How the comfort requirements can be used to assess and design low energy buildings: testing the EN 15251 comfort evaluation procedure in 4 buildings

Paolo Zangheri, Lorenzo Pagliano
& Roberto Armani
end-use Efficiency Research Group
Dipartimento di Energia
Politecnico di Milano
Via R. Lambruschini 4
20156, Milano, Italy
paolo.zangheri@polimi.it

Keywords
case studies, building design, building energy certification, thermal comfort assessment, low/zero energy buildings

Abstract
In the last years, one of the primary objectives of a building – that of offering a comfortable environment for human occupation – has been more explicitly defined and brought to the centre of design, construction, operation and evaluation of buildings by a number of co-evolving elements. These might be listed as the wider availability of laboratory-grade measurement instruments for monitoring in the field, the growing number of comfort monitoring and survey data, the continuing research efforts on the subject and the connected evolution of international standards related to comfort.

An important aim of the new Standard EN 15251 is to specify the indoor environmental parameters which have an impact on the energy performance of buildings and different categories of criteria for the assessment of the indoor environment.

As part of the Commoncense Project (co-financed by the Intelligence Energy Europe program), we analyzed (with detailed measurement campaigns and interviews) four existing buildings in Italy to assess their level of thermal comfort. The methodology proposed by the standard EN 15251 was tested to identify its critical issues and to investigate the possibility of its application on a large scale.

Starting from these data and critical evaluation, we analyze:

- The possible implications of these comfort targets on the design of low/zero-energy buildings and on the renovation of the existing building stock.
- The relationship between comfort assessment and energy certification of existing buildings: at present their complete integration is not possible.

Introduction
The wealth of research by Bedford (1936, 1964), Fanger (1970), Auliciems (1969, 1983), Humphreys and Nicol (1998), de Dear et al (2007) Griffiths (1990), Givoni (1992) and others has been partially taken and reorganized into international standards, where thermal comfort is defined as: "that condition of mind which expresses satisfaction with the thermal environment and is assessed by subjective evaluation" (ANSI/ASHRAE, 2004).

Occupant satisfaction was investigated through surveys of subjects both in laboratory settings and in actual buildings (Fanger, 1970; de Dear et al, 1997; McCartney and Nicol, 2002) in order to determine the physical and context conditions in which a thermal environment can be evaluated as acceptable (ANSI/ASHRAE, 2004) from the point of view of thermal comfort.

The standard ISO 10551-1995 presents ways of formulating questions to subjects by presenting them with scales on thermal comfort. It suggests evaluating the personal thermal state through three scales. The same standard suggests then that an evaluation of the thermal ambience or 'thermal surroundings (local climate)' might be made via two additional scales of personal acceptability and personal tolerance.

A large part of the thermal comfort surveys in laboratory and in the field have been using the seven degrees scale, (perceptual scale in ISO 10551, often called thermal sensation scale or also ASHRAE scale since it is the one scale present in the

Table 1 – Description of the applicability of the categories proposed by EN 15215 and relative comfort ranges.

Category	Explanation	FANGER MODEL		ADAPTIVE MODEL
		PMV	PPD [%]	T_C [°C]
I	High level of expectation and is recommended for spaces occupied by very sensitive and fragile persons with special requirements like handicapped, sick, very young children and elderly persons	-0,2 < PMV < 0,2	< 6	T_C -2 ≤ T_{op} ≤ T_C +2
II	Normal level of expectation and should be used for new buildings and renovations	-0,5 < PMV < 0,5	< 10	T_C -3 ≤ T_{op} ≤ T_C +3
III	An acceptable, moderate level of expectation and may be used for existing buildings	-0,7 < PMV < 0,7	< 15	T_C -4 ≤ T_{op} ≤ T_C +4
IV	Values outside the criteria for the above categories. This category should only be accepted for a limited part of the year	PMV < -0,7 and PMV > 0,7	> 15	T_{op} < T_C -4 and T_{op} > T_C +4

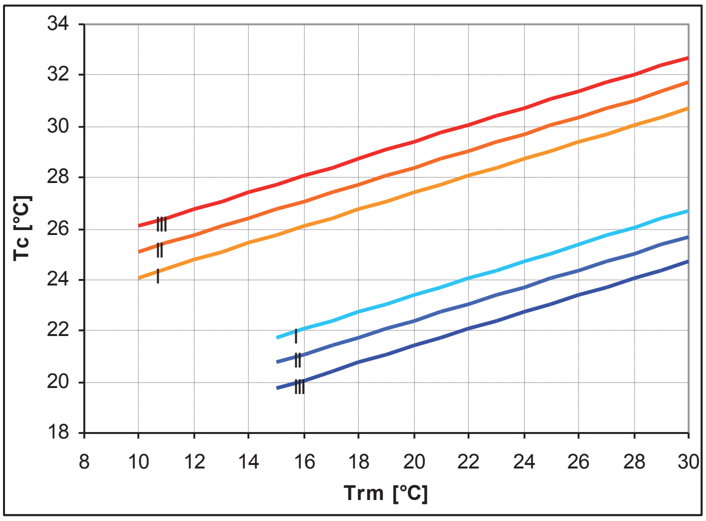


Figure 1. Adaptive comfort categories adopted by EN 15251 (Annex A.2): the comfort ranges (expressed in terms of comfort operative temperature T_C) as a function of outdoor air daily 'running mean temperature' T_{rm}.

survey suggested in the informative annex to ASHRAE 5), which offers a set of standard answers (from cold to hot) to the question: 'how do you feel at this time?' and a numerical scale (from -3 to +3) to accompany each grade.

