comfort parameters can be put in relation to each other through the use of categories suggested by the standard EN 15251.

- Introducing also categories for the energy consumption classification, energy performance of a building can be related to its comfort assessment.
- A good description about the performance of a building could include a synthetic representation of the results, but more detailed analysis permit to better know the dynamics of the building at boundary condition variation, allowing to make a diagnosis of the building too.

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8.4. PAPER IV

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Radiant electrical plates for space heating and thermal comfort: an experimental study.

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Radiant electrical plates for space heating and thermal comfort: an experimental study

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ABSTRACT

The use of electrical terminal devices for space heating is increasing in Europe, especially in low-energy or passive houses where the heating energy requirement reaches very low value. Some aspects are fundamental:

- low load in design condition
- low energy requirements during the winter season
- low inertial terminal devices
- due to the low operation time, the installation of low cost terminal devices is required.

According to these reasons, the use of radiant electrical plates may be successful, particularly when low energy requirements can be provided by site-production through photovoltaic modules. In this study, different types of radiant electrical plates are studied in a test chamber. After a description of the test room facilities and of the delivered experiments, the performances of the radiant plates are investigated from both energy and thermal comfort aspects. Moreover, the analysed equipments are applied to a low energy house in different sites in Italy to evaluate suitable combinations with photovoltaic modules.

KEYWORDS

Electrical radiant plates, heating, thermal comfort, low energy houses

INTRODUCTION

Radiant heating systems are widely diffused in Europe, mainly hydronic radiant systems because of the energy saving opportunities they may engender by using low temperature heat transfer carriers (Olesen, 2002; Babiak et al. 2007). Electrical systems are not as much common as hydronic systems, because, in typical dwellings, the use of electricity for heating purpose would cause an energy waste and, in many countries, it would also cause extremely high heating costs for the user. Nevertheless in new low-energy houses, heating is required few days or hours per year, and when it is required the system must react quickly to the thermal demand, to reinstate the proper thermal conditions (Feist et al. 2005 Isaksson et al. 2006, Thyholt et al. 2008, Nieminen 1994). Hydronic radiant systems have slightly low reactions to thermal demand: radiant ceiling are generally faster, because they have little inertia, but they are more expensive; radiant floor are generally cheaper, and more used in the houses, but slower. Due to the very little amount of heating energy required by low-energy houses, the use of cheap electrical systems could be suitable; furthermore the energy required by the heating system may be balanced, along the year, by the energy produced by a photovoltaic system, increasing the sustainability of the system. Electrical systems may be used for underheating floor or ceiling, and their comfort performance are the same of typical hydronic systems: they depends on the temperature level and on the surfaces area, related to the finishing material and to the control system as well (Watson et al. 2002). Nevertheless, radiant plates are much more typical, because they can be easily mounted on a wall when the building is already finished and can be shaped following many different styles. Radiant plates have nonetheless a reduced exchanged area and thus they must reach higher temperature compared with a floor or ceiling (Watson et al. 2002). Maximum radiant asymmetries due to warm walls are indeed fixed by thermal comfort standards; the thermal output of electrical radiant plates is therefore strictly limited by comfort reasons (Fanger et al. 1985).

Economical aspects, thermal comfort and thermal response of all the heating systems will not be faced in this paper because of the shortness of it, but it is important to not underestimate the importance of these three factors. In this paper, an experimental study about three different electrical radiant plates is reported. By means of dedicated facilities, their thermal output have been evaluated and compared to the thermal comfort conditions produced in the test chamber. Moreover, the possible use of the tested plates applied to low-energy houses at different latitudes in Italy was investigated and the combination with suitable photovoltaic system to provide electrical energy was discussed.

METHODS

The test facility

The test facility arranged to experimentally characterize the radiant electrical plates is made up of an insulated chamber (3.57 m x 3.49 m x 2.55 m) and a data-acquisition system, placed in the basement of the

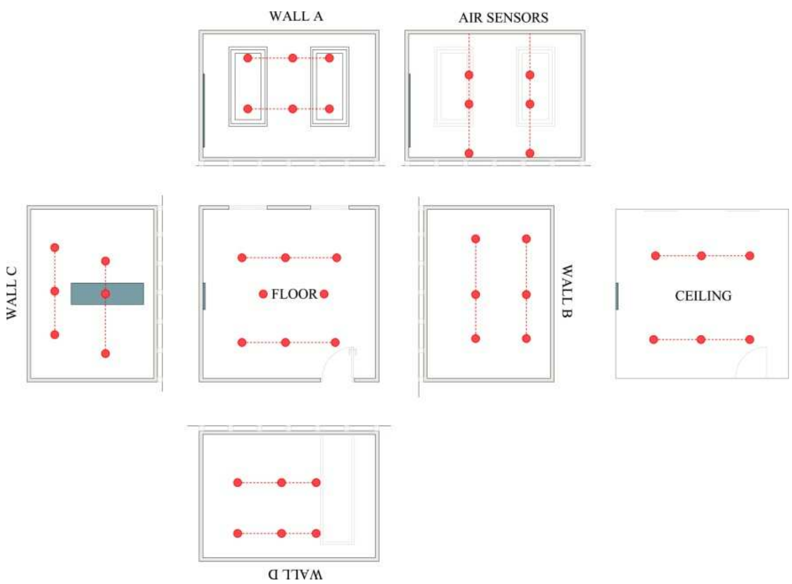


Figure 1. Position of the probes on the floor, on the ceiling and on the walls of the chamber.

"Politecnico di Torino" head office. The temperature of the environment around the test chamber can be controlled by means of an air-conditioning system, in order to simulate different heat loss conditions.

The walls and the ceiling of the chamber are built with a dry structure, made by a rook wool insulating layer (80 mm) placed between two plasterboard layers (12.5 mm). The floor, raised and separated from the floor of the basement by some wooden boards, is constructed with four layers: a plywood panel (35 mm), an insulating extruded polyethylene layer (25 mm), an electric radiant carpet and a MDF (Medium Density Fibreboard) floor tile layer (5 mm). Two sealed windows and a door were respectively placed on the walls A and D, for visual control and inspection during the tests, while the electrical plate was placed on the wall C (Fig.1).

Three different kinds of electrical plates have been analyzed:

1- dimensions: 1.55 m x 0.44 m, surface colour: white
2- dimensions: 1.50 m x 0.53 m, surface colour: white, presence of a fan
3- dimensions: 0.82 m x 0.54 m, surface colour: white

Experimental apparatus

The characterization of the radiant plates under test require several quantities to be measured, which are summarized below:

- air and wall temperatures inside the chamber;
- plate surface temperature and corresponding heat flux;
- temperature and relative humidity outside the chamber;
- electric energy consumption (of the plates).

For this purpose, a data-acquisition system has been arranged that embeds a set of sensors and a Personal Computer (PC) that collects the measured quantities. With the aim to minimize the cables, a wireless system has been employed for temperature measurements. Such a system includes a base station, which is connected to the PC through an USB interface, and 14 measuring nodes. Each node, is powered by means of a CR2477 button lithium battery and is equipped with a chip CC2510F32RSPR by *Texas Instruments*, which embeds both a microcontroller unit and a 2.4 GHz radio transmitter CC2510. A circular-shape antenna is directly printed on the circuit, thus allowing a wireless communication with the base station, which is equipped with the same radio device. The base station mainly acts as a data collector, but it has also the capability to configure the measuring nodes by setting different parameters, such as the measurement interval and the transmission trials for each measurement session. The measuring nodes embeds three T-type thermocouples, whose cold junctions are thermally coupled to a digital thermometer that acts as a reference junction. The thermocouple voltage-outputs are acquired by means of a 24 bit three-channel Analog-to-Digital Converter (AD7799 by *Analog Devices*), whose internal programmable-gain instrumentation amplifier has been configured in order to have an input range of 78 mV and a resolution of about 0.02 °C (17 bit). Thanks to the use of cheap temperature sensors and wide-spread electronic components, the cost of each measuring node could be about 10 Euros for a medium-scale production. Further details about the circuitry and the micro-controller firmware can be found in (Carullo et al. 2009). The thermocouple warm-junctions of 12 measuring nodes are employed to monitor the temperature of the chamber walls, while the other 2 nodes measure the air temperature inside the chamber at different heights (10 cm, 110 cm, 170 cm). The position of each thermocouple is shown in Fig. 1, where the thermocouple that records the temperature of the radiant plate under test is also shown. One should note that the solution adopted for temperature measurement offers several advantages besides those ones that are inherent to a wireless system. Above all, the number of measuring nodes can be dynamically managed by the system, thus offering the possibility to map the chamber temperature in the most suitable way. Furthermore, the nodes can be easily removed from the test chamber for maintenance or calibration purposes. Thanks to this feature, the calibration of the wireless system has been performed by inserting the measuring nodes inside a climatic chamber. Initially, the errors of the reference-junction thermometers have been estimated, then the thermocouples have been verified against a traceable standard thermometer. Once the errors of the reference-junction thermometers have been compensated, the nodes have shown measurement errors lower than 0.5 °C. Four heat-flux sensors (*Hukseflux* model HPF 01) were fixed to the surface of the radiant plate under test (two on the front and two on the back of the plate) for measuring the plate heat-flux output. The voltage signals of the four heat-flux sensors were acquired by means of a data-logger (*DataTaker* DT600), which was connected to the PC through an RS-232C interface. The relative uncertainty of the measured heat flux was about 5%, which takes into account the contribution of both the sensors and the data-logger, while the temperature of the external walls of the chamber were measured by wired thermocouple sensors with an uncertainty of 0.5 °C.

A digital wattmeter (*LEM Norma* model D6000) was employed to measure the energy consumption of the plate under test, which was obtained with a relative uncertainty of 0.2%. Temperature and relative humidity of the air outside the test chamber were measured by means of a thermo-hygrometer probe (*Rotronic* HP101A-L5W1F), whose output signals were sent to a conditioning unit (*Rotronic* A2); the conditioned signals were measured by means of a digital multimeter (*Agilent* 34401A). Both the wattmeter and the multimeter were connected to the PC through an IEEE-488 standard interface, thus fully automating the measuring process.

RESULTS

Thermal power assessment

The object of the measurements was to evaluate the thermal power output of the radiant plates as function of the temperature difference between the plates surface and the room reference temperature. In fact a good performance of the heating equipment can be assumed only when the temperature of the plate surface is not too high, in order not to create local thermal discomfort to the occupants. In order to properly evaluate the performance of the plates, three different test conditions were carried out for each plates: high heat loss, moderate heat loss, low heat loss. All the test were preformed under steady state conditions, only the plate temperature was sometime fluctuating (depending on the control system installed). Only when stable periodic fluctuations were recognized the measurement was considered completed. The thermal power output was derived from the plate electrical energy consumptions during the test time and it was checked with values obtained by means of heat flux meters. The power output of the electrical plate was finally evaluated by mean of a characteristic equation, as in the case of common radiators, based on the experimental data:

$$\Phi = K_M \cdot \Delta T^n \quad [\mathrm{W}] \tag{1}$$

where:

K_M = constant for the plate, n = constant for the plate [-]

In accordance with previous researches (Olesen et al. 2000; Causone et al. 2009; Causone 2009) the operative temperature in the centre of the chamber at 110 cm above the floor level was considered as the reference temperature.

Table 1. Thermal conditions during the tests and power output of the electrical plates.

		h	**E_{el}**	**T_{out}**	**T_p**	**$T_{a,110}$**	**T_{mr}**	**T_{op}**	**ΔT_{p-op}**	**Φ**	**$Φ_1$**
		[h]	[kWh]	[°C]	[°C]	[°C]	[°C]	[°C]	[°C]	[W]	[W/m^2_{pan}]
Plate 1	Test 1	8	2.13	16	55.0	20.6	21.1	20.9	34.1	266	403
	Test 2	24	3.95	18	41.8	20.9	21.2	21.0	20.8	165	250
	Test 3	20.3	1.34	20	31.1	21.2	21.4	21.3	9.8	66	100
Plate 2	Test 1	69	20.05	18.3	57.5	21.2	21.9	21.5	36.0	291	366
	Test 2	19.97	4.37	16.6	49.0	21.9	22.2	22.0	27.0	219	275
	Test 3	14.77	0.27	16	69.7	22.0	23.2	22.6	47.1	18	23
Plate 3	Test 1	6.87	1.26	13.9	60.8	18.7	19.5	19.1	41.7	183	413
	Test 2	5.18	0.75	16.9	51.0	20.1	20.8	20.4	30.6	146	329
	Test 3	8.75	0.40	19.5	32.4	21.0	21.3	10.5	21.9	46	103

In table 1, it is shown the average air temperature in the basement (T_{out}), the plate average surface temperature (T_p) , the air temperature in the test chamber (T_a), the radiant mean temperature (T_{mr}), the operative temperature (T_{op}) and the delta between the plate surface and operative temperature ($\Delta T_{p\text{-}op}$). T_{mr} and T_{op}, which characterize the room thermal conditions, have been calculated using the experimental data as input of the following algorithms:

$$T_{mr} = \frac{\sum_{j=1}^{n} S_j \cdot T_j}{\sum_{j=1}^{n} S_j} [°C] \qquad (2)$$

$$T_{op} = \frac{T_{mr} + T_a}{2} [°C] \qquad (3)$$

where:

S = area of the j^th surface, T = mean temperature of the j^th surface, n = number of surfaces.

