Energy 98 (2016) 122–134

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Assessment of thermal comfort in existing pre-1945 residential building stock

Manoj Kumar Singh [a, b, *], Shady Attia [c], Sadhan Mahapatra [d], Jacques Teller [a]

[a] Faculté des Sciences Appliquées, Department ArGEnCo, Local Environment Management and Analysis (LEMA), Université de Liège, Chemin des Chevreuils, 1 – 4000, Liège, Belgium
[b] Department of Human and Social Systems, Institute of Industrial Science, The University of Tokyo, 4-6-1, Komaba, Meguro-ku, Tokyo, 153-8505, Japan
[c] Faculté des Sciences Appliquées, Department ArGEnCo, Sustainable Buildings Design Lab, Université de Liège, Chemin des Chevreuils, 1 – 4000, Liège, Belgium
[d] Department of Energy, Tezpur University, Tezpur, 784028, Assam, India

ARTICLE INFO

Article history:
Received 16 October 2015
Received in revised form
30 December 2015
Accepted 12 January 2016
Available online 6 February 2016

Keywords:
Building stock
Thermal comfort
Energy efficiency
Thermal performance

ABSTRACT

The building sector is the third-largest consumer of primary energy in Belgium. This is partly because of the high percentage of old buildings (buildings constructed before 1945) in its building stock. Existing international standards on thermal comfort focus primarily on new construction and commercial buildings but tend to overlook old buildings. This study involves a thermal comfort assessment of fully functional (in use) residential buildings constructed before 1945 in Liège (Belgium). The research methodology is based on continuous long term monitoring of the indoor environment (November 2011 to May 2012) and followed by comfort surveys for selected houses in the city. The analysis of the collected data shows that family composition, envelope performance and the occupants' interaction with the indoor environment greatly affected occupant preferences and functioning of the indoor thermal environment. This study reveals that the occupants' interaction with the indoor thermal environment to restore comfortable thermal conditions varies throughout the day, by adjusting the temperature in different rooms of the house at different times of the day. This study argues that modern comfort standards have failed to estimate the comfort level in these old buildings and, if applied, they would lead to under estimation of their thermal comfort.

1. Introduction

The present worldwide economic crisis has affected the lives of people across the globe in several ways [1]. For some, their cost of living has risen or their standard of living has fallen; for others, their overall health has been affected (by fuel poverty or reduced affordability) [1]. This has forced policy makers to think ‘outside the box’ and bring ‘sustainability’ to the forefront of their decisions as never before [2,3]. Above all, the issue of climate change has aggravated the economic crisis and added uncertainty and unpredictability to the situation [1]. Most of the work on fixed, global thermal comfort standards to define the energy efficiency of houses ignores the ‘*contextual*’ nature of thermal comfort [4–6]. In the present context of economic crisis and global warming, energy consumption in buildings and per-capita energy consumption are no longer credible indicators of economic prosperity and social well-being [1]. Economic slowdown and climate change have now forced policy makers and scientists to incorporate rationalization (economic + clean + sustainable) in energy utilization numbers for various countries across the world [7,8].

In Belgium, the building sector is the third-largest consumer of primary energy. A high percentage of 'old' buildings, i.e., buildings constructed before 1945, in the existing building stock take its toll on the energy efficiency figures [9,10]. The study shows that residential buildings in Belgium have a 70% higher consumption of heating energy than their EU-27 counterparts, and this is reflected in the CO_2 emission figures (the household sector is the second-highest CO_2 emitter) [10]. Studies on existing building stocks across EU member countries reveal that large numbers of buildings are relatively old [10–14]. This sector has great potential for energy savings, greenhouse gas emission reductions and improvements in

---

* Corresponding author. Present Address: Department of Human and Social Systems, Institute of Industrial Science, The University of Tokyo, 4-6-1, Komaba, Meguro-ku, Tokyo, 153-8505, Japan.

E-mail address: mksinghtu@gmail.com (M.K. Singh).

http://dx.doi.org/10.1016/j.energy.2016.01.030
0360-5442/© 2016 Elsevier Ltd. All rights reserved.

the thermal aspects of the built environment. With this in mind, the European Commission formulated the ‘Energy Performance Building Directive’, which had a target of a 20% reduction in greenhouse gas emissions by 2020 in the building sector. This has to be achieved by (i) improving energy efficiency, (ii) reducing the use of fossil-fuel-based energy sources and (iii) increasing the share of renewable energy sources [5,7]. All member states, including Belgium, are to engage in the active promotion of ‘nearly-zero-energy buildings’ by 2020. In 2009, more focused definitions for low-energy houses appeared; the passive house and the zero-energy house were incorporated into Belgian federal income tax legislation, thereby providing initial guidance to the residential sector [15]. However, these zero-energy targets are inadequate for dealing with the urgent need for energy reduction with respect to climate change challenges, and they under estimate the potential for energy savings via renovations in Belgium's building sector [6,7].

International standards such as EN-ISO 7730, ASHRAE 55-2010, ASHRAE 62.1 and EN 15251 focus primarily on new construction and commercial buildings. The existing building stock of EU member states has a very high share of relatively old fully functional (in use) residential buildings and the rate of new construction is very low [8,10–12]. Moreover, there is a lack of understanding about the interaction between the built environment of relatively old residential buildings and their occupants. This study tries to address this issue and generate information that will help building professionals, researchers, municipality bodies and policy makers to understand the functioning of these buildings, in contrast to simply using the widely accepted present-day comfort standards and parameters [16–19]. This study also tries to address the rationale behind the use of present-day thermal comfort standards for estimating thermal comfort in fully functional, but relatively old, residential buildings. The study therefore provides a critical review of the applicability of existing comfort standards to old residential buildings. This critical approach is firmly supported by a number of recent studies that highlighted the existence of strong relationships between thermal comfort, the functionality of the house (e.g., when occupants use different rooms and for how long) and the occupants' behaviour, expectations and preferences with respect to the indoor thermal environment [20–22].

This research is carried out on fully functional residential buildings in the city of Liège that were built before 1945. These buildings, being more than 70 years old, were built when no energy efficiency norms were in place and there was limited understanding of energy-efficient building materials and technology. However, over the past 70 years, the lifestyle of the occupants has drastically changed and, to support these changes, the buildings have often been renovated and/or modified in recent years. In this study, long term thermal monitoring (first phase is winter monitoring period: November 2011 to February 2012; second phase is spring monitoring period: March 2012 to May 2012) of the indoor environment in 20 houses (10 each during winter and spring) has been carried out, followed by a comfort survey of 85 houses (including the 20 monitored houses). The data collected during the monitoring and comfort surveys are analysed to critically evaluate the rationale and applicability of thermal comfort standards in these relatively old residential buildings. Buildings constructed before 1945 fall into five different styles, namely *Maison Modeste* (modest house), *Maison Moyenne* (average house), *Maison de Maître* (house), *Maison Historique* (historic house) and *Maison Apartment* (apartment house) [10]. These styles can be differentiated according to height and width, window features and built-up area. Monitoring work is carried out in selected houses (10 houses in winter and 10 houses in spring) in winter and spring to cover different typologies of houses and to optimize the time constraint. It is found from the previous studies that residential buildings in Belgium consume 70% more heating energy than their EU-27 counterparts [10]. In winter season, heating system in most of the houses is ON and it is gradually switched OFF in spring season. Hence, it is appropriate to monitor the houses in winter and spring as it will provides maximum opportunity to capture transition, relation between functionality of the house, occupant's interaction with built environment and pattern of heating system use.