Often this is accompanied by a second question formulated using the three point McIntyre scale of thermal preference (for a warmer or cooler environment or no change), or a similar five point scale as used e.g. in the SCAT study (McCartney, Nicol 2002) corresponding to the spirit of the thermal preference scale in ISO 10551. This second survey step seeks responses to the question: 'how do you prefer to be now?'.

Until recently, few laboratory or field studies included the direct question about whether an environment was acceptable or not. Dissatisfaction and acceptability have generally been evaluated indirectly from whole-body thermal sensation votes. As for the terminology, we will follow here (Arens et al, 2009), who state: "we equate the terms 'accept' and 'acceptable' with 'being satisfied with' and 'satisfactory'. The term 'satisfied' is rarely used in questionnaires, even though 'predicted percent dissatisfied' (PPD) is a commonly invoked metric." This seems coherent with the interpretation of Fanger: "The PMV… prescribes a certain range around neutral temperature as acceptable, depending on the permitted percent dissatisfied" (Fanger and Toftum, 2002).

One traditional method of indirect evaluation of acceptability is based on ISO 7730 and equates voting within the central three degrees of the ASHRAE thermal sensation scale (-1: slightly cool, 0: neutral, +1: slightly warm) with "satisfaction". This is implicit in the definition of ISO 7730: "thermally dissatisfied people are those who will vote hot, warm, cool or cold on the 7-point thermal sensation scale". A second way of defining acceptability is to assume that only the subjects who want 'no change' on the 'thermal preference' scale are satisfied with the thermal environment. A third way is based on the comfort scale "affective evaluation". ISO 10551 suggests to assume as satisfied the subjects who vote 'comfortable'. It has been proposed (Brager et al. 1993) to extend the acceptability to 'slightly uncomfortable'.

These guidelines are reflected in the standards ASHRAE 55 (2004), ISO 7730 and EN 15251 and the most recent revision of the European standards additionally suggest the acceptability ranges:

- ISO 7730-2005 proposes three categories of comfort (A, B, C), only for the Fanger model, defined by the ranges of PMV (±0.2, ±0.5, ±0.7) and leaves open the choice about to which buildings apply a certain category.
- EN 15251-2007 proposes and it explains (Table 1) four categories of comfort (called I, II, III, IV) for both the Fanger model (defined by the same ranges of PMV) and the adaptive model developed by the SCAT project (McCartney and Nicol, 2002) and shown in Figure 1.

Comfort ranges are one of the basis inputs for the design and assessment of the comfort and energy performance of buildings. For example, in EN 15251 they are part of how design criteria are proposed for dimensioning of building envelope and systems and of the definition of inputs for building energy calculation and long-term evaluation of the indoor environment. The standard also identifies parameters to be used for monitoring and displaying the indoor environment, as recommended in the Energy Performance of Buildings Directive according to comfort range assigned to the categories.

EN 15251 also proposes that the different parameters for the indoor environment of the building meet the criteria of a specified comfort category when the parameter in the rooms representing 95 % of the occupied space is, for example, 97 %

Table 2 – Approaches used for the thermal comfort assessment within the Commoncense Project.

Code	Type	Description	Instrument	When/Duration	Where/Who
M1	Measurement (ASHRAE Class I or II)	Following the specifications of ISO 7726 and ASHRAE RP-884 (Class I or Class II), to measure all the physical variables defining indoor microclimate.	Mobile Measurement System (MMS)	During periods probably more critical: 2-3 weeks in winter and 2-3 weeks in summer. Frequency: 10-20 min (if possible max, min, average and standard deviation values for each time step).	Installation and removal days: point measurements in large part of the building. Other days: continuous measurement s in a representative room.
M2	Measurement (ASHRAE Class III)	To measure the principal indoor and outdoor parameters (air temp and relative humidity). (Plus CO2 concentration, if possible)	Temp-RH Dataloggers	3 months in winter (December, January, February) and 3 months in summer (June, July, August). Frequency: 10-20 min.	continuous measurements in 2-3 representative points of the building, in 1-2 critical points of the building and in 1 outdoor point.
Q1	Interview	Direct interview with Mobile Measurement System. Questions about sensations, preferences, productivity, clothing, activity and individual building control.	Questionnaire Q1	During the days of installation and removal of MMS. 2-3 interviews for each measurement point	To the larger number of occupants: at least the 50% of total occupants, better if more than 20.
Q2	Interview	Indirect (paper form) interview without Mobile measurement System. Simplified questions about sensations, preferences, clothing, activity and individual building control.	Questionnaire Q2	During the days when the MMS is installed. 2-4 interviews a day with each occupant	Where the MMS is installed and to the larger number of occupants: at least the 50% of total occupants, better if more than 20.

(or 95 %) of occupied hours a day, a week, a month and a year inside the limits of the specified category. This has some relevant implications for simulations (for design or evaluation purposes) and for metering-surveys for the evaluation of the category in which a building can be classified.

As it stands EN 15251 includes methodologies for testing compliance but these are not scientifically verified. Previous standards with inadequate testing and verification procedures have fallen into disrepute and disuse. Methods of testing compliance must approach comfort as resulting from a dynamic interaction of people with the built environment not as being associated only with highly-controlled, energy intensive environments. If this is achieved EN 15251 can overcome the prejudice that comfort and energy conservation are in competition.