Thermal Comfort Evaluation/Assessment

Comfort simulations were conducted with the software Hypercomfort®, an hypertextual tool for the evaluation of the thermal, visual, acoustic and olfactory comfort, developed at the Department of Energetics of Politecnico di Torino. The quantities Top, PMV (Predicted Mean Vote) and PPD (Predicted Percentage of Dissatisfied), calculated on the basis of measurements during three tests, are compared in Table 2. The aim is to assess how the three different plates can alter the thermal environment in which they appear, having analogous average thermal power end energy consumptions and time intervals of

Table 2. Air temperature inside and outside the chamber and thermal comfort indexes evaluated during the tests.

		T_{air} [°C] h.110cm	ΔT [°C] $\Delta T_{10\text{-}110}$	ΔT [°C] $\Delta T_{10\text{-}170}$	T_{out} [°C] Outdoor	ΔT_{prh} [°C]	PMV [-]	PPD [%]
Plate 1	Test 1	20.6	0.3	0.9	16	47.3	(-0.1)-(+1.5)	4.2-50.6
	Test 2	20.9	0.3	0.7	18	36	(+0.0)-(+1.2)	4.6-37.0
	Test 3	21.2	0.2	0.6	20	24.9	(+0.2)-(+1.1)	6.1-32.2
Plate 2	Test 1	21.2	0.8	1	18.3	53.6	(+0.0)-(+1.9)	4.1-70.0
	Test 2	21.9	0.6	0.8	16.6	28.2	(+0.1)-(+1.0)	4.9-25.2
	Test 3	22	1.2	1.4	16	58.9	(-0.1)-(+1.9)	3.9-72.9
Plate 3	Test 1	18.7	0.2	0.8	13.9	25.2	(-0.4)-(+0.4)	5.2-8.4
	Test 2	20.1	0.2	0.6	16.9	18	(-0.2)-(+0.3)	5.0-7.2
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

monitoring. The air velocity was measured in the chamber, but it was always very low (<0,1 m/s), the relative humidity, not controlled by the heating plate, was always assumed to be 60% RH, while the metabolic rate of occupants was supposed to be 1.2 met (sedentary activity according to EN ISO 7730/2005) and the clothing insulation 1 clo (typical value of the winter insulation according to EN ISO 7730/2005).

Analyses were performed evaluating T_{op} at the distances of 0.5 m and 1.5 m from the plate and at

height of 0.6 m above the floor.

Results are shown in the charts of fig. 2 and 3 according to the comfort categories expressed in terms of

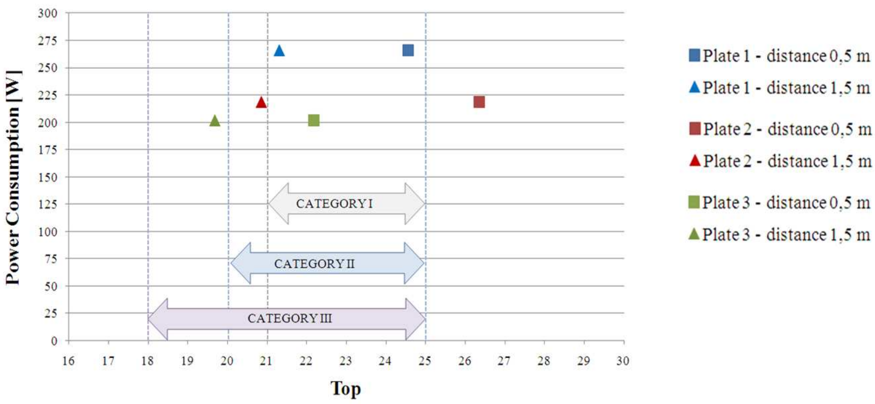
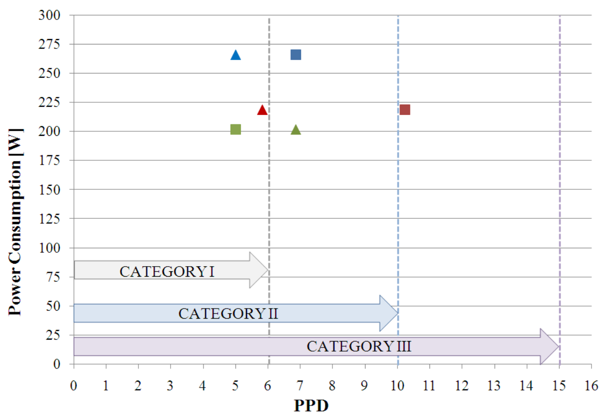


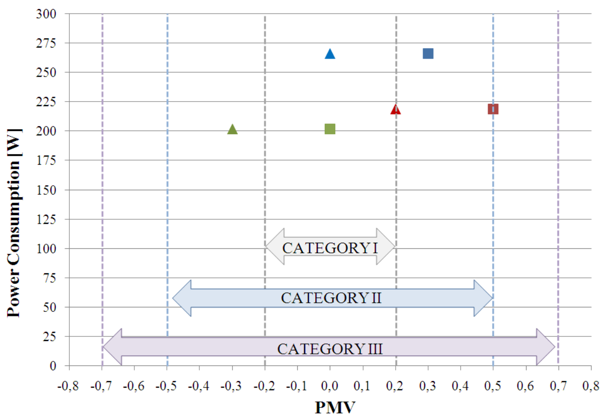
Figure 2. Operative Temperature calculated at 0.5 m and at 1.5 m far from the plates.

operative temperature as described in the UNI EN 15251 Standard:

- Category I - High level of expectation
- Category II - Normal level of expectation
- Category III - An acceptable, moderate level of expectation
- Category IV - Values outside the criteria for the above categories

The chart in fig. 2 shows the relation between monitored power consumptions and T_{op}. Plate 1 is able to hold the T_{op} value inside the Category I both for the distance of 0.5 m and for the 1.5 m. Plate 2, instead, gives good results at the distance of 1.5 m, but at the distance of 0.5 m the Top value exceed the category I





limit of 25 °C. This is because the surface temperature is slightly higher for the second plate than for the first. Plate 3 gives a satisfactory T_{op} at the distance of 0.5 m, while shows a limit value (Category II) at 1.5 m of distance. Nevertheless, the emitted power of the third plate is slightly smaller than the previously tested plates 1 and 2, it is possible to assume that raising the power output of Plate 3, both the T_{op} values (at 0.5 m and 1.5 m) would fall inside the Category I.

In figures 3a and 3b, PMV and PPD values are shown. According with the previous analyses, Plate 1 is able to maintain an environment in category I at the distance of 1.5 m, also using the PMV as indicator, while it is able only to reach Category II at the distance of 0.5 m. The PMV value calculated for Plate 2 is close to the acceptable limit of the category I at the distance of 1.5 m, while it is close to the acceptable limit of the Category II at the distance of 0.5 m.

The higher temperature of Plate 2, compared with Plate 1, is probably the cause of the difference reported above. Plate 3 shows a PMV in Category I at the distance of 0.5 m and in category II at the distance of 1.5 m. As previously highlighted this is due to the power output emitted by the plate 3, which is slightly lower than the power emitted by Plates 1 and 2. The PPD, being directly related to the PMV, shows relatively low values. Plates 1 and 3 show values in Category I and II, while only Plate 2, at the distance of 1.5 m, shows a percentage of dissatisfied next to the upper limit of Category II. Also the vertical air temperature difference between head and ankles was calculated but no values out of the limits suggested by the local discomfort due to EN ISO 7730:2005 Standard were reported. Some improper values were instead noted for the radiant asymmetry between vertical surfaces (ΔT_{prh} - Plane Radiant Asymmetry), which the standard EN ISO 7730:2005 suggests should not be higher than 35 °C in order not to generated a percentage of dissatisfied higher than 10%. Plate 1 shows a value over the limits suggested by the standard, while Plates 2 shows two values over the limits. In general it can be observed that, under the conditions simulated in the chamber, when the radiant plate assume temperature higher than 55 °C it can cause local thermal discomfort to the user.

Radiant plates in low-energy houses

As clearly stated in the introduction of the paper, the use of electrical radiant plates can be considered suitable only in houses with low-energy demand (low energy demand for heating).

In order to evaluate the number of radiant plates required by such a residential building (and consequently the initial costs), a case study was developed: a typical single family house with a floor area of 122 m^2 and a net internal height of 3 m (single floor). The ratio between transparent and opaque envelope was considered to be constant (Tab. 3), while the thermo-physic characteristic of the envelope have been changed in order to satisfy the building energy performance requirements of the Italian legislation for heating and domestic hot water, at different climatic areas in the North of Italy (Bolzano, Torino, Firenze).

The hot water production has been considered constant and calculated on the basis of the Italian Standard UNI-TS 11300-2 (15 kWh/m^2y). Simulations have been developed with a semi-stationary method, according to Standard UNI EN 11300-2, considering an air change per hour of 0.5 vol/h. It was furthermore calculated the amount of square meters needed to balance the heating requirement, by producing photovoltaic electricity on site. The heating requirements to fit a level vary from city to city, depending on the climatic area thus mainly on the HDD (Heating Degree Days) and on the solar radiation at the ground in the city analyzed. The climatic data used in the simulations derived from the weather data archive of the Italian Energy Agency (ENEA). An assumption of an efficiency of 13.7% of the photovoltaic modules have been made, which corresponds to polycrystalline silicon commercial modules.

Table 4. Number of radiant plates (type: P1, P2, P3) required to heat the house, heating demand calculated for the standard house in order to fit the different energy levels and photovoltaic area required to balance the heating energy consumptions for the three Italian cities considered.

	Heating demand	Required number of radiant plates (type: P1, P2,			Required delivered energy for heating	Required photovoltaic area to balance heating	
		P1	P2	P3	kWh/m^2y	m^2	kWp
Bolzano	Very low	8	4	4	10	9.3	1.3
	Low	12	6	6	24	23.1	3.3
	Standard	17	9	8	49	46.8	6.7
	Slightly high	26	14	13	82	78.1	11.2
Torino	Very low	7	4	3	12	10.7	1.7
	Low	9	5	4	24	21.5	3.1
	Standard	14	8	7	59	52.3	7.5
	Slightly high	19	11	9	77	68.9	9.8
Firenze	Very low	5	3	3	8	6.5	0.9
	Low	7	4	3	17	14.9	2.1
	Standard	11	6	6	48	41.3	5.9
	Slightly high	15	8	7	62	53.1	7.6

As confirmed by the results, the use of the tested electrical radiant plates can be considered suitable only in houses with low heating demand, where the number of elements is low and the area required for photovoltaic modules too.

CONCLUSIONS

The measurements and calculations reported in the paper showed that electrical radiant plates may be a

Table 3. Ratio between the transparent and the opaque envelope at different orientations.

	Nord	Sud	Est	Ovest
S_t/S_o	0.1	0.2	0.15	0.15

suitable heating system, equipped by control system. The main problem of a radiant plate can be a too high surface temperature, able to engender radiant asymmetries in the room.

Due to these reasons electrical radiant plates are particularly proper in houses with low thermal loss. This kind of buildings are highly insulated and fit properly a heating system with a quick reaction to eventual thermal stresses.

Due to the high quality and value of electrical energy, the use of it for heating is furthermore acceptable only in low-energy building, where the yearly heating consumption can be balanced by the production of photovoltaic energy on site. Low cost equipments can, under these conditions, be competitive with other systems: in fact, for economical sustainability, low energy requirements have to be faced by low cost technologies in order to give suitable payback time.

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8.5. PAPER V

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Field test of a Thermal Active Building System (TABS) in an office building in Denmark.

Submitted to Energy and Buildings.

Field test of a Thermal Active Building System (TABS) in an office building in Denmark

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ABSTRACT

An increasing attention has been addressed in the last years to the simultaneous assessment of energy performances and indoor environmental quality in buildings. At the same time, also use of low temperature heating and high temperature cooling systems in non-residential buildings has increased, due to the increased cooling and heating energy efficiency and the economical performance.

This paper presents an experimental study in an office building in Denmark where cooling in summer is provided by thermally activated building systems (TABS). Indoor environmental quality, cooling performance and energy consumption for a specific room were analyzed with different levels of internal gains. The experiments were carried out monitoring air, surface and operative temperatures, relative humidity and CO_2 levels in the room where internal heat gains from people were simulated and controlled by heated dummies positioned at the same workstations used by employees during the workdays. Supply and return water temperature in the pipes of the hydronic system, supply and exhaust air temperature in the ducts of the ventilation system, and thermal energy consumption were monitored. The performance of the system was also analyzed by using dynamic building simulation programs.