The paper is organized into seven sections. This introduction has identified the research problem, the objectives and their significance. Section 2 identifies the characteristics of residential buildings in Belgium and reviews the literature on thermal comfort standards. Section 4 explains the research methodology. Section 5 analyses the results and specifies the indoor environment quality and occupants' behaviour in pre-1945 houses. Sections 6 and 7 discuss the study outcomes, its implications and limitations.

2. Characteristics of residential buildings in Belgium

In Belgium, the building stock comprises almost 4,400,000 buildings, with more than 40% of the building stock predating 1945. Most of these buildings are concentrated in the large Belgian cities and their conurbations. The city of Liège is a major conurbation in the Walloon region. Before undertaking the study on thermal comfort in old residential buildings, it was important to understand the characteristics of the existing residential building stock in Liège. An analysis based on the ‘*General socio-economic survey 2001*’ reveals that 68.33% of Liège's buildings were constructed before 1945. The analysis of the building stock reveals that 75% of buildings have a central heating system (hot-water-based heating) using natural gas as the fuel, 80.5% of buildings do not have insulated walls and 50% have no roof insulation [10]. The analysis also shows that 60% of windows are fully insulated with double-glazing, 18% have partially insulated glazing and 22% have no insulated glazing. There is a considerable improvement in the overall heat transfer coefficient of building components over the years in new constructions [10]. This observation is supported by the decreasing heating energy requirements for the buildings over the period. The heating energy consumption (final energy) per year across the building stock varies from 383 kWh/m^2 (for buildings constructed before 1863) to 127 kWh/m^2 (for buildings constructed between 2001 and 2012) [10].

Most central heating systems use natural gas as fuel. Central heating is installed in 75% of the building stock; 74% of the central heating boilers are relatively old and, to improve their energy efficiency, they need regular monitoring, renovation and/or replacement [9,10]. These old buildings' overall insulation level has usually received minimal attention because improving insulation through renovation is a complex and cost-intensive process, particularly when the building is occupied or has historical value [9,10]. It is also important to note that about 55% of houses in Liège are used as rented accommodation, with only 41% of houses being owner-occupied (based on the housing quality survey data) [9,10]. This helps to explain the low thermal performance of the houses, because tenants have limited choices (possibly none) about improving thermal performance. Furthermore, it has limited importance to owners because they do not inhabit the houses and the energy bills are being paid by the tenants [9,10].

3. Thermal comfort standards

By definition, thermal comfort is subjective and involves a contextual response [23–25]. Studies over the past two decades have shown that thermal comfort can mean an altogether different set of parameters for people living in different climates. Several attempts have been made to develop a systematic methodology by incorporating the design features required for varying human thermal requirements and climatic conditions [18]. In addition, expectations about comfort for occupants who use mechanical means to control the built environment differ from the occupants who use building design parameters (windows, ventilators or shading) to modify the built environment ('free running') [26,27]. Therefore, there is a need to understand the interaction between the occupant and the built environment by considering both the dynamic thermal environment and the occupants' activities. The importance of thermal comfort studies is now well established in building design. A large number of studies have been carried out to make thermal comfort models more robust by incorporating regional and contextual parameters. Currently, heat balance approach and adaptive thermal comfort models are both being adopted in thermal comfort definitions [27–31]. Each approach has its own advantages and limitations. People have an inherent capability to adapt to the changing conditions of their indoor thermal environment; the adaptive thermal comfort model duly addresses this phenomenon. The adaptive principle expresses the fundamental assumption of the adaptive model: '*if a change occurs such as to produce discomfort, people react in ways that tend to restore their comfort*' [17,18,20]. The basis for the adaptive thermal comfort model is the findings of field surveys on thermal comfort. An occupant in a naturally ventilated building responds actively to changes in the thermal environment and uses the available adaptive opportunities to the fullest to restore comfort. The socio-cultural and traditional contexts also govern adaptive opportunities [25].

Adaptive thermal comfort studies use temperature alone as the parameter to accommodate the regional and contextual variables (thermo-physical properties of building materials, climatic parameters, age of occupants and activity level of occupants). EN-ISO 7730, EN 15251, ASHRAE 55 and ASHRAE 62.1 are the existing standards in this domain. These are widely accepted and referred in designing an indoor environment (thermal comfort, air quality, noise and light). The European standard EN 15251 covers all aspects of comfort, such as thermal comfort, air quality, acoustics and visual comfort [5,8,29,30]. It also allows designers, engineers and architects to perform energy calculations that have consequences for the environment. Table 1 shows the acceptance temperature and PMV (predicted mean vote) ranges according to the EN 15251 standard for mechanically cooled and naturally cooled buildings [6]. This standard is mostly applicable to new and relatively new existing buildings but is not applicable to old residential buildings (constructed before 1945) [6,7,29,30]. In particular, it has some important drawbacks:

- It recommends broad criteria only and thus has to be modified at the national level.
- It does not consider local discomforts (asymmetric radiant temperatures, day lighting, vertical air-temperature differences and surface temperatures), which often occur in historic buildings (typically, un-insulated buildings with heating systems).
- It provides design parameters instead of design methods, which can be confusing for designers.
- It does not discuss the number of rooms to be monitored when estimating comfort in multi-room buildings.

It is clear that considering only the history of outdoor temperatures (e.g., dry bulb temperature, running mean temperature and weighted running mean temperature) as a single variable to represent comfort in buildings fails to explain experimental thermal comfort results [17]. These results support an argument for increasing the complexity of the time scale that needs to be considered to account for the variations. Moreover, various studies show that incorporating occupants' clothing level and activity together with the temperature can cover a broad spectrum of contexts and both regional and local variables, thereby increasing the accuracy of the estimation of comfort [17]. A number of adaptive thermal comfort studies have demonstrated that clothing level (measured in 'clo') is strongly correlated with the running mean indoor temperature rather than the mean outdoor temperature [17]. This supports the proposition that the building itself should be considered, in addition to human thermal experience and comfort expectations, in contrast to a focus on outdoor temperatures [17,18]. For the old buildings of Liège, it is found that the clothing level of occupants is weakly related to the outdoor temperature but strongly related to indoor temperature variations. This interesting phenomenon was observed during the comfort survey. Because people stay in these old houses for a long time, it can be assumed that they have accustomed to the built environment and have altered the functionality of the rooms (i.e., by using different rooms and setting different preferred temperatures at different times of the day and year) to optimize their thermal comfort according to the affordability of energy and heating equipment.