Also for these reasons, the Commoncense project[1] ("Comfort monitoring for CEN standard prEN 15251 linked to EPBD" – concluded in October 2010) has been developed. About the assessment of existing buildings, its main objectives were:

- Provide technical specifications for thermal comfort measurements, taking into account existing guidelines (e.g. EN ISO 7726) and to identify an operative procedure for determining how the indoor climatic parameters should be monitored and how many measurements in time should be performed in order to assign a building to a certain category;
- Analyze the results of temperature monitoring and comfort surveys in existing buildings according to the procedure developed, with the aim to test in the field the chosen methodology and in order to detect critical elements for large scale application, estimate costs of the procedure, identify issues of interaction with occupants of the building during normal operation of the building itself;
- Evaluate the coherence of comfort categories with the level of comfort perceived by the occupants of real buildings and the meaningfulness (in term of costs and time) of a extended comfort certification.

Testing the EN 15251 procedure

METHODOLOGY

In order to evaluate different ways of comfort category assessing in existing buildings and to implement a wide-range test, the Commoncense Consortium selected four complementary approaches (Table 2).

THE ITALIAN CASE STUDIES

In Italy, the analysis involved four buildings, which briefly is described below. The attention has been focused mainly on buildings of recent construction, characterized by good to excellent performance of the building envelope and by different cooling strategies: two buildings are mainly conditioned in actively; two buildings are cooled through passive and low-energy strategies (natural ventilation, earth-to-air heat exchangers, solar

1. Website: www.commoncense.info

Table 3 – Summary of the Italian case studies.

ID:	**IT1**
Location:	Lodi, Italy (urban)
Use:	Office (and social housing)
Age:	2006
Size:	600 m^2
Floors:	2
Occupants:	10
Schedule:	Regular
Envelope:	Efficient (U_{opaque} = 0,15 W/m^2K; $U_{transparent}$ = 1,4 W/m^2K)
Heating strategies:	Air conditioning with fan coils.
Cooling strategies:	Natural ventilation, air conditioning with fancoils.
Enabled controls:	Windows, fancoils.

ID:	**IT2**
Location:	Varese, Italy (urban)
Use:	Office and laboratory
Age:	2002
Size:	3 000 m^2
Floors:	5
Occupants:	400
Schedule:	Regular
Envelope:	Typical Italian new building (U_{opaque} = 0,35 - 0,45 W/m^2K; $U_{transparent}$ = 1,4 W/m^2K).
Heating strategies:	Heterogeneous: HVAC, fan coils or radiators
Cooling strategies:	Heterogeneus: HVAC, fan coils or natural ventilation
Enabled controls:	Windows, internal blind, local fan.

ID:	**IT3**
Location:	Imola, Italy (urban)
Use:	School and administrative offices
Age:	2008
Size:	4 500 m^2
Floors:	3
Occupants:	300 students + 40 teachers + 10 employees
Schedule:	Regular
Envelope:	Efficient (U_{opaque} = 0,23 - 0,26 W/m^2K; $U_{transparent}$ = 1,4 W/m^2K)
Heating strategies:	Heat recovery, district heating with radiant panels.
Cooling strategies:	External solar blinds, natural night ventilation, earth-to-air heat exchanger, solar cooling with radiant panels.
Enabled controls:	-

ID:	**IT4**
Location:	Cherasco, Italy (rural)
Use:	Residential with home office
Age:	2005
Size:	200 m^2
Floors:	2
Occupants:	4
Schedule:	Regular
Envelope:	Comply to the Passivhaus Standard (U_{opaque} = 0,15 W/m^2K; $U_{transparent}$ = 0,7 W/m^2K)
Heating strategies:	Heat recovery, air-to-air heat pump, biomass stove.
Cooling strategies:	External solar blinds, natural night ventilation, earth-to-air heat exchanger
Enabled controls:	Windows, blinds, mechanical ventilation

Figure 2. MMS-1 and MM2-2 during a measurement campaign (Lodi and Cherasco).

Table 4 – Mobile system for measurements in heterogeneous environment used in Italy.

	Heigt above floor [m]	Measured Parameters	Transducers (commercial name)	Accuracy	Indicative Costs [euro]
Sensor	1.1	Air Temp	Pt100 standard	0.15°C	€ 150
		Globe Temp	LSI LASTEM - BST131®	0.15°C	€ 400
		Air Speed	LSI LASTEM - BSV105®	$0.02+0.05 \cdot V_a$ m/s	€ 1 100
		Turbolence Intensity		-	
		Plane radiant Temp Asimmetry	LSI LASTEM - BSR231®	0.15°C	€ 1 000
	0.6	Air Temp	LSI LASTEM - BSU102®	0.15°C	€ 600
		Dew Point Temp		0.15°C	
		Relative Humidity		2%	
		Globe Temp	LSI LASTEM - BST131®	0.15°C	€ 400
		Air Speed	LSI LASTEM - BSV105®	$0.02+0.05 \cdot V_a$ m/s	€ 1 100
		Turbolence Intensity		-	
	0.1	Air Temp	LSI LASTEM - DME816®	0.15°C	€ 700
		Relative Humidity		3%	
		Globe Temp	LSI LASTEM - BST131®	0.15°C	€ 400
		Air Speed	Standard	$0.02+0.05 \cdot V_a$ m/s	€ 800
Acquisition system	Acquisition Unit		BabucABC® – E-Log®		€ 2 500
	Software, memo-card, cables, supports, power packs and other				€ 2 000

cooling). The building stock is also distinguished by the use (office, laboratory, school, residential) and size (from 200 m^2 to 4,500 m^2). About the climatic context, all buildings are located in the Po Valley in the north of Italy, but in different cities: Lodi, Varese, Imola and Cherasco.