Introduction

Interest in low temperature heating and high temperature cooling systems in non-residential buildings has increased in the last years. The reason of this attention is due to the high energy efficiency and the cost reductions achievable with this kind of systems. These systems are characterized by the pipes, embedded in the structural concrete slabs of multi storey buildings [19], in order to get more mass and thermal capacity [9]. According to [1] different system configurations based on the building thermal storage activation are called TABS (Thermo-Active Building System). Slabs are thermally activated by water or air [2-4] that operate with small difference between room air and HVAC system temperature allowing the use of low temperature heat sources [5]. Except for this thermal storage effect, , the TABS design is based on the same parameters characterizing other radiant systems (spacing and diameter of the pipes, thickness of concrete layer, water temperature, water mass flow rate) [6,7]. The high water temperature for cooling shows an overall energy consumption lower than conventional air conditioning systems and offers the possibility of using renewable or recovery sources of energy, or technologies not usable in traditional systems [13]. Ventilation combined with TABS appears to be very promising alternative to conventional all-air system even for continental climates, offering both significant primary energy savings as well as thermal comfort advantages [5]. In fact the ventilation systems are here designed to provide only standard-requested amount of fresh air, to remove latent loads and to supplement in peak hours, while thermal loads can be balanced using TABS. For this reason, the ducts size of the ventilation system can be smaller and suspended ceilings are not needed. [14] Talking about passively cooled low-energy office buildings, in moderate European summer climate a good thermal comfort can be provided removing heat loads only by TABS using ground cooling and/or night ventilation. Moreover this kind of system allows to remove the daytime peaks loads during the night time, when the prices of electricity are lower [17], and to use water temperature in the pipes close to desired room temperature. It is important to highlight that operative temperature drifts in the room can be expected because it cannot be controlled as a fixed level [6]. Significant energy saving can be achieved using adapted system topologies and applying appropriate control solutions for TABS [20] [21].

Examples of TABS application in architectures are described in [5,10]. In literature studies about performance of the systems, controls and thermal comfort are mainly conducted through simulations tools, like TRNSYS and Energy Plus [6, 13, 19, 20, 21]. In particular in [5] primary energy and comfort performance of ventilation assisted thermo-active building systems, relative to a conventional all-air system in a compact office building, are compared. In [11] simulation with TRNSYS and CARM are conducted for a building located in two different countries, with two different strategies of ventilation and two possibility of systems, with good results for comfort conditions in both heating and cooling season. In [22] a method for dimensioning and for automated controls of TABS is proposed with the support of dynamic simulations.

In some cases long term measurements are performed to calibrate and validate the simulation model [12,16]. In other cases, the model supports the measurements in the evaluation of thermal comfort and energy performance of HVAC [9]. Only in very few studies is the performance of a TABS system evaluated mainly by measurements [8].

Aim of the work is to evaluate the TABS performance through field test in a real office building, using simulations tools in the start-up and in the final phase of the process to support the investigations. The study consists in the assessment of the TABS hydronic system with the variation of internal loads in summer.

7. Methods

The field tests took place during summer 2011, in an open plan office that was part of a bigger office building situated in Denmark. Heated dummies were positioned at the same workstations used by employees during the workdays, and located homogeneously in other empty areas of the room, with the aim to simulate internal heat gains from people, computers and other sources. During the experiments, dynamic simulations performed through energy simulation tools were conducted simultaneously with physical measurements.The entire investigation process can be divided in four different phases, as shown in Figure 1.

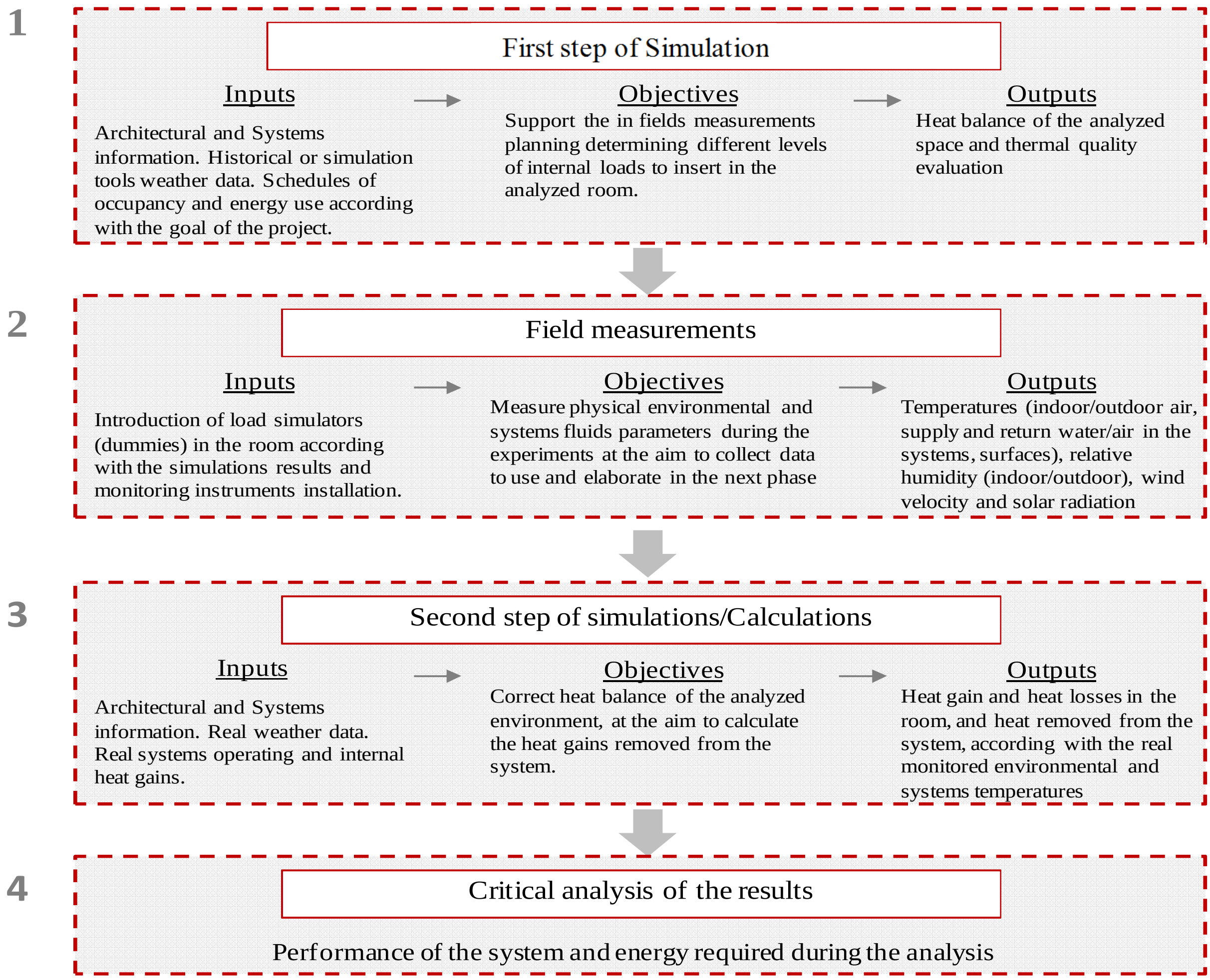


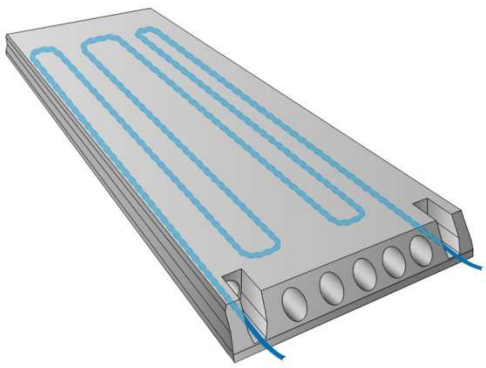
Figure 1. Operative approach used during the experiments.

8. Case study

The office is a 5380 m^2 building situated in Denmark (Lat: 55.5°, Lon: 9.75°). The building has a complex shape, and the roof represents the most relevant architectural element. Most of the building areas are occupied by the owner, while some rooms have been designed in order to be rent to external activities (bookshop, cafè, real estate agent, etc.). The building is structured in three different levels. The working areas (basically open space offices) are mainly located on three open terraces, internally connected by broad staircases. On each floor also single offices, meeting rooms and other rooms for dedicated services are placed. The building envelope is made mainly by structural glass, with thermal transmittance U=1.1 [W/m^2K], and with the transmission coefficient (visible light/solar energy) equal to [0.64/0.35]. The offices are normally occupied during daily time from 8:00 to 18:00, from Monday to Friday. Thermal and air quality in the building are guaranteed by a different combination of systems. Heating in winter is provided in part by convectors, and in part by an hydronic systems (floor heating). While cooling in summer is given in part by a hydronic system (floor cooling) and in part by TABS (for South-West exposed offices). Also the ventilation system, in addition to air quality control, contributes to add or remove loads respectively in peak winter and summer period, in some part of the building. The ventilation is in the large open space hybrid ventilation, partially mechanical and partially controlled natural, while meeting rooms and single offices have mechanical ventilation.

The specific investigation has been performed in one selected room of the building, situated at the first floor. This room has a South-East exposition, and the floor surface is equal to 268 m^2. In winter time heating is guaranteed by convectors, located on the floor along the façade, and balanced mechanical ventilation. In summer a thermal active building system integrated in the ceiling (Figure 2-3), combined with mechanical ventilation, provides to cool the environment. Both the floor and the ceiling slabs of the room have a raised floor with acoustic insulation, and pipes embedded in the lower part of the concrete slab. A floor heating/cooling is situated in the upper layer of the ceiling slab, with the aim to heat/cool the room above. The lighting level in the room is controlled by sensors of presence and the intensity of the artificial lights is balanced with the natural light. There are automatic and manually curtains for solar radiation control, and the employees have the possibility to open/close the windows.

Even if one of the characteristics of the TABS is that it allows to avoid the suspended ceiling [7], in this case a suspended ceiling made in steel bars, distant 60 cm from the slab, integrates the light and hides the ducts of the ventilation system .



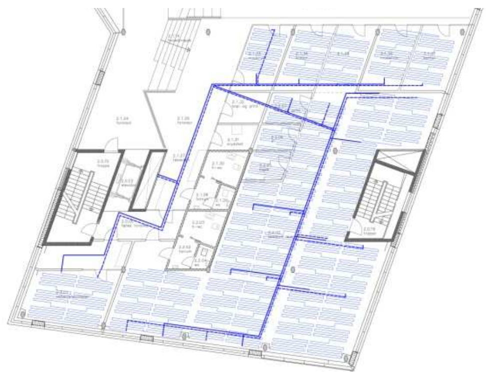


Figure 2. (left) Prefabbricated module of slab with pipes embedded in the concrete, installed in the building.

Figure 3. (right) Design of the termal active building system in the case study room.

9. Experimental activities

Phase 1: Determination by dynamic simulations the room internal loads to be used in field measurements

In order to determine the level of internal loads to install in the examined room, dynamics simulations were performed with the support of the energy simulation tool TRNSYS (16.1.0003). The use of simulations in the first phase of the process allowed to solve the energy balance of the room in cooling mode, giving as outputs the total heat loads and the operative temperature in the room. The TABS was originally designed to maintain thermal comfort conditions at the work places until 40 W/m^2 of cooling loads. Through the simulation model, it was possible to test different levels of internal gains in the room to reach 40W/m^2 by adding people and computers in the office. The objective was to estimate how many dummies (1 dummy = 1 person + 1 computer = 170 W) had to be placed in the room to reach the designed value of ~40 W/m^2.
The simulations were performed considering:

- Artificial lights: regulated according with the solar radiation
- Ventilation system (total flow rate: 3.6 ach, estimated from design documentation, air supply temperature: 20 °C - average value estimated from the data collected through measurements performed in May)
- U value for windows: 1.1 W/m^2
- U value for walls: 0.2 W/m^2
- TRNSYS weather file for the city of Copenhagen.

Simulations have been performed considering the ventilation system always on and people in the room for 24 h a day, because it was decided to carry out experiments also during night time, and with the ventilation system always on.

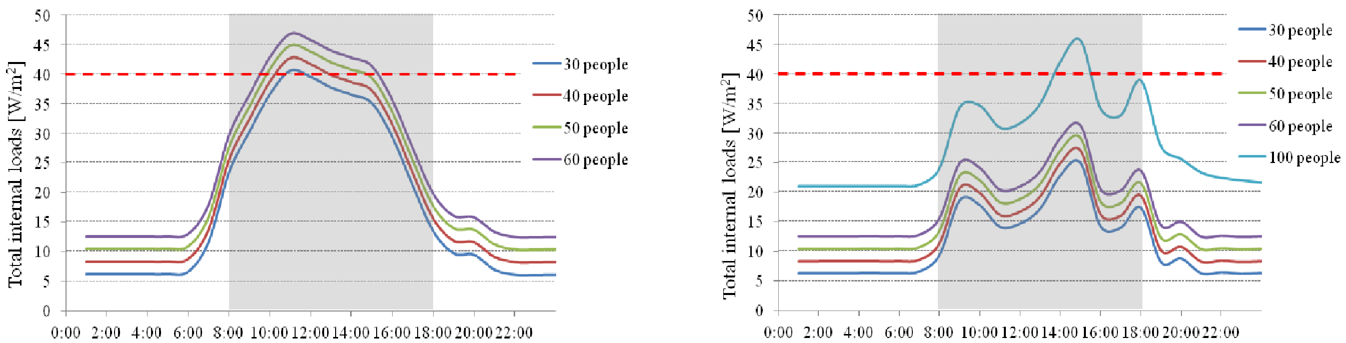


Figure 4- Simulation results: total internal loads evaluated in a sunny day and in a cloudy day.