4. Methodology

The characteristics of the residential buildings of Liège are discussed in Section 2. This is important because it underlines the relevance of this study, which is carried out on pre-1945 residential buildings. The high percentage of functionally active buildings in this category demands the investigation of occupants' thermal comfort preferences and expectations, in contrast to the widely discussed existing thermal comfort standards (mostly applicable to new buildings). To judge the applicability of the existing standards for defining comfort in fully functional pre-1945 residential buildings, long term thermal monitoring has been carried out in 20 residential buildings, followed by a questionnaire-based thermal comfort survey in 85 houses. ASHRAE 55 protocols for field studies are followed in the thermal comfort survey [10]. The long-term monitoring of the indoor environment is carried out in two phases. The first phase involved 10 houses during winter (November 2011 to February 2012), when the heating system is ON in most houses. The second phase involved another 10 houses during spring (March to May 2012), when the heating systems are mostly OFF. The comfort surveys are carried out between 17:00 h and 20:00 h on weekdays and from 11:00 h to 20:00 h on weekends to

Table 1
Acceptance temperatures and PMV ranges according to the EN 15251 standard for mechanically and naturally cooled buildings [13].

Expectation level	Explanation	EN standard category	Range	
			Mechanically cooled buildings	Naturally cooled buildings
High	Space occupied by a very sensitive and fragile person	I	±0.2 PMV	±2K
Normal	New buildings and renovations	II	±0.5 PMV	±3K
Moderate	Existing buildings	III	±0.7 PMV	±4K
Low	Short period of occupancy	IV	± > 0.7 PMV	±>4K

enable the collection of sufficient information. The local temperature and relative humidity are measured at body height (1.1 m from the ground) by using a handheld data acquisition system (environmental meter, Omega instruments, UK). In each thermal comfort survey, occupants were advised to sit ideal for 20 min before taking measurements and recording the preference. An average of five measurements is taken for analysis to minimize the errors. Building design parameters, such as external façade characteristics, materials used for construction, built-up area, type of heating system and renovations, are also recorded. Occupants are questioned about the various strategies they followed to make themselves comfortable in their houses. The measured data, together with information collected during the thermal comfort survey, are used to evaluate the actual thermal comfort in accordance with the thermal performance of the houses [10]. The questionnaire for the comfort survey is designed to address the objectives of the study, in addition to providing enough specific and subjective information to draw meaningful conclusions. The data collected during the comfort survey are analysed to evaluate the prevailing comfort status in those houses. This study identifies the parameters that need to be considered to improve the energy efficiency of the occupied historic houses.

A thermal performance evaluation of buildings with respect to outdoor temperature variations and prevailing indoor temperatures is an important aspect of judging the overall thermal performance of residential buildings. These house numbers have ‘W’ prefixes to denote ‘winter’. During this time, the heating systems in all houses were ON. In the second phase, another 10 houses are monitored in the months of March to May 2012, with the house numbers having ‘S’ prefixes to denote ‘spring’. During this period, the heating system in most houses was switched OFF. Table 2 presents the details and important characteristics of all the 20 houses that have an influence on the indoor thermal environment. All the houses considered in this study are terraced (exposed to the air on two sides). It is observed from Table 2 that most of the houses used natural gas for heating despite having relatively old heating systems. The long term monitoring included recording the temperature, relative humidity profiles and illumination level (inside and outside of each house). Table 3 presents the significant parameters that define thermal comfort, such as family configuration, temperature profile and comfort status for the monitored houses. All the parameters are measured via data loggers (HOBO-U12 RH/Temp/Light/External Data Logger, USA). The data loggers were installed in the living room, bedroom and outdoor area of each house because the functionality of rooms may differ. Different rooms were occupied during different times of the day and for different durations. This influences the patterns of dominant temperatures in living rooms and bedrooms. The temperature sensor accuracy was ±0.35 °C, humidity sensor accuracy was ±2.5% RH and light intensity measurement instrument accuracy was ±20 lux. All these parameters are recorded at intervals of 30 min. The houses are being used normally throughout the monitoring period, without imposing any restrictions on the occupants, to make the monitoring results realistically. Occupants are also invited to behave normally. The collected data are analysed to obtain the thermal profiles for the living rooms and bedrooms of the houses and the dominant temperatures during different times of the day and seasons of the year.

Section 1 of the thermal comfort questionnaire covered the socio-economic status of the occupants and their family composition. Section 2 covered the building's age and its type of construction. Section 3 addressed any specific issues about the house and its functioning. Section 4 constituted the heart of questionnaire and collected information about the thermal comfort, expectations and preferences of the occupants during both winter and spring. Section 5 recorded the occupants' past, current and intended future activity level when expressing their comfort status. Section 6 focussed on collecting supplementary information covering a broad range of indoor environment characteristics that might be the cause of discomfort or indirectly influence the comfort status of the occupant (e.g., indoor air quality and natural lighting level).

Table 2
House details and characteristics for the 20 monitored houses [10].