SURVEY CAMPAIGNS

Two Mobile Measurement Systems (MMS) was used in order to obtain M1 measurements of class I (in accord with the ASHRAE classification: de Dear et al., 1997). Field experiments in which all sensors and procedures were in 100 % compliance with the specifications set out in ASHRAE Standard 55 and ISO 7730. In particular, three heights of measurement with laboratory-grade instrumentation including omni-directional anemometry capable of turbulence intensity assessments. In the realization of the second MMS, the thermal interference (typically on the measurements of the globe thermometers) of the support cart was considered and reduced using L-shaped and black electro coloured alluminium profiles.

A description of these systems (costs included), allowing also verification of the homogeneity of the environment around the occupant, is provided in Table 4. All sensors meet the accuracies identified by the ISO 7726 standards.

The M1 instruments measured every 10-60 seconds and recorded mean, max, min and standard deviation values, with an acquisition rate of 15 minutes. In the last monitoring campaigns, a measurement of the CO_2 concentration has been added to the MMSs, using a combination of Telaire 7001® Monitor (accuracy of 50 ppm) and HOBO U12® Logger (about €700 for each combination).

M2 measurement were conducted with portable dataloggers, recording air temperature and relative humidity every 15 minutes: Tinytag Ultra® (about €150 each), with an accuracy of 0.4 °C (Temperature) and 3 % (Relative Humidity). In addi-

Table 5 – Number of data collected in Italy.

Approach	IT1 - Lodi	IT2 - Varese	IT3 - Imola	IT4 - Cherasco	Total
M1	12 370	7 457	17 005	2 281	39 113
M2	64 298	71 145	79 256	32 412	247 111
Q1	82	140	61	-	283
Q2	502	1 309	80	-	1 891

tion to the indoor measurements, hourly data were obtained of outdoor temperature and other outdoor measurement from meteorological public stations (of the regional agencies ARPA) close to the site of each of the buildings.

About the comfort surveys, following the SCAT experience, two levels of questionnaires have been used. With the Q1 the following subjective responses were polled from the subjects:

- Temperature – comfort vote (7 point scale) and preference (5 point scale);
- Air movement – comfort vote (7 point scale) and preference (5 point scale);
- Humidity – comfort vote (7 point scale) and preference (5 point scale);
- Lighting – comfort vote (7 point scale) and preference (5 point scale);
- Noise – comfort vote (7 point scale) and preference (5 point scale);
- Air quality vote (7 point scale);
- Overall comfort (6 point scale).

And details were also collected of :

- Clothing worn (a record was made of each item being worn, normal underclothing was assumed in order to avoid causing offence): the clo value of the full assembly of garments worn was calculated from standard tables, inclusive of the chair on which the subject was seated where appropriate;
- Activity over the last hour: where more than one activity had been undertaken this meant dividing the hour into five minute periods and assessing the period of time for each activity; the weighted mean metabolic rate was calculated for all the activities reported;
- The use of the controls (doors, heating/air conditioning, windows, blinds, lights, fans) at the time of the survey.

In the simplified survey (Q2) a number of copies of the questionnaire were left with the subject, who then filled them in one to four times a day, in function of the subject's availability. The subjects filled the questionnaire simply as a check-list with ticks. The subjective questions were limited to the thermal environment and there was an abbreviated version of the clothing descriptions and the activity. The temperature and the relative humidity close to the subject were recorded by the M2 miniature datalogger.

While the M2+Q2 campaigns lasted about 3 months during the winter and in the summer, the M1+Q1 approach focused on shorter periods (2-4 weeks).Typically the comfort surveys were made when the mobile system (MMS) was installed and removed and 1-2 times during its operation. As shown in the following table, a total of 39,113 measurements M1 and 247,111 measurements M2 were collected; 281 Q1 and 1 891 Q2 were drawn. Considering the use of the building, here residential, and the limited number of occupants (2 adults and 2 children) of the building IT4, the questionnaires Q1 and Q2 were not proposed. Instead a rough assessment of clo and met levels was conducted.

RESULTS

In order to achieve the objectives of the project and compare the different approach implemented, the data collected were properly processed. In particular, through several processing steps (Table 6), three comparable diagrams (in form of foot-print) were generated:

- percentage distribution on sensation vote, aggregating -1, 0 and 1 votes (not thermally dissatisfied people, in accord with ISO 7730) in order to visualize a magnitude of thermal acceptance;
- percentage of time in the four building categories of EN 15251 (foot-print classification), second the comfort model of Fanger (PMV-PPD), based on the M1 monitoring (short period);
- percentage of time in the four building categories of EN 15251 (foot-print classification), second the adaptive comfort model, based on the M2 monitoring (long period).

A variation was introduced in order to be able to better characterize the category IV (Discomfort). For providing a clue in the comparison with the questionnaire statistics in term of thermal acceptance, the category D ("Dissatisfied") was added, aggregating the instant with PMV < -1 or PMV > 1.

In this way, the comparison of the results can provide qualitative, but interesting indications about:

- the correspondence between occupant's sensations and the comfort models of Fanger;
- the level of expectation of occupants, in reference of comfort categories.