Figure 4 shows the profiles of internal loads obtained by the simulations in a sunny day and in a cloudy day of August. Results show that in a sunny day, 30 dummies in the room allow to reach a cooling load of 40 W/m^2 for about one hour. In order to analyze the system for a longer time with peak cooling load, increasing of internal loads is necessary. Increase the internal loads as if there were 20 more people means insert other 3.4 kW in the room. Totally different is the situation in case of cloudy/rainy day. To reach the cooling load of 40 W/m^2, the internal loads need to be increased at least of 12 kW (like there were 70 more people).

This kind of analysis is really useful because it highlights how the peak cooling load is influenced by the solar gains. In case of field measurements, where the boundary conditions cannot be controlled, a preventive evaluation is necessary in case changing of the experiments setting are needed, according with the weather condition, when measurements are already running.

Phase 2: In field measurements

Measurements were carried out in the selected room from August 13 to August 16, 2011. During these experiments different levels of internal loads were inserted in the office, according with outside weather condition and based on the results from the simulations. Indoor and outdoor environmental parameters, and supply and return temperature of the air in the ventilation system and of the water in the hydronic system were monitored.

Different Scenarios of analysis

As explained before, different scenarios of analysis were considered during the tests. These three settings were characterized by the introduction of internal loads as it follows:

- First Scenario (S1) - 30 dummies and 3 heaters
- Second Scenario (S2) - 30 dummies
- Third Scenario (S3) - in addition to the 30 dummies, in the room there were 11 people with 11 computers.

Because of the limited number of available dummies, and because of the absence of solar radiation, in S1 the internal heat loads were increased by inserting electric heaters. The distribution of dummies, heaters and people in the three scenarios is shown in figure 5. In the same pictures, the position of the stand with air and the operative temperature sensors (explained in the next paragraph) are shown too. Note that S1 and S2 differs just for the presence of the heaters in the first case.

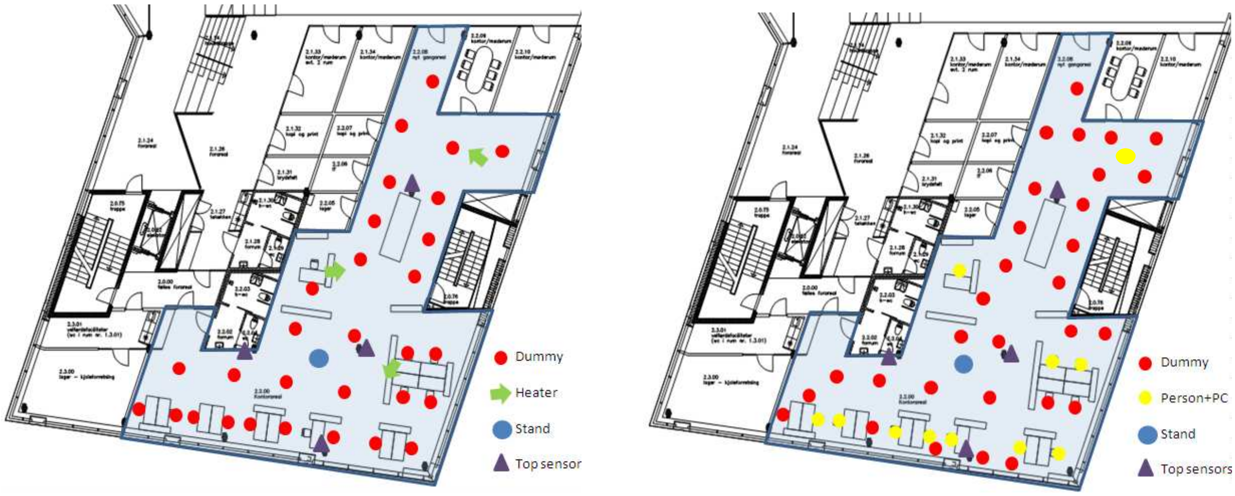


Figure 5 - Scenario 1-2 (without heaters) *Scenario 3*

Monitored parameters during the experiments

During the tests, physical parameters (Table 1) were collected in the room through the use of a stand positioned in the center of the room (Figure 5), on which sensors were located at different heights. Then, operative temperature and surfaces temperatures were also collected in different points of the room. At the same time a weather station was logging data about the outside environment, and sensors of temperature were measuring temperature of the fluids in the systems. All the monitored parameters, the typology of sensor used, their position, and the frequency of acquisition are listed in Table 1.

Table 1. Monitored parameters during experiments.

	Parameter	Number of sensors	Position of the sensors	Instrument	Frequency of acquisition
ENVIRONMENT IN THE ROOM	Operative temperature [°C]	4	Homogeneously distributed in the room, at the high of 110 cm	Operative temperature sensor	10 minutes
		4	Positioned on one stand in the center of the room, at 4 heights: 10cm, 60 cm, 110 cm, 170 cm	Operative temperature sensor	1 minute
	Air Temperature [°C]	1	Installed attached to a wall, in a central position of the room, at the height of 170 cm	Thermo resistence (permanent)	10 minutes
		4	Positioned on one stand in the center of the room, at 4 heights: 10cm, 60 cm, 110 cm, 170 cm	Thermo resistence	1 minute
	Air Velocity [m/s]	4	Positioned on one stand in the center of the room, at 4 heights: 5 cm, 10 cm, 20 cm, 60 cm	Anemometer	1 second
	Surface Temperature [°C]	1	Different points of the room: windows, walls, floor, ceiling and suspended ceiling	Thermocamera	3 hours (if possible)
	Relative Humidity [%]	4	Positioned on one stand in the center of the room, at 4 heights: 10cm, 60 cm, 110 cm, 170 cm	Anemometer	1 minute
	CO_2 concentration [ppm]	1	Installed attached to a wall, in a central position of the room, at the height of 170 cm	CO2 sensor	10 minutes
OUTDOOR ENVIROMENT	Air Temperature [°C]	1	Installed on a Weather Station positioned outside the building	Thermoresistence	10 minutes
	Relative Humidity [%]	1		Psycrometer	10 minutes
	Wind Speed [m/s]	1		Anemometer	10 minutes
	Wind direction [deg]	1		Wind direction sensor	10 minutes
	Solar radiation [W/m2]	1		Solarimeter	10 minutes
SYSTEMS	Supply Air temperature in the ventilation system	1	Positioned in a diffuser of supply air in the centre of the room	Thermoresistence	10 minutes
	Return Air temperature in the ventilation system	3	Positioned in ducts of exhaust air in different points of the room	Thermoresistence	10 minutes
	Opening of the dampers	8	Situated in proximity of the dampers in the supply and exhaust ducts of the ventilation system	Damper percentage of opening meter	10 minutes
	Supply Water temperature in the TABS	1	Positioned in the pipe of supply water in the beginning of the circuit (of the room)	Thermoresistence	10 minutes
	Return Water temperature in the TABS	1	Positioned in the pipe of return water in the end of the circuit (of the room)	Thermoresistence	10 minutes

Results of the monitoring

Outside weather conditions, in temperature profiles and operating of the cooling and ventilation systems during the experiments are shown in this paragraph. Figure 6 shows the solar radiation and the outside air temperature collected by the weather station. The graph also illustrates the three scenarios. During S1 and S2 the solar radiation was really low. In the third scenario the solar radiation was higher, but discontinuous. The average outdoor temperature raised of about 2°C each day during the day time.

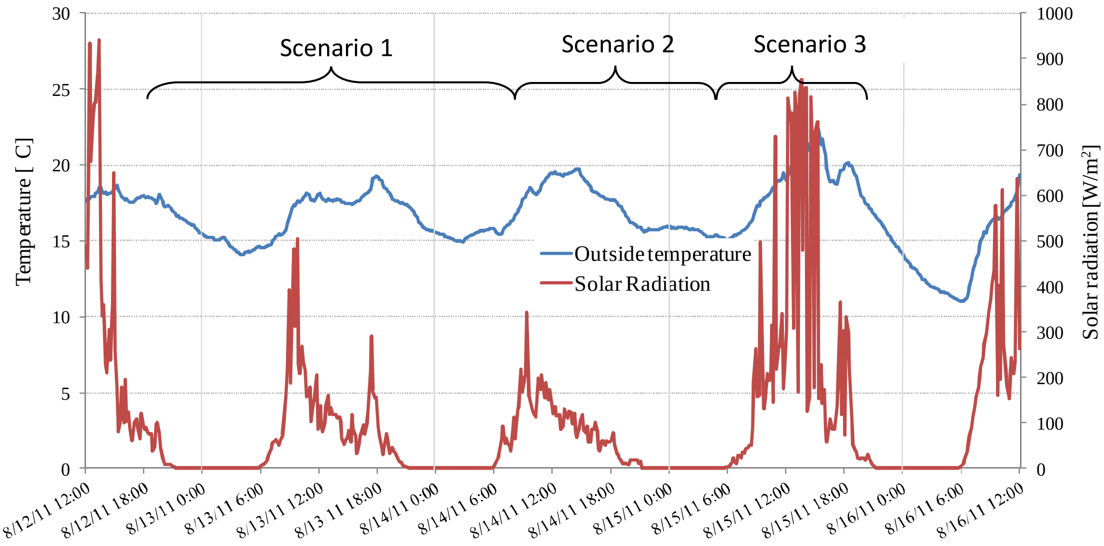


Figure 6 –Outdoor temperature and solar radiation during the experiments.

Profiles of average operative temperature at 110 cm in the room, of supply and exhaust air temperature in the ventilation system and of supply and return water temperature in the pipes are shown in figure 7. The graph illustrates that the ventilation system started to run in the middle of S1 (at 18:00), and from that moment the supply water temperature in the pipes fluctuated between 15 and 19 °C. The temperature in the room was set as 23°C. The ventilation system was working in S1during the day time, with little flow rate, and supply air temperature 23°C. It was switched off during S2, and switched on again from during S3. In the beginning of S1 both ventilation and tabs systems were not working. During the day just the ventilation system was cooling, and then in the night just the tabs system was operating. In S2 the cooling was provided by TABS. In S3 both tabs and ventilation systems were working together.

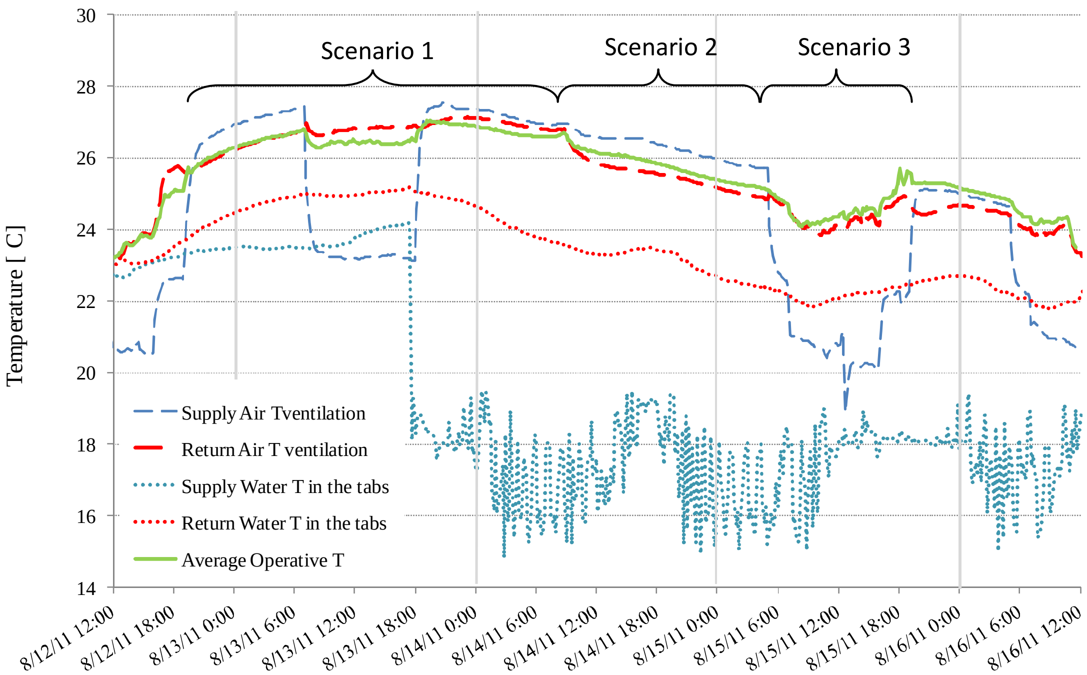


Figure 7- Temperature profiles of average operative temperature in the room, supply and exhaust air temperature in the ventilation system and supply and return water temperature in the pipes.