House number	Typology of house and year of construction	House arrangement	Insulation (walls, roof)	Fuel used and age of heating system (years)	House ownership and category of income	Glazing system	Renovated	Magnitude of average swing in temperature during monitoring period (°C)			
								Bedroom		Living room	
								Start	End	Start	End
W_1	a, 1919–1945	Terraced	No, No	Fuel oil, >15	Owner, Average	Mixed	Yes	1–3	2–4	6–8	4–8
W_2	a, 1875–1918	Terraced	Yes, Yes	Natural gas, <15	Owner, High	Double	Yes	1–2	1–2	3–4	4–6
W_3	b, 1875–1918	Terraced	No, Yes	Natural gas, >15	Owner, Average	Mixed	Yes	4–5	2–3	4–5	4–5
W_4	b, 1875–1918	Terraced	Yes, Yes	Natural gas, <5	Owner, Average	Double	Yes	3–4	3–4	3–4	3–4
W_5	c, 1875–1918	Terraced	No, Yes	Fuel oil, >15	Owner, High	Double	Yes	0.5–1	0.5–1	2–3	2–3
W_6	c, 1875–1918	Terraced	No, Yes	Natural gas, <5	Rent, Average	Double	Yes	2–3	2–3	3–6	3–6
W_7	d, 1919–1945	Terraced	No, No	Natural gas, <15	Rent, Low	Mixed	Yes	2–6	1–7	2–5	2–5
W_8	b, 1875–1918	Terraced	No, Yes	Natural gas, >15	Owner, Average	Mixed	Yes	2–6	2–7	4–8	4–9
W_9	c, 1875–1918	Terraced	No, Yes	Natural gas, <10	Owner, Average	Mixed	Yes	2–4	0.5–1	2–4	2–4
W_10	c, 1875–1918	Terraced	Yes, Yes	Natural gas, <5	Owner, Average	Double	Yes	2–4	3–4	4–5	4–7
S_1	c, 1875–1918	Terraced	No, Yes	Natural gas, >15	Owner, Average	Mixed	Yes	1–2	2–3	3–4	1–2
S_2	c, <1875	Terraced	Yes, Yes	Natural gas, <5	Owner, Average	Double	Yes	0.5–1	0.5–1	4–5	0.5–1
S_3	c, 1919–1945	Terraced	Yes, Yes	Natural gas, <10	Owner, Average	Double	Yes	3–4	1–2	4–5	2–3
S_4	c, 1919–1945	Terraced	No, Yes	Natural gas, >15	Owner, Average	Double	Yes	0.5–1	0.5–1	2–3	1–2
S_5	c, 1919–1945	Terraced	No, Yes	Natural gas, <5	Owner, Average	Double	Yes	1–2	2–3	2–3	1–2
S_6	c, 1875–1918	Terraced	Yes, Yes	Natural gas, >15	Owner, Average	Double	Yes	0.5–1	1–2	1–2	1–2
S_7	c, 1875–1918	Terraced	No, Yes	Fuel Oil, >15	Owner, Average	Double	Yes	1–2	1–2	1–2	1–2
S_8	c, 1919–1945	Terraced	No, Yes	Natural gas, >10	Owner, Average	Double	Yes	NA	NA	2–3	2–3
S_9	c, 1875–1918	Terraced	Yes, Yes	Natural gas, >15	Owner, Average	Double	Yes	NA	NA	2–4	1–2
S_10	d, 1919–1945	Terraced	No, No	Electricity, <10	Rent, Low	Double	Yes	NA	NA	1–2	1–2

W: winter; S: spring; a: Maison de Maitre (house); b: Maison Modeste (modest house); c: Maison Moyenne (average house); d: Maison Apartment (apartment house); NA: not available.
Category of income (Euros/year): Low ≤ 20,000; 20,001 < Average ≤ 30,000; High > 30,001; Mixed: combination of single and double glazing.

Table 3
Family configurations, temperatures and comfort statuses in the monitored houses [10].

House number	Average indoor temperature over the monitoring period (°C)	Family configuration			Range of age of the occupant's participated in comfort survey and gender	Numbers of occupants in the age group 40–60/60–70 years	Clo	Overall comfort[a]	TSV	Met (20 min before voting)	Mean outdoor temperature (°C)	Indoor temperature corresponding to TSV (°C)
	Bedroom	Living room	Adults	Children (<12 years)								
W_1	16.8	17.2	2	0	20–40, M	NA	0.86	b	−2	2.4	4.9	12.5
W_2	18.6	22.0	5	2	40–60, M	2	1.11	a	2	1.6	3.0	21.8
W_3	11.2	13.2	2	0	20–40, F	NA	1.1	b	−1	2.4	3.8	13.4
W_4	14.2	13.9	1	0	20–40, F	NA	1.01	b	−1	1.2	3.9	12.8
W_5	14.3	18.2	2	0	40–60, F	2	1.01	a	0	2.4	5.7	15.4
W_6	17.2	19.1	2	0	20–40, F	NA	0.31	b	1	2.4	5.5	19.6
W_7	14.4	16.0	2	0	20–40, F	NA	0.56	b	−2	1.6	6.1	13.2
W_8	13.9	20.6	3	1	40–60, F	2	1.04	e	2	1.6	4.9	16.9
W_9	15.1	19.4	2	2	20–40, M	NA	1.19	b	0	1.6	5.0	18.4
W_10	17.7	17.8	2	1	20–40, M	NA	1.19	b	0	1.6	6.5	17.6
S_1	20.6	20.9	3	0	40–60, M	2	0.94	b	0	1.0	13.3	19.2
S_2	17.6	17.9	2	0	60–70, F	2	1.05	b	1	1.2	13.3	18.2
S_3	19.7	20.6	2	2	40–60, M	2	0.77	b	−2	1.6	13.4	15.0
S_4	20.6	20.7	2	1	40–60, M	2	0.86	a	−1	1.6	13.6	18.0
S_5	18.6	21.6	2	0	60–70, F	2	0.69	b	1	1.6	12.3	17.3
S_6	19.7	21.6	4	0	40–60, F	2	1.11	b	0	1.6	13.1	19.8
S_7	17.3	20.2	5	0	40–60, M	2	1.19	c	−1	1.2	13.0	17.5
S_8	NA	18.7	2	2	40–60, M	2	0.81	a	1	1.2	12.0	21.4
S_9	NA	21.8	3	0	40–60, M	2	0.77	b	0	1.2	14.0	19.6
S_10	NA	22.5	1	0	20–40, F	NA	0.69	b	1	1.2	13.5	21.5

W: winter; S: spring; M: Male; F: Female.

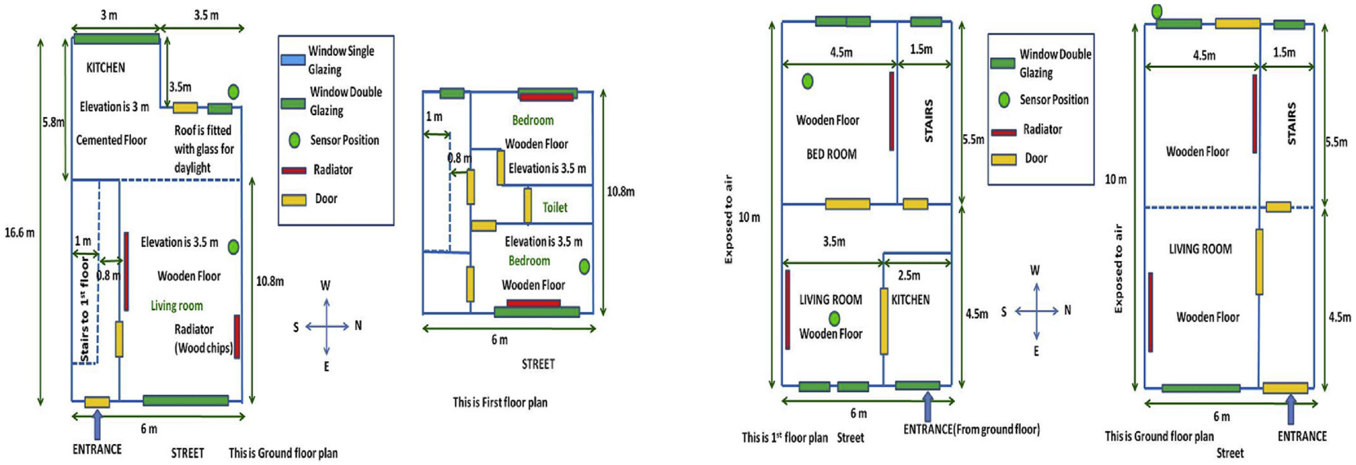
[a] Overall comfort rating of house by occupant: Very comfortable (a); Moderately comfortable (b); Slightly comfortable (c); Slightly uncomfortable (d); Moderately uncomfortable (e); Very uncomfortable (f); NA: not available.