In order to provide a short and exhaustive report of thermal certification for each building, some collateral information was added:

- General: qualitative notes about the survey experiences; assessment about the occupant response and the representativeness of the M1+Q1 period respect the wider M2+Q2 period;

Table 6 – Steps of data elaboration.

Approach	Steps of elaboration
Q1 and Q2	• Translation of the questionnaires in an electronic format (excel). • Check of the coherency between sensation and preference votes in order to extract the valid questionnaires. • Statistical analysis of seasonal votes. • Calculation of mean value and standard deviation of clo and met for M1 elaborations. • Calculation of foot-print (% distribution on thermal sensation vote) diagrams, in order to compare the acceptability from questionnaires with the results of measurements.
M1	• Verification of monitoring data. • Application of a hourly filter in order to extract the measurements during the occupation (typically from 8:00 to 19:00), verified with the CO_2 measurements (if available). • Check of the homogeneity on the 3 measuring heights. • Evaluation of the difference between air temperature and operative temperature. • Calculation of instantaneous values of PMV and PPD during the surveys (using clo and met values from the relative questionnaire) and the entire measurement period (considering the mean value of clo and met from all questionnaires). • Calculation of foot-print (% of time in the 4 categories) diagrams, based on the comfort model of Fanger. • Calculation of the seasonal PPD weighted indicator.
M2	• Verification of monitoring data. • Application of a hourly filter in order to extract the measurements during the occupation (typically from 8:00 to 19:00), verified with the CO_2 measurements (if available). • Comparison between M2 and M1 data in order to evaluate a posterior the period of detailed monitoring. • Calculation of the series of running mean temperature from weather data. • Calculation of foot-print (% of time in the 4 categories) diagrams for each monitored zone, based on the adaptive comfort model of EN 15251. • View of indoor condition with (indoor temperatures – running mean temperature) graphs.

- Questionnaire (Q1 and Q2[2]):
  - number of collected questionnaires;
  - percentage of votes finding air movement, humidity, lighting, noise and indoor air quality acceptable;
  - distribution of temperature preference;
  - questionnaire statistics (clo, met, building controls);
- Detailed measurements (M1):
  - homogeneity of the environment (in case of Class I measurements);
  - cause of discomfort (information not obtainable from the foot-print view);
- Simplified measurements (M2):
  - indoor temperature distribution in 2-4 zones of building.

As example, an overall evaluation sheet produced for one of the analyzed buildings (IT1 – Lodi) is shown in figure 3.

Discussion

ABOUT THE COMMONCENSE EXPERIENCE

As inferred from the shown result sheet in figure 3, is not always possible to obtain unambiguous indication about the comfort category that best represents the thermal behaviour of a building. As expected, the adaptive elaborations can produce results quite different from those relative to the Fanger model and, moreover, the statistics derived from questionnaires (distribution on thermal sensation votes) may in some cases be in disagreement with both the comfort models and even indicate as predominant the opposite cause of discomfort (cold instead of warm and vice versa).

Having observed this incongruity in the presence of both a limited and a large number of interviews, there seems to be a need for further study on how a category systems better can reflect the opinion of the occupants of a specific building.

Moreover this field application has shown the possibility of obtaining diverse comfort categories for different thermal zones and in different seasons. In the following Table 7[3] a summary of results is shown, which are obtained by applying the EN 15251 procedure, qualitatively compared with the occupants' response.

We recognize many critical issues in the present procedure. In particular the following issues deserve deeper analysis both in terms of the adoption of the standard at national level and for its coming revisions:

2. In the format proposed (Figure 3) the statistics relative to the simplified questionnaire Q2 are reported in brackets.