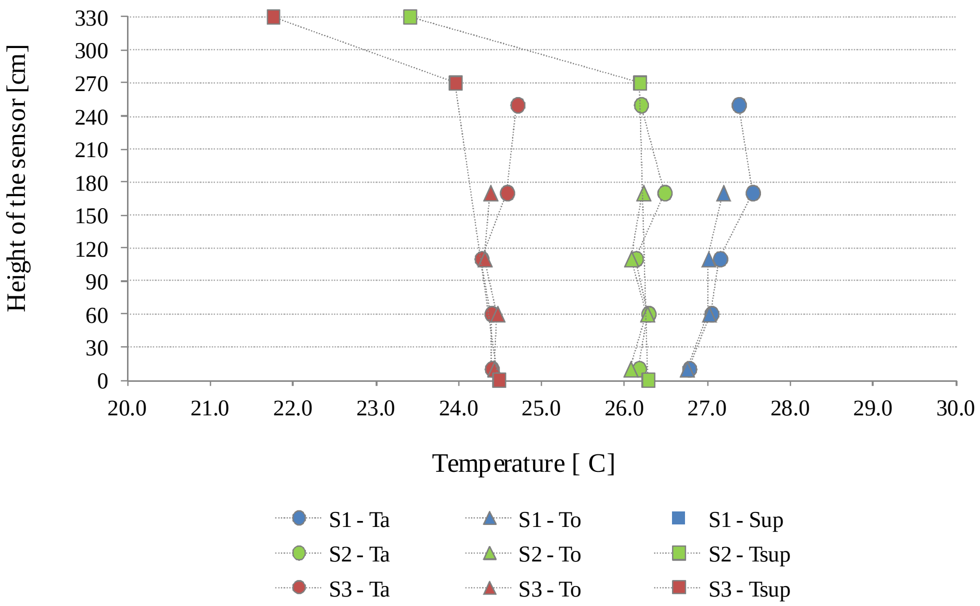


Figure 8- Average air, operative, and surfaces temperature in the room, for the three scenarios.

Figure 8 show, together with the average air and operative temperature, the average surfaces temperature measured with the an infrared camera. The surface temperatures of: floor, ceiling at 270 cm (suspended ceiling) and ceiling at 330 cm (concrete surface). While floor and suspended ceiling temperatures were in general really close to the air temperature in the room (almost constant at different heights in all the scenarios), ceiling temperature differed at least 2°C from the air temperature, when the system was operating. The surface temperatures of the floor denote that the tabs integrated on the ceiling of the room below (ground floor) were not removing any significant heat load from the room. The average values showed by the graph represent a time interval where temperatures were almost constant, and the systems were working,.S1 the interval represent a period of night time in which surfaces temperatures could not be collected.

Phase 3: Second step of dynamic simulations and loads calculation with integration of real monitored data

Through dynamic simulations, performed this time with the support of Energy Plus, internal gains were calculated for the duration of all the experiment. Energy Plus allowed to make a more realistic simulation models, using the room temperature as set-point temperature, and setting the range of water temperature in the hydronic circuit. In the simulations real monitored data where insert as input, like outside air temperature and relative humidity, and solar radiation. The model, simplified as shown in figure 9, has been useful in particular for the internal gains. Since results of simulations, in terms of internal temperature, differed a little from the real monitored data, heat losses through envelope, infiltrations, and heat loads removed by the systems were calculated later using as reference the real temperatures.

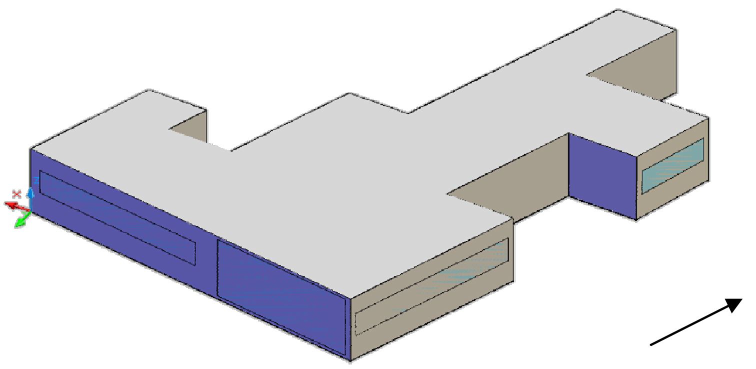


Figure 9- Model of the room simulated with Energy plus for the internal loads calculations.

Knowing supply and return water temperature in the tabs system, and flow rate in the pipes, loads removed by the TABS were calculate by using the basic equation:

$$Q/A= m*cp*DT \quad (1)$$

Where:

m = flow rate in the pipes

Cp = specific heat of the water

DT = return and supply water temperature difference in the pipes

In the calculations, the flow rate in the pipes was set at its nominal value, equal to 0.42 l/s.

Figure 10 shows both the profiles of the heat removed from the room and the heat removed by the water in the slab pipes. As we do not have complete steady state these two values may not be equal.

During S1 the TABS were not working, the cooling loads in the room exceeded 40 W/m^2 and the temperatures in the room increased (except when the ventilation system was operating). During this time, the slab accumulated a lot of heat that began to be removed by the TABS when they started to work. Supply temperature in the circuit was in the beginning about 18°C, and then started to fluctuate between 16 °C and 18°C. During the normal working days, over the experiments, the temperature in the room is usually between 22 °C and 23 °C, and the supply water temperature in the TABS is around 20°C. At the end of S1 the difference of water temperature between supply and return reached 8°C, and the loads removed by the system on the water side reached 60 W/m^2. This was due to the heat stored in the concrete slabs.

During S2 the heat loads in the room were reduced, and also the loads removed by TABS reduced. The room operative temperature, between the beginning and the end of the scenario, decreased of about 2°C. Same trend for the return water temperature in the pipes, while the supply water temperature kept constant as it was in S1. During normal working days return water temperature is almost equal to operative temperature, while during the experiments the ΔT was always about 2K.

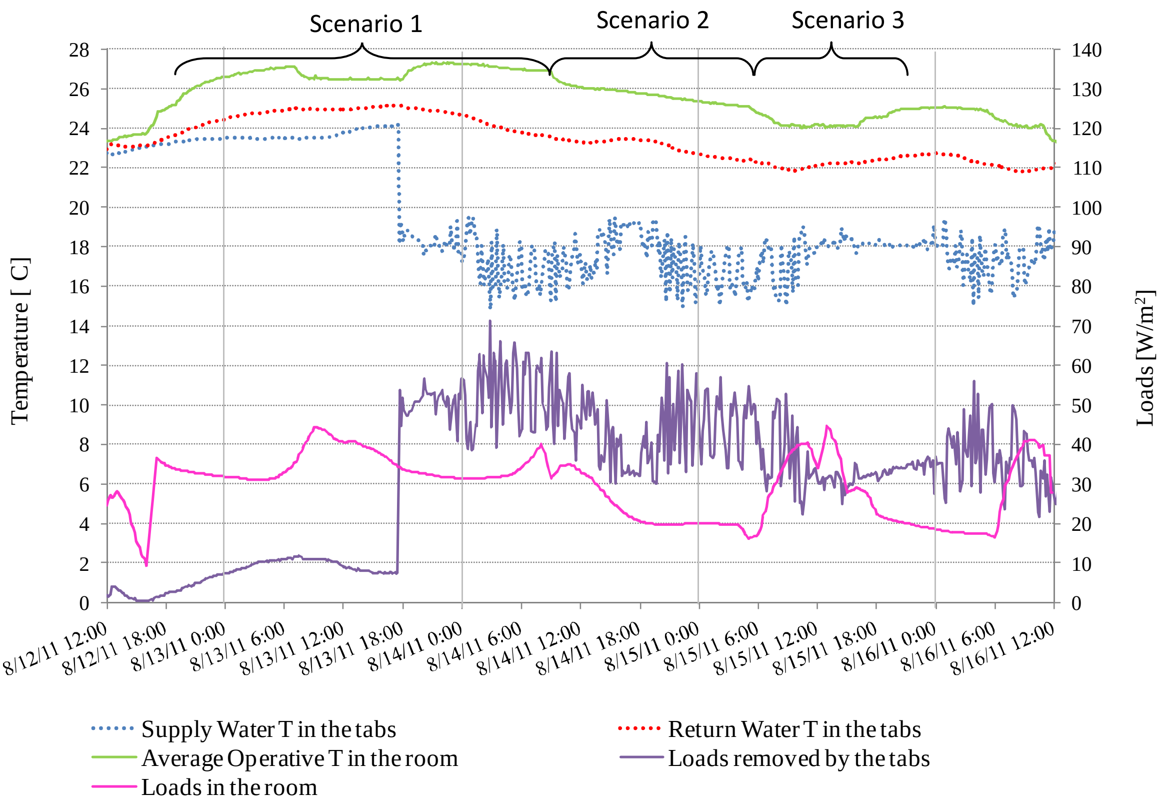


Figure 10- Profiles of Operative temperature, supply and return water temperature, loads removed by the tabs and cooling loads in the room

During S3 also people were in the room together with the dummies. Both TABS and ventilation system were working together: ventilation system contributed to remove heat gains from the room. The "cooling loads in the room" represented in the graph are at the net of the loads removed by ventilation. The temperature in the room decreased at 24 °C and the supply water temperature in the pipes was almost constant around 18°C. Considering that the air temperature set point was 23°C, for to reach lower temperatures in the room, in case of high heat loads in the room, the supply water temperature in the tabs needed to be reduced.

Phase 4: Critical analysis of the results

In order to evaluate the performance of the cooling system, three different intervals of time (6 hours), one for each scenario, were analyzed during the system operating time:

Interval of Scenario 1: From 13/08/2011, 20:00 to 14/08/2011, 02:00

Interval of Scenario 2: From 14/08/2011, 12:00 to 14/08/2011, 18:00

Interval of Scenario 3: From 15/08/2011, 09:00 to 15/08/2011, 15:00

During these intervals of time, air temperature in the room and water temperature in the hydronic system were almost constant. For these intervals a steady state heat balance was evaluate in the room, and results are illustrated in figure 11.

Average values of measured parameters during the three time intervals are listed in table 2. From the data it is seen that outside temperature increased from scenario 1 to 3, while indoor air temperature decreased. This explains the higher losses for transmissions through walls and windows, and infiltrations, of S1 respect to S2 and S3 indicated in figure 11.

Table 2- Measured temperature in the tabs system, in the ventilation system, in the room and outside.

Scenario	TABS				Ventilation				Average temperatures		
	Supply [°C]	Return [°C]	DT	Flow rate (kg/s)	Supply [°C]	Return [°C]	DT	Flow rate (kg/s)	To [°C]	Ta [°C]	Tout [°C]
1	18.1	24.7	6.6	0.42	27.4	27.1	-0.3	no	27.0	27.1	16.1
2	18.1	23.4	5.3	0.42	26.5	25.7	-0.8	no	26.1	26.1	18.8
3	17.9	22.1	4.2	0.42	20.5	24.1	3.6	1.40	24.3	24.2	19.6

For radiant systems a large part of the heat transfer between heated/cooled surface and room is by radiation, which can be highlighted by comparing the radiant and convective transfer coefficients [23][25]. From [15] the approach to calculate a combined heat transfers can be expressed as:

$$Q/A = (hc+hr)*DT \quad (2)$$

Where:

$(hc+hr)_{floor} = 6\ W/m^2K$

$(hc+hr)_{ceiling} = 11\ W/m^2K$

DT= difference of temperature between the average air temperature in the room and the surface temperature.

With this method, in addition to the already calculated loads removed from the slab by the TABS, also the loads removed instantaneously from the room were determined.

Results of all the analysis can be summarized in the schemes of figure 11.

During the interval of S1 surfaces temperatures were not collected. In this case, just an energy balance of the environment and the loads removed by the TABS were calculated. As already said, in the 2 days before the hydronic system was not running. The slab accumulated a lot of radiant heat that was removed during the following days. The temperature in the room was high, but this is explained by the fact that no systems were working. From this interval of time the temperature started to decrease.

During the interval of S2 TABS continued to remove the loads accumulated in the previous days. Loads removed by the room were almost the same than the load calculated with the heat balance. This means that in that interval of time, the TABS were balancing the cooling needs of the room.

Here, the indoor operative temperature was around 26°C (upper limit of category II according with [24]). During all S2 the temperature was between 25°C and 26°C. This means that the comfort requests were respected, being that the building has been designed to be in category II of thermal comfort.

During the interval of S3 the ventilation was contributing to remove loads from the room. The calculations denote that the system was not removing instantaneously enough heat as required by the energy balance. The slabs accumulated heat that was later removed. However it is important to specify that people in the office were moving and opening windows and doors. This means than the heat balance determined with dynamic simulations could not be constant during all the 6 hours of analyzed interval. Also the ventilation system allowed to remove heat from the room, and the operative temperature was around 24°C, respecting category I of thermal comfort.