5. Results

5.1. Winter thermal performance analysis

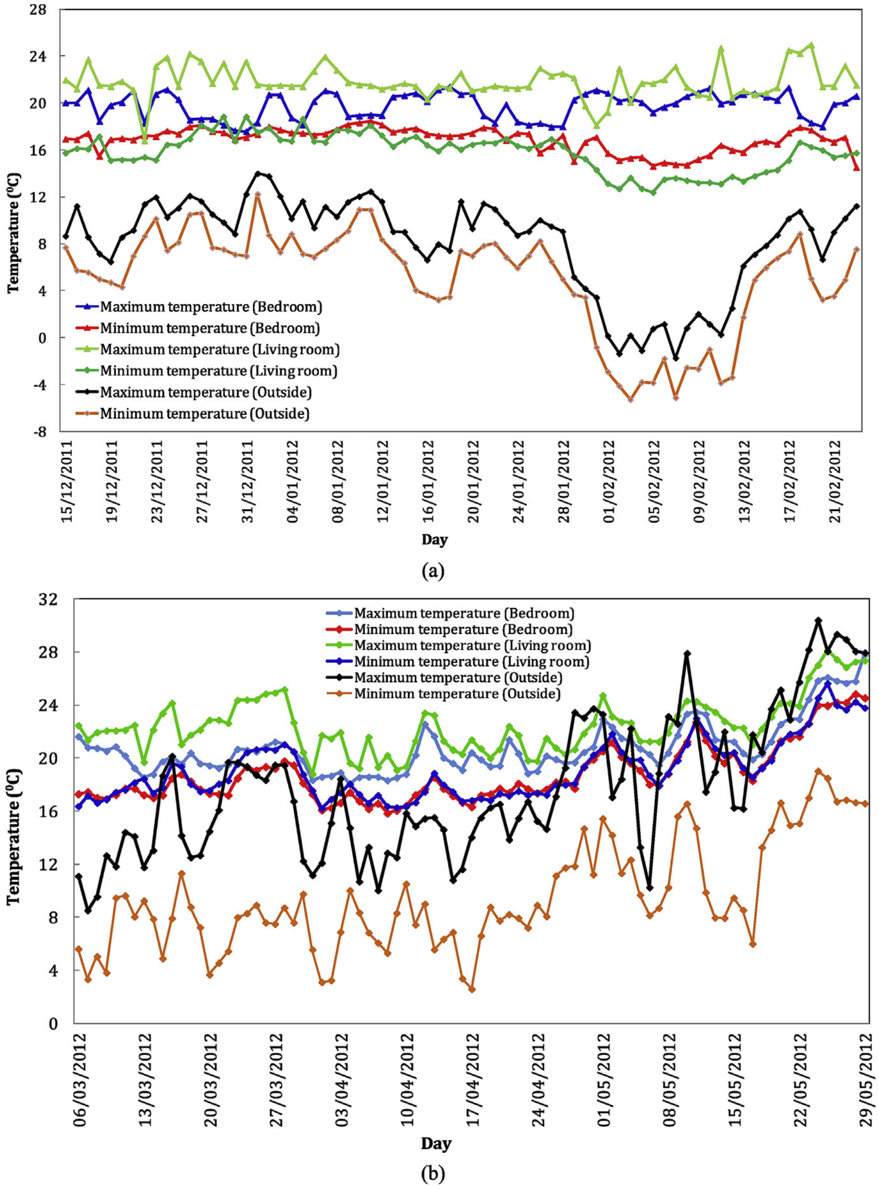
5.1.1. Winter thermal characteristics of the monitored house

In the first phase of the monitoring exercise, the indoor thermal conditions for 10 pre-1945 residential buildings in Liège are monitored. Table 2 shows that most houses are over 100 years old and also presents the 24-h average temperature swing for living rooms and bedrooms at the start and end of the monitoring period. Table 2 shows that the swing in living room temperature is always higher than that in bedrooms. Only one house temperature profile is presented in this paper, as similar temperature profiles are observed in all the 10 houses that are monitored during winter. Fig. 1 presents the layout of house W_10 and S_3. Fig. 2 shows the daily maximum and minimum temperatures profiles of the living room and bedroom of the monitored houses with respect to outdoor temperatures. These house falls under typology Maison Moyenne (Average house) [10]. External wall of the houses are massive and overall thickness of external wall is about 0.3 m thick including insulation (0.22 m + 0.08 m) [10]. Insulation is applied from inside. Internal walls are 0.07 m to 0.12 m thick. These types of houses are constructed at the end of the 19th century and in the beginning of the 20th century. These houses are constructed in the urban area along the street and in groups (have shared façade on two sides). These houses also have adjoining gable, width of the house is 5–6 m



Monitored house W_10   Monitored house S_3

Fig. 1. Layout of the monitored houses.



(a)

(b)

Fig. 2. Daily maximum and minimum temperature profiles for the monitored houses (a) W_10 (b) S_3.

and room height ranging from 3.5 to 4 m. These houses consist of 2–3 floors with significant height. This type of houses has pitched roof with a provision to allow skylight to the interiors. Front facade is made up of brick and decorated with decorative stone or projections or coloured bricks [10]. It is observed from the temperature profiles (winter) that the decay in the living room temperature is rapid compared with that in the bedroom. For house numbers W_3 and W_4, low temperatures are observed in the living room, caused by renovation work in the living room during the monitoring period (frequent opening of doors and windows led to high infiltration by colder outside air). The temperature profiles of the monitored houses reveals that the living room is functionally more active (occupied for more hours in a day) and occupants prefer higher temperature compared with their temperature preferences for the bedroom. It can be concluded from the temperature swing that living rooms lose heat quickly in winter compared with bedrooms. The un-insulated walls and large glazing areas on the façades of the monitored houses are responsible for the radiant temperature asymmetry. This conclusion is supported by the relatively high indoor clothing level of occupants and the temperatures corresponding to thermal sensation votes (TSVs). Relatively old heating systems in combination with un-insulated walls raise questions about the efficient functioning and overall efficiency of these buildings. This issue can be linked to the presence of large glazed areas on the front and rear façades of the houses. Finally, it can be concluded that the glazing on an external façade is an important reason for discomfort in winter (sensations of cold).