3. According with EN 15251, the adaptive categories have not been evaluated in winter.

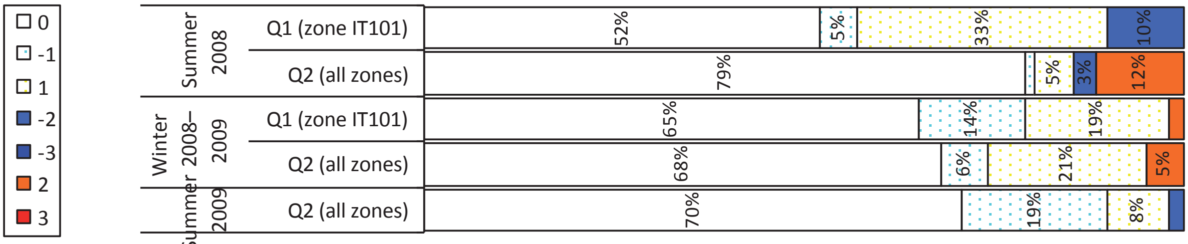
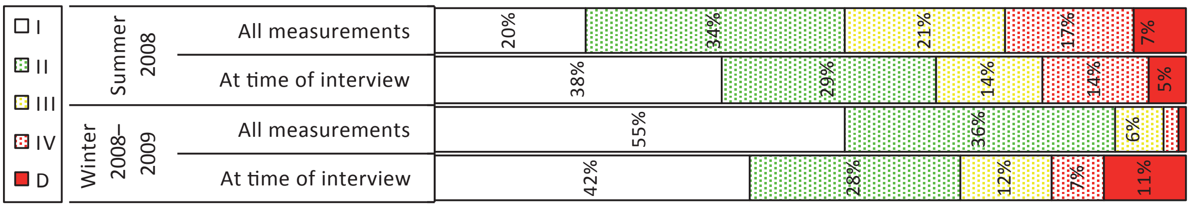
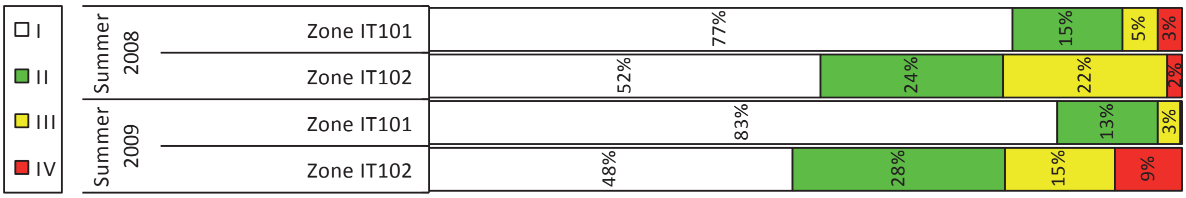
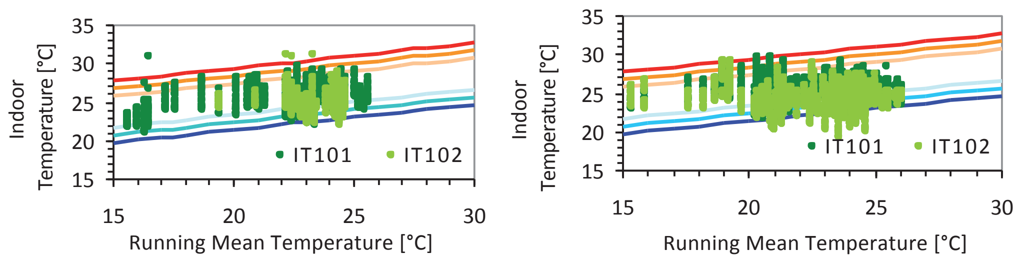
Notes	Assessment of responses	Good								
	Representativeness of the M1+Q1 period:	Discrete			Discrete			–		
Q1 (Q2)	**Season**	**Summer 2008**			**Winter 2008–2009**			**Summer 2009**		
	Number of questionnaires	21 (373)			57 (66)			– (63)		
	Temperature acceptable (%)	90% (85%)			98% (95%)			– (97%)		
	Air movement acceptable (%)	100%			98%			–		
	Humidity acceptable (%)	86%			88%			–		
	Lighting level acceptable (%)	90%			88%			–		
	Noise level acceptable (%)'	90%			60%			–		
	IAQ acceptable (%)	100%			91%			–		
	Distribution of temperature preference (%)	Colder	Unch.	Warmer	Colder	Unch.	Warmer	Colder	Unch.	Warmer
		43% (23%)	43% (73%)	14% (3%)	12% (26%)	74% (68%)	14% (6%)	– (10%)	– (67%)	– (24%)
	Distribution on thermal sensation votes									
	Statistics	Mean	SD		Mean	SD		Mean	SD	
	Clo	0.56 (0.32)	0.14 (0.07)		0.88 (0.54)	0.12 (0.13)		– (0.44)	– (3.13)	
	Met	1.21 (1.21)	0.13 (0.17)		1.26 (1.14)	0.15 (0.09)		– (1.06)	– (0.09)	
	Typical controls	door-windows, AC, blind			heating, door			door-windows, AC blind		
M1	Homogeneity of environment:	Homogenous			Homogenous			Homogenous		
	Discomfort source	Warm side			Cold and warm side			–		
	Foot-print (FANGER) classification of Zone IT101:									
M2	Foot-print (ADAPTIVE) classification									
	Temperature distribution in summer 2008 and 2009:									

Figure 3. Example of a summary report for the comfort assessment, used in the Commoncense project (IT1 – Lodi). We underline the introduction of the category D ("Dissatisfied") in the foot-print classification of Fanger (from M1), which allows a qualitative comparison between it and the distribution on sensation votes (from questionnaires).

Table 7 – Summary of results: thermal comfort classification of all Italian buildings in terms of thermal comfort corresponding to the Fanger and the adaptive comfort approach.

Building:	IT1		IT2		IT3		IT4	
Season	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter
Fanger	IV	III	IV	III	IV	II	III	II
Adaptive	III	-	III	-	I	-	II	-

Legend: green = "coherent with occupants response"; red = "partly incoherent with occupant response", white = "not assessable coherency".

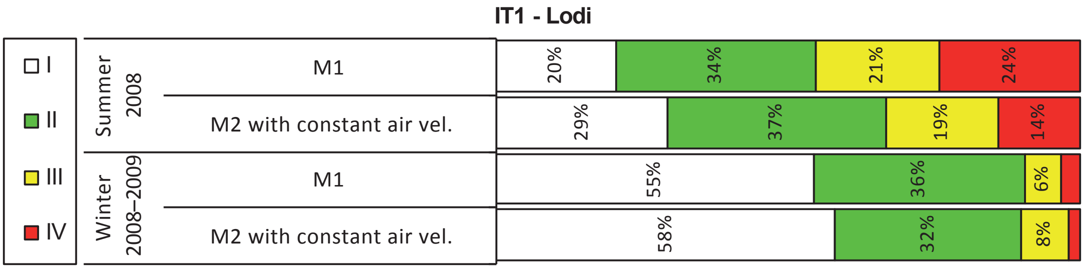


Figure 4 – Comparison between Fanger foot-print indicators generated starting from M1 and M2 measurements.