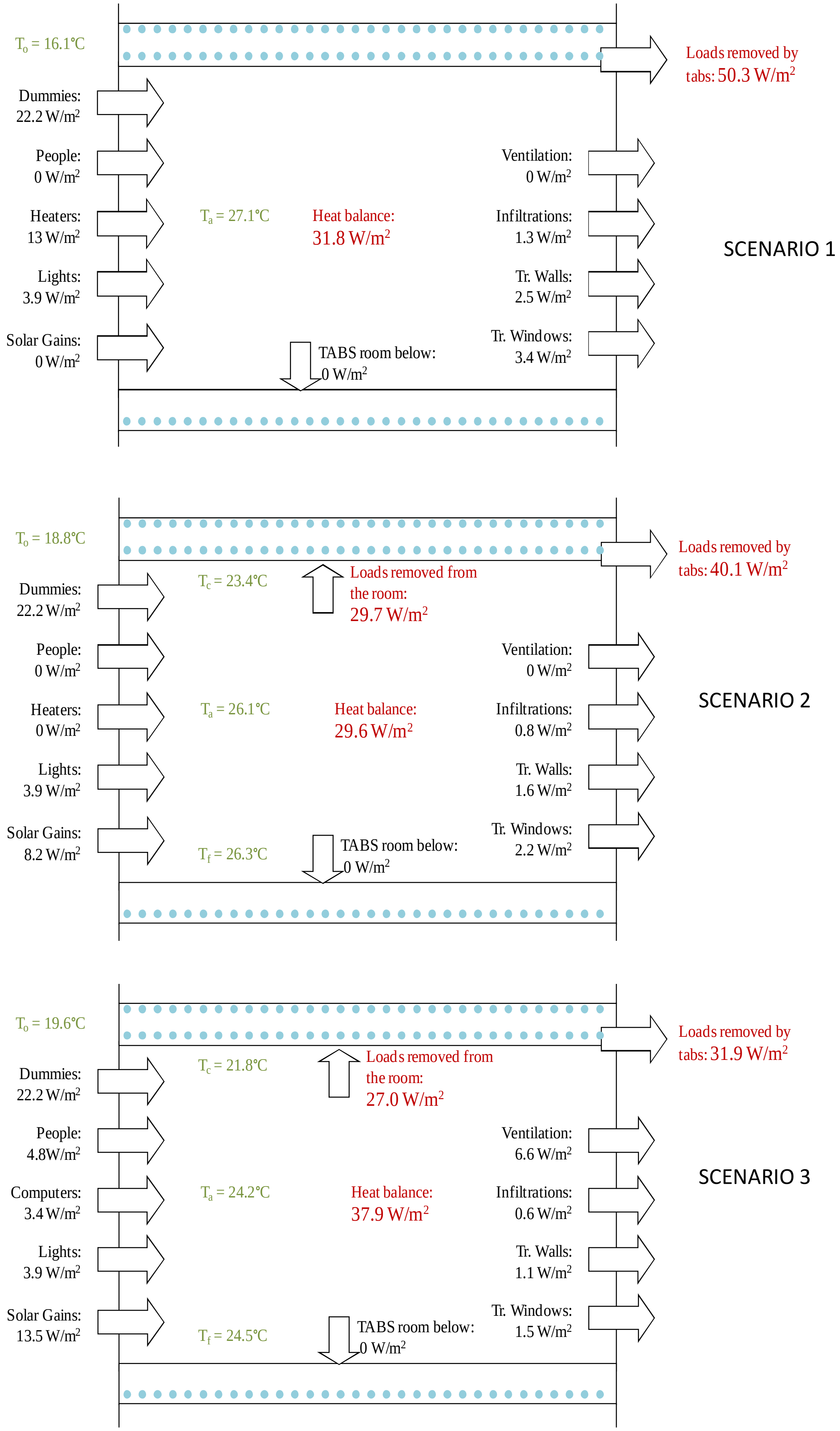


Figure 11 – Total Energy balance - intervals of scenario1, 2 and 3.

In order to analyze the performance of TABS, the loads removed by the TABS for the three scenarios were calculated in relation to the difference between the average water temperature and room operative temperature This is equivalent to the total heat exchange coefficient between water and room7:

$$htotal = L / [Top – (T_{supp} + T_{ret}) / 2] \quad (3)$$

Where:

L_{rt} = Total heat exchange coefficient i.e. loads removed by the TABS for degree temperature difference between average water temperature in the circuit, pour square meter [W/m^2°C]

L = loads removed by the TABS, calculated with (1) [W/m^2]

Top = operative temperature [°C]

T_{supp} = Supply water temperature in the TABS [°C]

T_{ret} = Return water temperature in the TABS [°C]

Results are shown in figure 12.

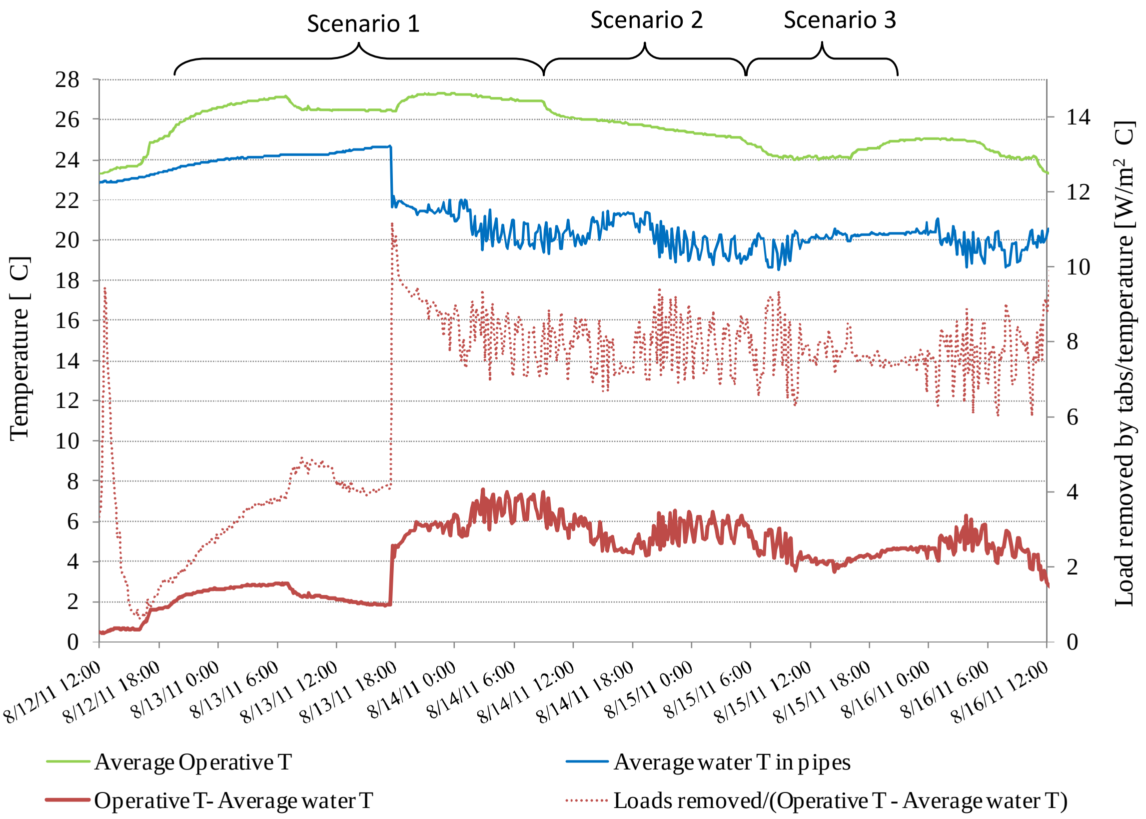


Figure 12 - Loads removed by the system per degree temperature difference between average water temperature in the pipes.

Figure 12 shows that the system removed averagely about 8 W/m^2 per degree temperature difference between average water temperature (cooling capacity = 8 W/m^2°C), during all the scenarios. This means that also in case of different heat loads in the room, the system control allowed to maintain a good performance.

From the graph the average water temperature in the pipes was always around 20°C, while the operative temperature decreased from S1 to S3. When for example the operative temperature was 26°C (S2), and consequently the temperature difference was 8°C, the system could remove about 48 W/m^2. Wanting to evaluate how much loads could be removed by the system at lower water temperature, if the average water temperature in the pipes in that case was 18°C, it could be said that the system could then remove about 64 W/m^2, but in that case the supply temperature would be too low (< 18C), which could increase the risk for condensation on the supply pipes (not concrete surface) and it would be more difficult to control. So a cooling capacity of 40-50 W/m2 can be documented by the present test.

Conclusions

In this paper the performance (cooling capacity) of a Thermal Active Building System (TABS) was studied by field measurements and dynamic simulations, . The following results were obtained:

- Support of dynamic building simulations is useful for designing a more accurate field test and for the analysis of the results, in particular in the calculation of internal loads.
- The measurements show that under different scenarios the total heat exchange coefficient between the average water temperature and the room (operative temperature) was almost constant about 8 W/m^2 per degree temperature.
- The analyzed system could remove from the room a cooling load of 30 W/m^2 using an average supply water temperature in the pipes of 18 °C. Higher cooling loads could be removed with lower temperature.
- The presence of the suspended ceiling did not interfere with the ability of the system to keep comfort in the room.
- Also with high loads in the room the hydronic system was able to keep the thermal comfort conditions. In particular when also the ventilation system was running. Employees that were working in the office during the third scenario confirmed that fact filling subjective questionnaires.

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8.6.PAPER VI

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A system for the comparison of tools for the simulation of water-based radiant heating and cooling systems.

Building simulation 2011, November 14-16, Sydney, Australia.

Proceedings of Building Simulation 2011:
12th Conference of International Building Performance Simulation Association, Sydney, 14-16 November.

A SYSTEM FOR THE COMPARISON OF TOOLS FOR THE SIMULATION OF WATER-BASED RADIANT HEATING AND COOLING SYSTEMS

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ABSTRACT

Low temperature heating and high temperature cooling systems such as thermally activated building systems (TABS) offer the chance to use low exergy sources, which can be very beneficial financially as well as ecologically when using renewable energy sources.

The above has led to a considerable increase of water based radiant systems in modern buildings and a need for reliable simulation tools to predict the indoor environment and energy performance.

This paper describes the comparison of the building simulation tools IDA ICE, IES <VE>, EnergyPlus and TRNSYS. The simulation tools are compared to each other using the same room and boundary conditions.

The results show significant differences in predicted room temperatures, heating and cooling degree hours as well as thermal comfort in winter and summer.

INTRODUCTION

Over the past years, building simulation has become more and more important for the design of new buildings. Building simulation can be used to (i) increase comfort, (ii) decrease energy consumption and at the same time (iii) lower the overall costs for heating and cooling.

Providing better comfort can increase productivity and reduce sickness or other problems of the occupants. Reducing the energy consumption in buildings can contribute greatly towards the goal of a sustainable society. From 2006 to today, the delivered energy for residential and commercial buildings has risen and its share has increased from 15 to 20 per cent (U.S. Energy Information Administration, 2009, 2010). The use of low temperature heating and high temperature cooling systems, such as thermally activated building systems (TABS) can help to reduce this share. TABS can be operated using temperature levels close to the desired room temperature due to the use of large heat transfer areas. The consequential decrease of the temperature difference leads to the opportunity to use renewable energy sources, many of which can also be considered as low exergy sources. In this way not only energy consumption can be reduced but also exergy destruction can be minimized.

A transition from current heating and cooling systems to low temperature heating and high temperature cooling is also needed to be able to decrease losses in the distribution systems of centralized energy supply like district heating and cooling plants and increase energy performance of decentralized energy systems like heat pumps, chillers, boilers, co-generation etc..

Compared to full air conditioning systems the use of water based cooling may reduce investment costs in equipment, lower operation costs and reduce building height (building materials). Reducing the overall first costs of a building increases its attractiveness to investors. Whereas reducing the running costs is attractive for the user. It is however, important in future cost analysis to look both at investment and running costs, when evaluating the cost benefits of different concepts.

Whereas the simulation of air based heating and cooling systems is supported by most simulation tools, not all of them support the use of thermally activated building systems (TABS)(Crawley et al., 2005b). In most cases the simulation of TABS requires the installation of an additional module to the regular simulation tool or can only be performed by some questionable modification like simulating the TABS as an additional space.

In the end, the question remains how reliable the simulation of TABS is and how the results compare to an actually existing building. This paper is trying to answer this question for a selection of simulation tools.

PROGRAM OVERVIEW

Different commercial available simulation tools have been used to model a modern office building using TABS for heating and cooling purposes. These simulation tools are IDA ICE (4.101), IES <VE> (6.3 April 2011), Energy Plus (6.0.0) and TRNSYS (16.01.0003).