The layout of the house W_10 presented in Fig. 1 shows that the front and rear façades and the south wall of this house are exposed to the environment without any shading (by trees or other buildings). This house is oriented on an East–West axis (front façade facing East) and has double-glazed windows with internal movable blinds. It has a central heating system using natural gas with an automatic thermostat. The heating system is less than five years old. In winter, the thermostat is set to 20 °C. The orientation of the house is such that the front façade received sunlight only in the morning and the rear facade received sunlight only in the afternoon. Therefore, overheating in summer, caused by solar gain, is a possibility. The availability of more sunlight in the afternoon until the late evening hours in summer could lead to discomfort (mainly for the rooms on the first and second floor) if the movable blinds on windows are not used effectively. It is observed that, in winter, the maximum temperatures of the living room and bedroom are 25 °C and 22 °C, respectively (Fig. 2a). These temperatures are well within the range for a comfortable indoor environment with typical winter clothing.

It is also important to analyse the daily minimum and maximum temperature fluctuations to assess the thermal comfort of the building. For this house, an interesting pattern is observed, whereby the maximum and minimum temperatures of the bedroom are always between the maximum and minimum temperatures of the living room, suggesting that the temperature fluctuation in the bedroom is less than that in the living room. For this house, the temperature in both the living room and bedroom is well regulated over the full 24-h period. This may be a preference related to the presence of infants in the house. The 24-h average temperature profile of this house suggests that the swing in average temperature in the bedroom is maintained well within 0.5 °C–1 °C but in the living room it is 1.5 °C–2 °C (Fig. 2a). The minimum temperatures of the living room and bedroom fluctuated less than the maximum temperatures, with fluctuations ranging from 0.5 °C to 1 °C over the 24-h period for both rooms (Fig. 2a). It is important to study the minimum-temperature profile because it not only affect the comfort level but also affects heating energy consumption. This effect is also reflected in the average temperature profiles. There is a high level of thermal regulation in this house. The energy consumption is reasonably high being 4750 kWh (750 kWh for electricity and 4000 kWh equivalents for natural gas) during the monitoring period. As per present guidelines, EPBD 2010, in residential buildings Belgium is trying to limit heating energy consumption 130 kWh/m^2/year for existing and new construction. Zero energy building guideline is trying to limit heating energy consumption 15 kWh/m^2/year [7].

5.1.2. Winter temperature profile in the monitored house

The functionality of a house is related to the context and behaviour of its occupants. Indoor temperature data collected during the thermal monitoring of the 10 houses in winter are analysed to find the dominant temperatures and their durations (in hours) for the bedrooms and living rooms. Figs. 3–5 show the duration (in hours) for which different temperature ranges are observed in the bedrooms and living rooms in winter monitoring period. During the monitoring period, renovation work was occurring in the living room for houses W_3 and W_4, leading to a living room temperature of less than 15 °C. For house W_2, relatively high temperatures are maintained in both the living room and bedroom because the owner of the house was ill.

The survey would be incomplete if it does not provide information about the time of day for which particular ranges of temperature are preferred by the occupants of the houses. Therefore, the 24-h day is divided into three periods:

a) 08:00 h to 17:00 h: This period is selected because the occupants of the house tended to be at work (except on weekends).
b) 17:30 h to 22:00 h: In this period, the occupants tended to have returned from work and be spending most of their time in the living room after dinner. It is assumed that, after 22:00 h, most occupants has gone to bed.
c) 22:30 h to 07:30 h: This period is important for examining the patterns of heating before the occupants leave for work.

Fig. 3 shows that, between 08:00 h to 17:00 h, there is a small difference between bedroom and living room temperatures. In the bedroom, the dominant temperature ranges are between 15.1 °C and 18 °C and <15 °C. However, for the living room, the dominant temperature ranges are 15.1 °C–18 °C and 18.1 °C–21 °C. For houses W_3 and W_4, it is observed that the dominance of the <15 °C temperature range is because of renovation work at the time of monitoring. High infiltration by outside air, caused by the frequent opening and closing of doors, may have led to these low indoor temperatures. For houses with infants and occupants in the age group of 40–60 years, the preferences are for higher temperatures than those for occupants in the age group of 20–40 years (houses W_2, W_8, W_9 and W_10). Temperature preferences for bedrooms and living rooms between 17:30 h to 22:00 h are presented in Fig. 4. It is observed from these profiles that there is a drastic difference in the dominant temperature ranges between living rooms and bedrooms. The dominant temperature range for bedrooms is the same as that between 08:00 h and 17:00 h. However, for living rooms, the dominant temperature ranges are 18.1 °C–21 °C and 21.1 °C–24 °C. Again, for the houses with older occupants and children, the preferences are for higher temperatures (houses W_2, W_8, W_9 and W_10). A detailed analysis (half-hourly recorded temperature) of the temperature profile revealed that, in winter, the heating system in most houses is switched ON between 16:30 h and 17:00 h (a gradual increase in temperature is observed in the living room temperature). Fig. 5 shows the profile of dominant temperatures in the bedroom and living room for the period from 22:30 h to 07:30 h of the next day. These temperature profiles indicate that occupants prefer bedroom temperatures in either the range 15.1 °C–18 °C or <15 °C. That is, occupants of historic houses seem to prefer low temperatures in the bedroom while sleeping. These temperatures

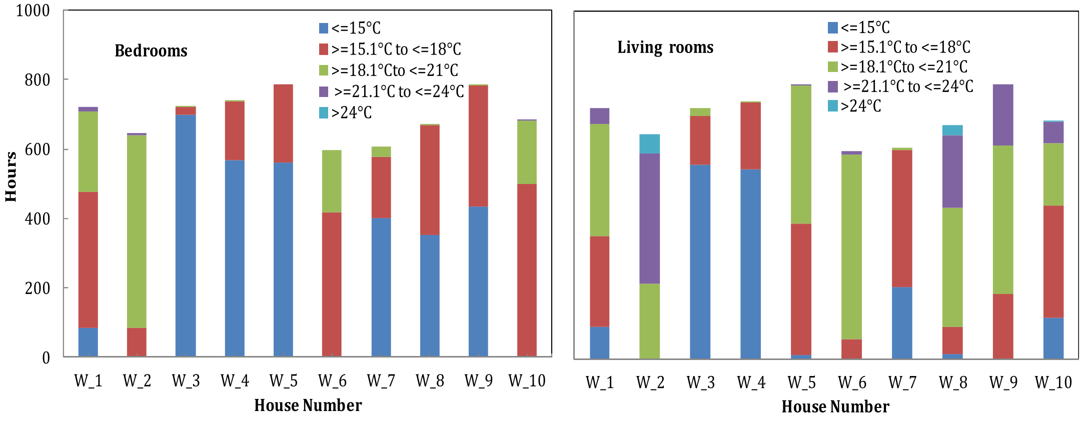


Fig. 3. Temperature ranges and their durations between 08:00 h and 17:00 h in winter in the monitored houses.