- In large buildings, it is to be expected that different environments provide different comfort levels, but it is complicated to assess it a priori and, for economic reasons, to investigate a building in the 100 % of its spaces (especially with detailed measurements);
- In a building, the thermal environment – and consequently the comfort assessments – also depends on the occupants behaviour and on the contingent climatic conditions, and as a result it can change as a function of them. It would be advantageous to find a way to normalize these factors;
- Considering all the uncertainties related to the data acquisition (representativeness of the monitored environment, accuracy of instruments[4], clo and met identification, etc.), It is proposed that the value of acceptable deviation (3–5 %) is too restrictive;
- Most activities concerning the check and the elaboration of collected data are left to the professional 'common sense' of the evaluator. On one hand they should be standardized in order to ensure consistency of results and to allow their comparison. On the other hand qualifying criteria for building professionals should be proposed (many competences are needed);
- Reducing a comfort assessment to the indication of a category can be restrictive and it can misrepresent the comfort demand of occupants and stakeholders; we propose the adopted format of our report (with the addition of the category "Dissatisfied") for further assessment in order to clarify the results;
- It is not obvious that the presence of a mechanical cooling systems implies a greater reliability of the Fanger model as opposed to the adaptive one (a counterexample was found in the building IT1); if comfort questionnaires are available, we suggest to show their statistics in the "summary report of comfort assessment" together with the footprint classification relative to both models.

About the need for detailed measurements – issue crucial to the cost of monitoring campaigns and the plausibility of their results – it is observed that:

- In the investigated buildings (monitored with Class I instruments) the homogeneity in the neighbourhood of the subject is usually verified; thus measurements at three heights can be avoided in similar buildings;
- Since the operative temperature is often very close to air temperature, but it is difficult to assess this aspect *a priori*, long-term measurements able to detect the operative temperature are preferable;
- Elaboration of an adaptive foot-print does not require air velocity measurements and the estimation of clo/met values; it can be accomplished through simplified measurements (M2 in this study);
- As shown below (Fig. 4[5]), a Fanger foot-print generated starting from M2 data may differ – more than the acceptable deviation of 3–5 % – from that considering M1 measurements. The main source of discrepancy is the lack of a measurements of air velocity that should be taken consistently for the entire period (typically at low values to reduce the error). Air velocity measurements are unavoidable if the occupants often open windows (e.g. IT1) and especially during the summer (in winter we observe marginal deviations).

ABOUT THE RELATIONSHIP WITH THE ENERGY CERTIFICATION

A long-term objective of the EN 15251 procedure is to place the foundations for accompanying the energy certification of a building with an assessment of its indoor comfort. But at the

4. The effect of measurement on PMV calculation has been evaluated by Alfano (2001) and Arens (2009).

5. A constant air velocity of 0,1 m/s was assumed when generating the footprint starting from M2 measurements.

moment, while energy certification has begun in much of Europe (in application of the EPBD Directive), comfort evaluation is in its infancy.

To assess the energy needs or primary consumption of a building in the framework of energy certification procedures, standardized calculations (through steady-state or semi-dynamic software) were undertaken for existing buildings. In this context – the steady state approach standardizes the indoor conditions (e.g. indoor temperature equal to 20 °C in winter and 26 °C in summer) – the comfort assessment can only be done in a second phase, using a verification.

To equate and integrate them, there are two main possibilities: de-normalising the energy certification (e.g. monitoring the real energy consumption of a building or using the energy bills) or normalizing the comfort assessment (e.g. adopting dynamic simulation approaches for existing buildings as well). In view of all the previous considerations, probably this second alternative is likely to have greater success.

ALTERNATIVES TO BE TESTED

The possibility of evaluating the indoor comfort through dynamic simulation should also be tested in existing buildings (at the moment the standard EN 15251 proposes this option only for assessing the new buildings). Certainly it would reduce costs and it would evaluate the entire building. But this may mean a loss of precision, especially through using unsuitable software or unskilled modelling techniques. The constant improvement of these tools (for example in dealing with radiative aspects and exact operative temperature calculation) can only benefit this approach.

Another possible alternative is the use of Building Energy Management (BEMs) in the collection of data. In recent years a large number of buildings have adopted these systems which can ensure an extended monitoring (in more rooms of a building and maybe for more seasons), without extra cost. An improvement of the sensors presently used (e.g. globe-thermometers for measuring operative temperature instead of air temperature sensors, adding anemometers for measuring air velocity and a general increase in accuracy) would be advisable, as well as their constant calibration.

DESIGN OF LOW/ZERO-ENERGY BUILDINGS

The Commoncense project started from the consideration that, if incorrectly applied and interpreted, EN 15251 could work against the most important objectives of the EPBD by encouraging a perception that comfort and energy efficiency are in conflict. In fact, the introduction of more restrictive comfort requirements (e.g. Category I) may involve the risk of discouraging low-energy building technologies (such as passive cooling and solar heating) and increasing the power of active systems.

Efforts are ongoing in order to systematize the wealth of data produced in recent decades; further work is needed in order to produce larger scientific and technical consensus on the criteria of acceptability and sometimes also on the scales of subjective judgement to be used for assessment of acceptability. At the same time, uniform protocols for in-field assessment (as that used in the Commoncense project) will enhance the reliability and comparability of data needed, for example, to clarify the open issues about which comfort model should be applied in which conditions. The categorization of buildings to be analysed via one or the other of the models is not clearly described in the literature and standards, for two main reasons:

- the limited number of surveys in the overlapping area of hybrid buildings;
- the conceptual difficulty to sharply assign buildings to two different typologies, given the number of variables involved in characterizing envelope, plant, availability of individual local controls and time-varying conditions (conditioned vs free floating) within a certain building.