IDA ICE 4

URL: www.equa.se/ice

The modular dynamic multi-zone simulation tool, IDA Indoor Climate and Energy (IDA ICE), is a commercial program which was first released in May 1998. It can be used for the study of the thermal indoor climate of individual zones as well as the energy consumption of the entire building. IDA has been programmed in the simulation languages Neutral Model Format and Modelica using symbolic equations. Depending on the experience of the user and the complexity of the problem at hand, three different, but integrated user levels are available: Wizard, Standard and Advanced.

The Wizard level can be used to make fast and easy simulations of a single room. It can be used to calculate heating and cooling loads. Both, the Standard as well as the Advanced level are capable of simulating multiple zones within a building. The Standard level is used to build the general simulation model using the available domain specific concepts and objects, such as zones, heating devices or windows. The Advanced level can then be used to edit the mathematical model of the system.

The modular nature of IDA ICE makes it possible to write individual models extending its capabilities as needed by the individual user. (Crawley et al., 2008)

IES <VE>

URL: www.iesve.com

IES <VE> is a commercial simulation platform with the first major version 3.0 released in the late 1990's. The program combines several software components for different simulation tasks.

The main modelling tool in IES <VE> is ModelIT, where it is possible to construct a 3D model of rooms or a whole building. Additionally, CAD data can be imported using plug-ins (e.g. in Revit or SketchUp) or by importing CAD files (e.g. DFX).

For the dynamic thermal simulation, the component ApacheSim is used, whose calculations are based on first-principle mathematical models of heat transfer processes.

ApacheSim can be linked to other components of IES <VE> to include detailed results of shading devices and solar penetration (SunCast), airflow analysis (MacroFlow), component based HVAC systems (ApacheHVAC) and lighting (LightPro, RadianceIES). The results can also be exported for a more detailed CFD simulation by Microflow. (Crawley et al., 2005a; IES, 2011)

EnergyPlus

URL: http://apps1.eere.energy.gov/buildings/energyplus/

EnergyPlus is a new-generation building energy simulation program based on DOE-2 and BLAST, with numerous added capabilities. It was released in April 2001, and developed by several U.S. Universities with support from the U.S. Department of Energy, Office of Building Technology, State and Community Programs. EnergyPlus is actually a trademark of the U.S. Department of Energy and a new version of the tool is periodically available online.

EnergyPlus is a stand-alone simulation program without an (user friendly) graphical interface. EnergyPlus is capable of making whole building energy simulations. It enables to model heating and cooling loads, levels of light, ventilation, other energy flows and water use. It allows to simultaneously model different kinds of embedded systems, obtaining simulation output as the real building would. It includes many innovative simulation capabilities, like, but not limited to, time-steps less than an hour, modular systems and plants with integrated heat balance-based zone simulation, multi-zone air flow, thermal comfort, water use, natural ventilation, and photovoltaic systems.

The building model and the input files can be made through the program itself or imported from different building design programs (EERE, 2011).

TRNSYS

URL: http://sel.me.wisc.edu/trnsys/index.html

TRNSYS, standing for transient system simulation program, is a complete and extensible simulation environment. It is commercially available since 1975 (Klein, 2006). It is a flexible tool designed to simulate the transient performance of thermal energy systems. TRNSYS was first developed in a joint project between the University of Wisconsin-Madison, Solar Energy Lab and Colorado State University, Solar Energy Applications Lab in the 1970's.

TRNSYS is an algebraic and differential equation solver in which components are connected graphically in the simulation studio. In building simulations, all HVAC components are solved simultaneously with the building envelope thermal balance and the air network at each time step. The simulation results are based on the individual component simulation performances which can be selected from the simulation studio. It is suitable for the simulation of complicated systems. Users can easily accomplish the desired system control strategies by writing the logical programming or use simple equations thanks to TRNSYS open source code.

TRNSYS also includes the program TRNEdit, which is an all-in-one editor for reading and writing TRNSYS input and output files. TRNEdit can also perform parametric TRNSYS simulations and plot data from the TRNSYS simulation output (Crawley et al., 2008; Klein, 2006; Price and Blair, 2003).

METHODS

In order to analyse the quality of the simulations, it was decided that they should start on a basic level. The complexity of the simulations has been increased from one stage to the next. At the final stage, which is not part of this paper, the simulations will represent a real building, for which extensive measurement data for multiple years is available. Through comparison of the simulation results with the genuine measurement data, it is then possible to evaluate the simulation quality. In the present paper only the results of the different tools are compared with one another.

Comparison of operative temperature

Through the analysis of the operative temperature it is possible to quickly assess the general correlation of the simulation results. If the trend of the lines is synchronized, it is possible to conclude that the programs react similar to the changing input data.

Deviation of operative temperature

By comparison of the average calculated operative temperature of all included tools with the individual operative temperature, it is possible to observe how the differences between the tools change over the course of the year.

Degree hours

Degree hours of overheating for summer as well as for insufficient heating in winter were calculated. In this case however they can naturally not be used to assess the quality of the installed system. Instead, they can be used to easily compare the programs.

Thermal comfort

The thermal environment can be assessed through the thermal comfort categories introduced by the standard EN 15251 (CEN, 2007). This method of representing the results describes the percentage of occupied hours when the operative temperature exceeds the specified ranges.

Other metrics

For the comparison of any heating or cooling system, a number of other metrics such as energy consumption or other comfort factors are of cause relevant. However, due to the nature of the simulation tools , parameters such as draught, vertical air temperature gradients, and radiant temperature asymmetry cannot be calculated.

In the present study the energy use for auxiliary equipment like fans and pumps are not included. Some of the tools can calculate this directly and in other tools the information for calculating this part of the total energy consumption will be available

Using default settings

As far as possible the different default settings of the tools have been used. This will likely result in a lower correlation between the results of the different tools. On the other hand, it is not likely that a user is adjusting any of the default values without any incentive. It was therefore decided that - rather then trimming all possible variables to unison in order to get the highest possible correlation - to leave them as they were to get a more realistic deviation.

TABS

For the final stage in this paper, TABS were modelled in all tools. In the following, the used approach for each of the tools is described.

- IDA allows for the simulation of TABS on both, the Standard and the Advanced level. The TABS is hereby inserted as an additional layer in the slab construction.
  On the Standard level, the input values are limited to design cooling and heating power, temperature difference for design power, controller (Pi, Proportional, Thermostat or always on), coil mass flow, depth in the slab and a heat transfer coefficient that should be selected in accordance to standard EN 15377-1 (CEN, 2008).
  On the Advanced level, additional changes to the system can be made, including, but not limited to, changing the pipe length and inner diameter, the heat capacity of the liquid in the pipes or fine tune the control of the system.
  In both cases the slab temperature is assumed to be constant over the entire area.
- In IES <VE>, TABS are simulated by splitting the internal ceilings into a ceiling - room - ceiling construction.
  The ceiling construction should be divided at the pipe level. The room representing the slabs should be small and the surface resistances should be adjusted to give the construction a more realistic heat transfer behaviour.
  The easiest way to obtain results for the thermal behavior of the office room is to use ApacheSim. Here, the temperature of the fictive room between the ceilings is set to the supply temperature of the real system. It can be controlled by either giving it absolute values or using a profile based on, for instance, the air or operative temperature of an office room, the outside air temperature or an equation including both.
  A more complicated, but also more promising approach for evaluating TABS is ApacheHVAC. In which ”radiators” or ”cooled ceilings” should be introduced into the fictive room between the ceilings. In this case, care should be taken also of heat transfer coefficients, water flow rates and heating or cooling areas of the systems.
- EnergyPlus allows to simulate TABS including an internal source layer in the floor/ceiling construction. Water flow and internal diameter, length of the pipes and distance between the tubes are required. Supply water temperature in the system/tubes can be set, but the final system control has to be based on a set point temperature (here the indoor air temperature).
- TRNSYS simulates TABS by defining an active layer in the floor or ceiling. The definition process begins similarly to that of a normal wall. The parameters like pipe spacing, pipe outer diameter, pipe wall thickness and pipe wall conductivity are required when defining the active layer.
  To ensure a correct calculation, a minimum mass flow rate (generally greater than 13 kg/m^2h) has to be set. The ordinary piping system has been modelled in two segments in this simulation.

The reasoning behind this approach

The comparison of computer tools is a laborious and time consuming business. Virtually all parameters have to be controlled and sometimes this might not even be completely possible. In any case, one can argue that this approach is valid and offers a high insight into the program at an academic level. On the other hand many of these adjustments might be omitted while ”just” simulating a real building, simply because they are unknown. Consequently this means that many of the default values remain unchanged and influence the outcome of the simulation. For this reason it is important to see how the results are changing with increasing complexity of the simulations.

SIMULATION

As mentioned before, the comparison is made through a number of stages. In the following, the stages presented in this paper are explained in more detail. In the end, some fundamental differences between the tools are mentioned, that should also be controlled for further analysis.

Stage 1 - Basic building

As a first step of the comparison, a basic simulation has been made in the selected simulation tools. For this comparison, only the building envelope has been modelled and placed in the outdoor thermal environment. Internal loads as well as any installations (e.g. heating and cooling systems, lighting and others) have been neglected.

- Building dimensions and construction as reference building (see figure 1).
- Infiltration is at 0.2 ACH.
- Simulation of zones A, B, C and D as indicated in figure 1 (only zone A used).
- No HVCR&H systems.
- No internal loads.
- Weather data for Brussels (TRY from ASHRAE 2001).

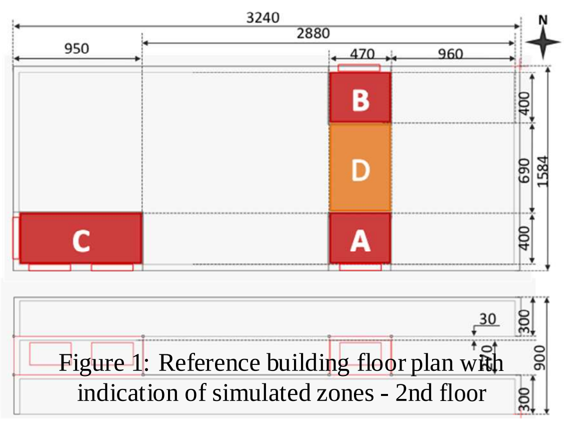


Figure 1: Reference building floor plan with indication of simulated zones - 2nd floor

Stage 2a and 2b - Shading

In the second stage of the simulations, the simple model was extended with shading. For Stage 2a internal shading and for Stage 2b external shading was used. In both cases the shading was modelled to represent Venetian blinds with an angle of 45°.

Stage 3a and 3b - Ventilation

Both stage 3a and 3b have been based on stage 2a. For both stages the air was supplied untreated from the outside and exhausted without heat recovery. In stage 3a 5.6 $l/s \cdot$ person and in stage 3b 10 $l/s \cdot$ person of outside air have been provided.

Stage 4 - Internal Loads

Starting from the model of stage 3b, internal loads were introduced for stage 4. The loads for stage 4 where:

- Occupants: 2 with 1 MET and summer: 0.5 CLO, winter: 1 CLO; Schedule: Workdays from 7:00 to 16:00 with break from 12:00 to 13:00, else not present.
- Lighting: 10 W/m^2; Schedule: Workdays from 7:00 to 8:30 at 100 %, then linear decline to 0 % at 11:00, else off.
- Equipment: 75 W/Occ (Computer and Screen); Schedule: Workdays from 7:00 to 16:00, else off.

Stage 5 - TABS

For the modelling of TABS the data given in table 1 has been used as indicated for each program. For the comparison the default values from TRNSYS have been used except for the h-value (H-water-pipe-fin coefficient as defined in EN 15377-1) wich is only used by IDA and suggested within the program.

Differences between tools

The following points are differences between the four programs that can have a considerable impact on simulation results. The different approaches for the calculation of a TABS system were introduced in the TABS section of the METHODS.

- All tools but IES <VE> have the possibility to model occupants based on MET and CLO values. In IES <VE> it is necessary to specify the heat generation in absolute values (e.g. W/m^2). This means that in IES <VE> the heat delivered to the zones is constant for the entire year, whereas it depends on the room temperature when a real occupant model is used. Between IES <VE> and IDA, this difference can exceed 200W.
- In all simulation tools it is possible to adjust a number of parameters. These parameters can influence the run time of the simulation as well as its accuracy. Bad selection of these parameters can even lead to a premature termination of the simulation. This is especially true for IDA as it becomes more and more challenging to solve the

Table 1: Input data used for the simulation of TABS depending on the simulation tool

parameters	Values	IDA	IES	E+	TRNSYS
pipe conductivity	$1.26 \frac{kJ}{h \cdot m \cdot K}$	–	+	–	+
pipe spacing	150 mm	*	+	+	+
inner pipe diameter	12 mm	*	+	+	+
pipe wall thickness	2 mm	*	+	–	+
depth in slab	200 mm	+	+	–	+
constant water flow	350 kg/h	+	–	+	+
supply temp. summer	22 °C	+	+	+	+
supply temp. winter	24.5 °C	+	+	+	+
h-value	$30 \frac{W}{m^2 K}$	+	–	–	–

+ required; – not used by tool;

* optional on advanced level

system of differential equations the more complex it gets. For instance the by default existing heat recovery unit should be deleted if it is not used. It can otherwise prolong the simulation time considerably and in extreme cases even lead to the premature termination of the simulation.