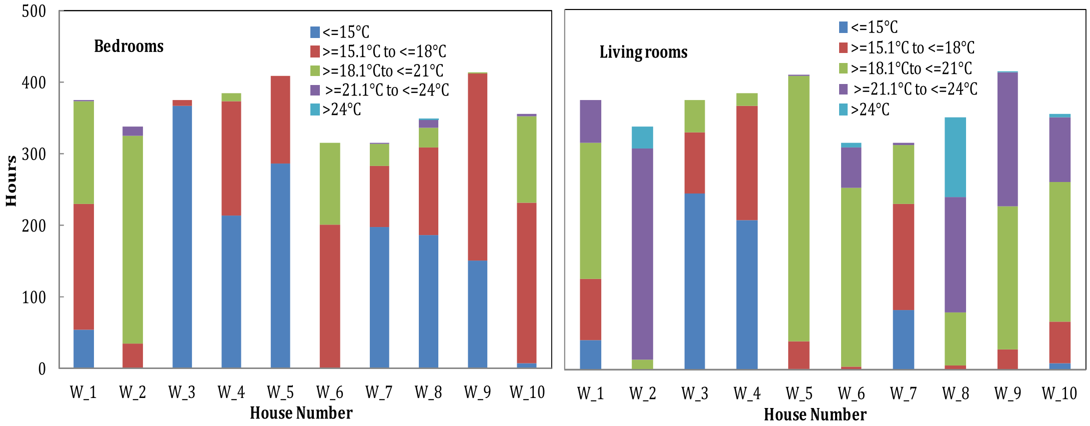


Fig. 4. Temperature ranges and their durations between 17:30 h and 22:00 h in winter in the monitored houses.

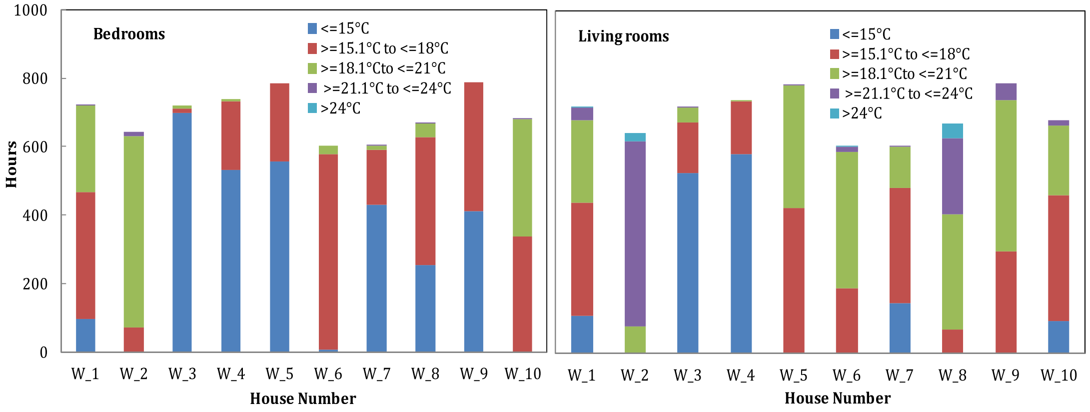


Fig. 5. Temperature ranges and their durations between 22:30 h and 07:30 h in winter in the monitored houses.

are much lower than the temperature range stated in international standards [8,30]. In contrast, it is found that the dominant temperature ranges are 15.1 °C–18 °C and 18.1 °C–21 °C for the living room. For almost all houses, the temperature in the living room increases after 05:00 h (heating is switched ON). This phenomenon is exemplified by the maximum and minimum temperature profiles for the house W_10, as shown in Fig. 2a. Based on the above analysis, occupants of all the monitored houses prefer relatively low bedroom temperatures throughout the 24-h cycle. It is also clear that occupants prefer not to heat all the rooms at the same time and to the same temperature. This type of arrangement and heating schedule is not only economical but also optimizes the indoor thermal conditions. However, this phenomenon is virtually ignored in present-day international standards (ISO 7730, ASHRAE 55 and EN-ISO 15251). Finally, it can be concluded that, when applying modern standards for defining thermal comfort to pre-1945 residential buildings, there is a high probability that these standards will underestimate the actual thermal comfort and overestimate the potential energy savings through insulation. Table 4 presents a dominant temperature matrix for bedrooms and living rooms in winter and spring.

5.2. Spring thermal performance analysis

5.2.1. Spring thermal characteristics of the monitored house

The indoor thermal environments of 10 pre-1945 residential buildings are monitored during spring (March to May 2012). The monitored houses' characteristics are presented in Table 2 (see 'S' codes). Table 3 presents the mean indoor temperatures for living rooms and bedrooms over the monitoring period and indicates that the difference between the mean temperatures for bedrooms and living rooms is lower in spring than in winter. It can also be observed that the living rooms in all the monitored houses are functionally more active (occupied for more hours of the day) and the preference is for higher temperatures in spring than in winter. Figs. 1 and 2b show the layout of house S_3 and the daily maximum and minimum temperature profiles of the living room and bedroom with respect to outdoor temperatures. This house also falls under typology Maison Moyenne (average house) [10] and have façade characteristics similar to house described in winter monitoring phase. There were four occupants in the house, two aged between 40 and 60 years and two children younger than 12 years. The occupants owned the house, and the house was built between 1919 and 1945. It is a three-storey house in the Maison Moyenne (medium house) style. It is terraced, with front and rear façades exposed to the air with no shading on either façade. The house is oriented on an East–West axis (front façade facing East) and has double-glazed windows fitted with internal and external movable blinds. It has a central heating system using natural gas with an automatic thermostat. The heating system is less than 10 years old. In spring, the thermostat is set to 18 °C. One occupant reported that, within the past 10 years, the house underwent major renovations, including changed window glazing, an extra room, additional insulation in the walls and roof and the installation of radiators and a new boiler. The roof and walls of the house are insulated to a depth of 0.12 m and 0.16 m, respectively. For this

Table 4
Observed temperature matrix.