In order to conceive a design process for low/zero-energy buildings, based on the comfort optimization, a suitable long-term comfort (or discomfort) index is needed. It should consider the distance in degrees outside a specific comfort range defined according a specified comfort model, consider the percentage of time outside the comfort range, be built on a well defined scale, consider both overheating and overcooling and be of simple comprehension (i.e. graphic representation). It could be also useful to show the aggregated and disaggregated weights of overheating and overcooling, both in winter and summer.

As discussed in our previous paper (Pagliano and Zangheri, 2010), during the warm period part of the discontinuities between the two variants (Fanger and adaptive) arising in the optimization procedure with the use of long-term indexes may be reduced when considering the large influence that certain variables such as clothing (and total) insulation and air velocities have on the calculated values of PMV. Ensuring lower levels of clothing insulation (e.g. by appropriate relaxation of explicit or implicit dressing codes) enables the use of the ASHRAE correction (in augmentation of the value calculated by the PMV formula) to operative comfort temperature when velocities higher than 0,2 m/s are experienced by the occupants. These two changes have the effect of reducing the ambiguous zone between the two comfort ranges.

At the moment these considerations are being discussed within the IEA Task 40-Annex 52 (NZEB): in this context we are providing analysis on how comfort categories defined in EN 15251 and other international standards can influence the definition and design methodology of Net Zero Energy Buildings.

Conclusion

In conclusion, the experiences conducted within the project Commoncense – the first ones specifically organized to test the standard EN 15251 in existing building – allowed the recognition of critical issues. These deserve more detailed analysis, in order to ensure a satisfactory wide application of the procedure. Recommendations are given to support this process of improvement that might be helpful for future tests, both in the evaluation of existing buildings and drafting a solid procedure for the design of the new generation of low-energy and high-comfort buildings.

References

Alfano, G., d'Ambrosio, F. R. and Riccio, G. (2001) 'Sensibility of the PMV index to variations of its independent variables', in Proceedings of Thermal Comfort Standards into the 21st Century, Windsor, April, pp158–165.

ANSI/ASHRAE 55 (2004): 'Thermal Environmental Conditions for Human Occupancy'.

Arens, E., Humphreys, M. A., de Dear, R. and Zhang, H. (2009) 'Are "class A" temperature requirements realistic or desirable?', Building and Environment, Vol 45, no 1, pp4–10.

Auliciems, A. (1969) 'Effects of weather on indoor thermal comfort', International Journal of Biometeorology, vol 13, pp147–162.

Auliciems, A. (1983) 'Psychophysical criteria for global thermal zones of building design', International Journal of Biometeorology, No. 8, Part 2, Supplement to vol 26 (1982), pp69–86.

Bedford, T. (1936) 'The Warmth Factor in Comfort at Work', MRC Industrial Health Board Report No. 76, HMSO, London.

Bedford, T. (1964) 'Basic Principles of Ventilation and Heating', H.K. Lewis, London.

Brager, G. S., Fountain, M., Benton, C. C., Arens, E. A. and Bauman, F. S. (1993) 'A comparison of methods for assessing thermal sensation and acceptability in the field', in N. A. Oseland and M. A. Humphreys (eds) Thermal Comfort: Past, Present and Future, Building Research Establishment, Garston, Watford.

EN 15251 (2007): 'Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics'.

de Dear, R. J., Brager, G. and Cooper, D. (1997) 'Developing an Adaptive Model of Thermal Comfort and Preference', Final Report ASHRAE RP-884.

Fanger, P. O. (1970) 'Thermal Comfort: Analysis and Applications in Environmental Engineering', McGraw Hill, New York.

Fanger, P. O. and Toftum, J. (2002) 'Extension of the PMV model to non-air-conditioned buildings in warm climates', Energy and Buildings, vol 34, pp533–536.

Givoni, B. (1992) 'Comfort, climate analysis and building design guidelines', Energy and Buildings, vol 18, no 1, pp11–23.

Griffiths, I. (1990) 'Thermal Comfort Studies in Buildings with Passive Solar Features'; Field Studies, Report to the Commission of the European Community, ENS35 090 UK.

Humphreys, M. A. and Nicol, J. F. (1998) 'Understanding the adaptive approach to thermal comfort', ASHRAE Transactions, vol 104, no 1, pp991–1004.

ISO 10551 (1995): 'Ergonomics of the Thermal Environment – Assessment of the Influence of the Thermal Environment Using Subjective Judgement Scales'.

ISO 7726 (1998): 'Ergonomics of the thermal environment - Instruments for measuring physical quantities'.

ISO 7730 (2005) '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'.

McCartney, K. J. and Nicol, J. F. (2002) 'Developing an adaptive control algorithm for Europe: Results of the SCATS project', Energy and Buildings, vol 34, no 6, pp623–635.

McIntyre, D. A. (1980) 'Design requirements for a comfortable environment', in K. Cena and J. A. Clark (eds) Bioengineering: Thermal Physiology and Comfort, Elsevier, Amsterdam, pp157–168.

Pagliano, L. and Zangheri, P. (2010) 'Comfort models and cooling of buildings in the Mediterranean zone', in Advances in Building Energy Research (ABER) , 2010, Volume 4, p. 167-200 (ISSN 1751-2549).