- The warm-up phase is handled differently for all of the programs. The used settings are:
  IDA: 14 days of periodic simulations with the first day of the simulation period.
  IES: 30 days of dynamic simulations with the last days of the previous year.
  EnergyPlus: Up to 100 days (default 25) of warm up. Iterations are aborted once the start-up temperature (23°C) converges with the ambient temperature.
  TRNSYS: Two year simulation, first year as start-up phase.
  If any of these times are set too short it will have a negative impact on, at least, the beginning of the simulation. Also the different approaches, periodic or dynamic, can have an influence since they will lead to different starting conditions for the simulations.

Apart from these points many other settings could have an influence on the outcome of the simulations.

RESULTS AND DISCUSSION

Stage 1

For the simulations at stage 1 the results for the operative temperature (T_{op}) are shown in figure 2. The development of T_{op} for all tools shows the same characteristic. The differences in the beginning of the simulations are a result of different start-up procedures between the programs. The lower peak temperatures for IDA and IES found in the summer time could be explained by a higher sensitivity to small infiltration rates, for EnergyPlus and TRNSYS it seems to be vice versa. For simulations without any infiltrations (not presented in this paper) the highest temperatures were found to be in a much closer range of one another.

For reference the outdoor air temperature is included here.

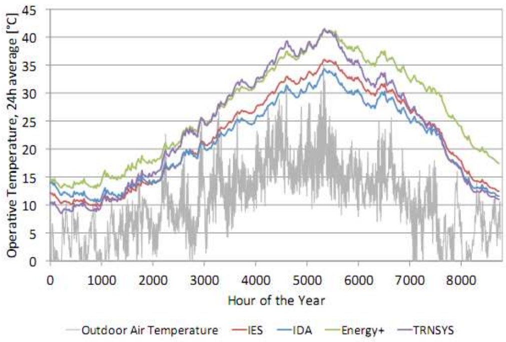


Figure 2: Operative temperature (24h moving average) for Stage 1

Figure 3 shows the deviation of the operative temperatures (T_{op}) for each simulation tool from their common average simulation result. For the basic building the deviation is very high. This deviation however decreases from here on as can be seen in figure 6b.

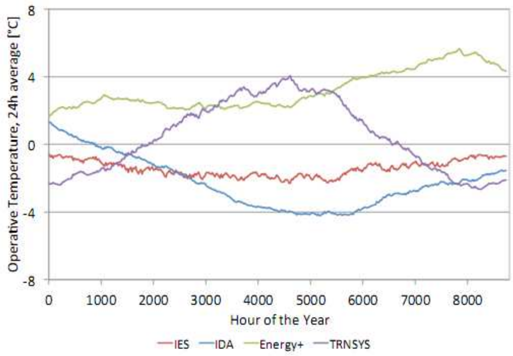
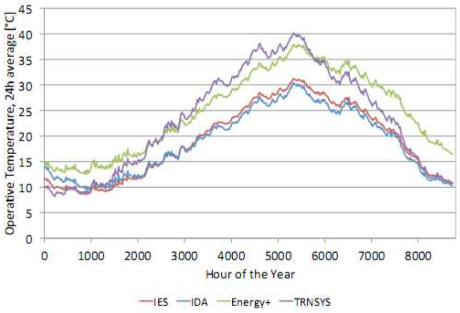


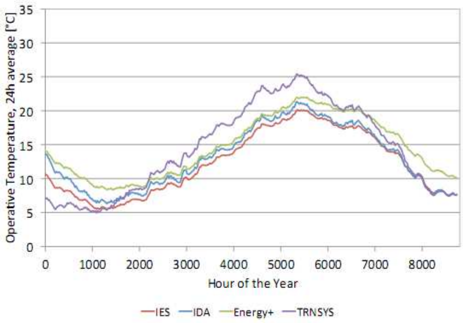
Figure 3: Operative temperature difference between average simulation results and indicated tool for stage 1. (24h moving average)

Stage 2

Introducing blinds (internal for stage 2a and external for stage 2b) lowers the temperature and results in a smoothed short term temperature fluctuation as can be found by comparing figures 2, 4a and 4b. Between the simulation of internal and external shading, the agreement between the tools is higher for external shading. The overall shape of the curve however remains unchanged.

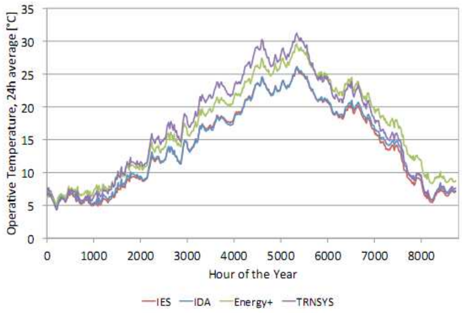


(a) Stage 2a - Internal Blinds

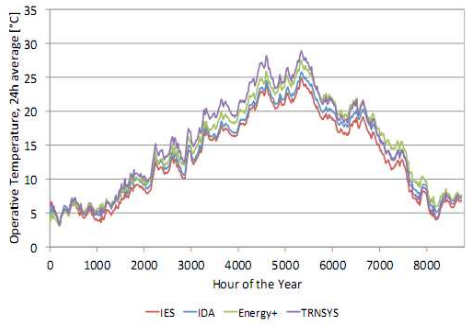


(b) Stage 2b - External Blinds

Figure 4: Operative temperature for internal and external shading.



(a) Stage 3a (2a + Ventilation: 5.6 l/s ∗ person)



(b) Stage 3b (2a + Ventilation: 10 l/s ∗ person)

Figure 5: Operative temperature for two different ventilation rates.

Stage 3

Through the introduction of ventilation the, results of the simulation tools are coming closer together. IES and IDA show significant lower temperatures during the summer for Stage 3a (5.6 l/s · person), compared to EnergyPlus and TRNSYS as seen in figure 5a. Looking at figure 5b for Stage 3b (10 l/s · person) all simulation tools are much closer to each other.

Stage 4

Starting from Stage 3b, the addition of internal loads increases T_{op} for all tools. Figure 6a shows that the agreement between the tools however remains high. The deviation of the operative temperature, from the average has its maximum at about 2 K as ilustrated in figure 6b.

Stage 5

Finally TABS are added to the building simulation. As can be seen in figure 7, the calculated temperatures are fluctuating by around 5°C (based on a 24 h average) for all tools. However, the fluctuations are not, as on all previous stages, synchronous between the tools.

Figures 8a and 8b show the comfort categories achieved with the used rudimentary controll for TABS. Both, for winter and summer the results are not the best. This is not due to the TABS itself but rather to the poor control of them. However, the results for each tool are quite different and would not necessarily trigger the same reactions by the engineer using the tool.

Degree hours

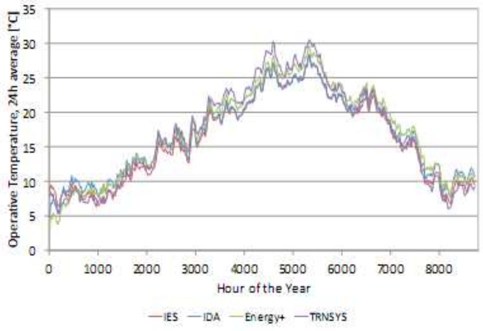
Tables 2 and 3 show the calculated degree hours of cooling and heating for each tool and stage for setpoint temperatures of 24.5°C and 22°C respectively. As has been expected, the degree hours for each tool show the same consistent pattern.

For cooling (Table 2) they drop from stage 1 to stage 3a gradually with each building improvement. The increase from 3a to 3b is due to the higher ventilation rate. Especially for TRNSYS the higher air supply has an overall cooling effect, which is also reflected in the heating period. Naturally, the values for stage 4 are increasing again as additional loads are present in the zone. The addition of a cooling system (TABS) again reduces the remaining degree hours.

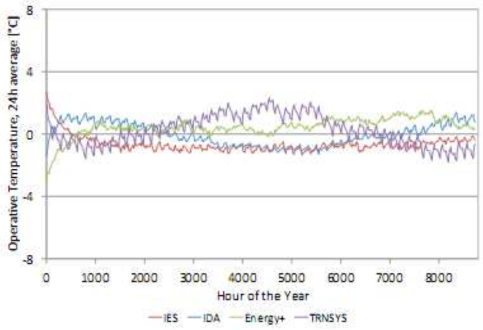
Comparing the different tools to one another, it is apparent that the results are significantly different for most stages. IDA shows for all stages the by far lowest cooling degree hours. EnergyPlus and TRNSYS calculate the highest cooling degree hours.

For heating (Table 3) the pattern is exactly reversed. This is of cause only consequent. Shading reduces solar gains, the ventilation replaces warm indoor air with colder outside air and the internal loads provide heat. Regarding the heating degree hours, the results are closer together the more complex (higher stage number) the simulation becomes.

The degree hours presented in tables 2 and 3 show that results of each tool are too different to always draw



(a) Stage 4 (3b + Internal Loads)



(b) Stage 4 (3b + Internal Loads)

Figure 6: Operative temperature and temperature difference with internal loads.

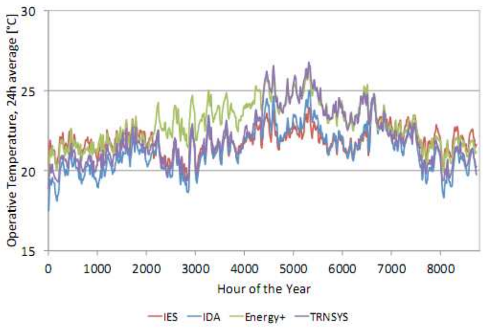


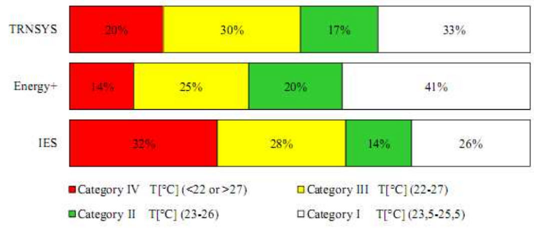
Figure 7: Operative temperature for Stage 5 (24h moving average)

the same conclusion from them. This shows the dangerous potential of building simulation. Depending on the used tool (and detail of the simulation), one might come to different conclusions depending rather on the choice of the tool than the building itself.

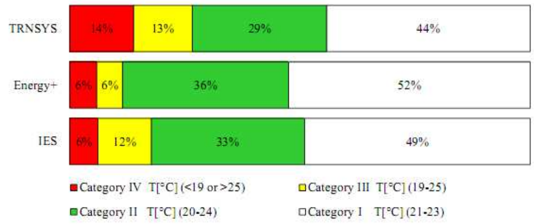
CONCLUSIONS

The present study has shown that different building simulation tools lead to essentially different results for building simulations under the given conditions. This result is not unexpected considering that not all possible settings were controlled. However the magnitude of the differences was higher than expected.

Part of these differences can be explained through the different detail between the models. The way occupants, shading, TABS and other things are modelled



(a) Stage 5 - Comfort Categories Summer



(b) Stage 5 - Comfort Categories Winter

Figure 8: Comfort categories with operating TABS.

differs greatly. For instance in IES occupants are more similar to equipment, having a constant heat production, in IDA this heat production is greatly depending on the air temperature.

A second reason for the differences between the tools are the default parameters that have not been adjusted. Using different parameters will consequently effect the outcome of the simulation.

Even though the tools did not predict the same results at each stage, the relative changes in the results new

Table 2: Calculated degree hours of cooling to 24.5°C from April through September

Stage	IDA	IES	Energy+	TRNSYS
	[degree hours in thousand] (cooling)			
1	14.2	20.3	36.1	34.9
2a	5.7	8.5	26.0	31.0
2b	0.0	0.0	0.0	0.2
3a	0.0	0.0	0.0	0.2
3b	0.2	0.2	3.3	5.6
4	1.4	1.4	3.1	4.7
5	0.1	0.1	1.7	1.2

Table 3: Calculated degree hours of heating to 22°C from October through March

Stage	IDA	IES	Energy+	TRNSYS
	[degree hours in thousand] (heating)			
1	28.3	29.0	16.3	31.0
2a	33.9	34.9	18.7	32.6
2b	50.7	54.0	41.4	53.2
3a	50.7	54.0	41.4	53.2
3b	54.0	55.8	46.0	50.6
4	42.9	46.9	43.5	47.6
5	6.2	1.9	2.6	4.4

input parameters (from stage to stage) are similar for all tools.

Inserting a TABS system in the model showed a reduction in operative temperature differences between the simulating tools.

Essentially the results show that the choice of the simulation tool can greatly influence the building evaluation through the simulation, since in a real world case not all variables are known.

The simulation of TABS has lead to a much smaller deviation of simulation results than on any previous stage.

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