Season	Room in house	Time of day (h)	Temperature range (°C)				
			≤15	15.1–18	18.1–21	21.1–24	>24
Winter	Bedroom	08:00–17:00	xxx	xxx	x		
		17:30–22:00	xxx	xxx	xx		
		22:30–07:30	xxx	xxx	x		
	Living room	08:00–17:00		xxx	xxx	xx	
		17:30–22:00		x	xxx	xxx	
		22:30–07:30		xxx	xxx	x	
Spring	Bedroom	08:00–17:00		xxx	xxx	xx	
		17:30–22:00		xxx	xxx	xx	x
		22:30–07:30		xxx	xxx	xx	x
	Living room	08:00–17:00			xxx	xxx	x
		17:30–22:00			xxx	xxx	x
		22:30–07:30			xxx	xxx	x

x: dominant temperature range for period in order of x < xx < xxx.
x: Short time; xx: Moderate time; xxx: Long time.

house, the maximum temperature of the living room is always higher than that of the bedroom. The living room temperature is more sensitive to outdoor temperature variation. An almost identical pattern is observed for minimum temperatures. At the end of the monitoring period, it is observed that there is the possibility of overheating in the bedroom and the living room, given that a steep rise in indoor temperature accompanied a rise in outdoor temperature. The 24-h average temperature profile of this house suggests that temperature swings in the living room and the bedroom are both in the range of 1 °C–1.5 °C. The minimum temperature profiles indicate that the minimum temperatures of the living room and bedroom fluctuate more than the maximum temperatures. This behaviour is observed because the heating system is not continuously switched ON. In contrast to the functioning of living rooms and bedrooms in winter, the living room and bedroom temperatures started tracing each other once the heating system is completely switched OFF, and there is the possibility of an inversion occurring if the bedroom temperature always remains higher than the living room temperature. This is mainly caused by the arrangement of rooms in the house. Living rooms are generally on the ground floor, and their façades are thus less exposed to sunlight, whereas the bedrooms are on the top floor of the house and receive sunlight throughout the day. This conclusion is supported by the sharp rise in average bedroom temperature compared with that for the living room (Fig. 2b). The fluctuation in temperature in the living room is more rapid than in the bedroom. In the initial period of monitoring, the thermostat was working effectively, maintaining the temperature close to 22 °C when the living room was occupied and allowing it to fall to 17 °C–18 °C when unoccupied. Similar patterns are observed for the bedroom, but to a lesser extent and more smoothly.

5.2.2. *Spring temperature profile in the monitored house*

The spring monitoring period is also analysed in terms of the same three time periods during the day as like winter monitoring. The analysis aimed to find the dominant temperature ranges in the houses at different times during the day in spring. Fig. 6 presents the temperature ranges for the 08:00 h to 17:00 h period (note that the occupants of houses S_8, S_9 and S_10 did not agree to install data loggers to monitor temperature profiles in bedrooms). The dominant temperatures for bedrooms and living rooms are different during the 08:00 h to 17:00 h period. For bedrooms, the dominant temperature ranges are 15.1 °C–18 °C and 18.1 °C–21 °C. However, for living rooms, they are 18.1 °C–21 °C and 21.1 °C–24 °C. House S_2 is anomalous, because the occupants were absent from the house most of the monitoring period. This explains the increased duration of temperatures in the range 15.1 °C–18 °C (in both the bedroom and living room). The hours spent between 17:30 h and 22:00 h in each temperature range are shown in Fig. 7 for the bedroom and living room, respectively. The dominant temperature ranges for the bedroom are 15.1 °C–18 °C and 18.1 °C–21 °C. Moreover, the temperature rose within the range of 21.1 °C–24 °C for a significant time. Detailed analysis shows that this occurred during May, when the temperature in the bedrooms of most of the houses reaches 24 °C (most bedrooms were on the top floor, receiving sunlight until late afternoon, and a high percentage of glazing with no external shading worsened the situation). In the living room, the temperature is usually maintained in

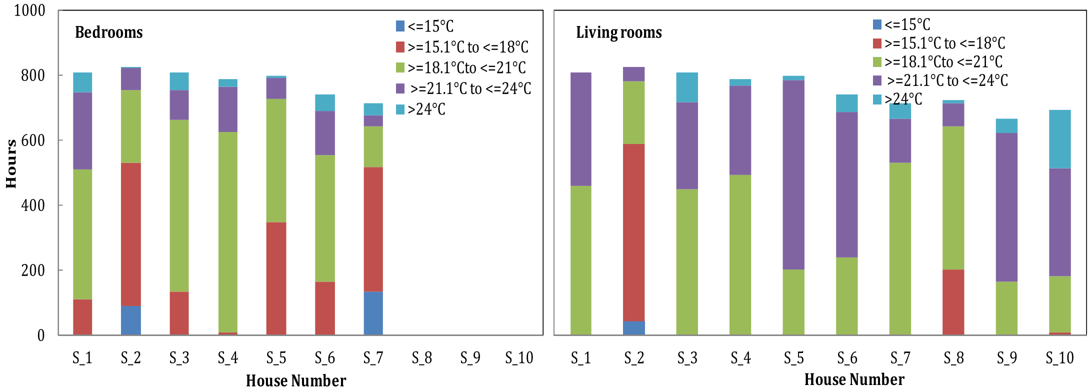


Fig. 6. Temperature ranges and their durations between 08:00 h and 17:00 h in spring in the monitored houses.

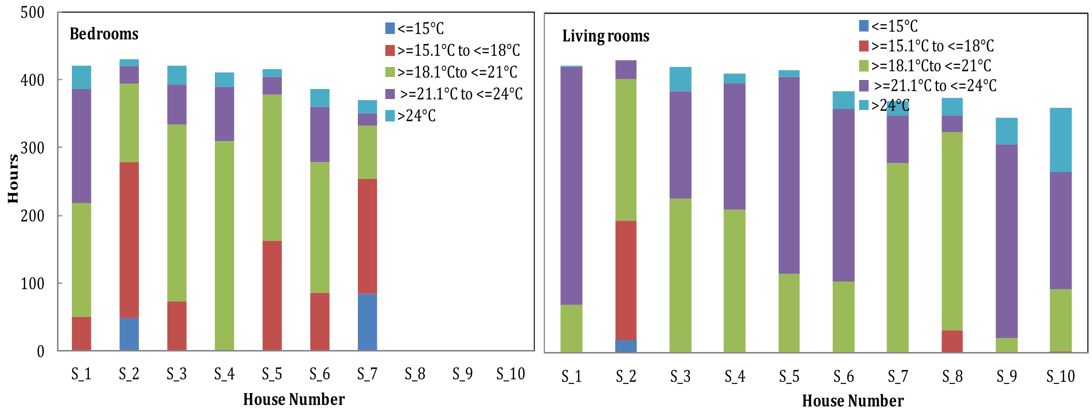


Fig. 7. Temperature ranges and their durations between 17:30 h and 22:00 h in spring in the monitored houses.

the ranges 18.1 °C–21 °C and 21.1 °C–24 °C. For a significant number of hours, the temperature of house S_10 is above 24 °C. This house is a top-floor apartment and oriented on an East–West axis. The living room in this house faced West, and 50% of the external façade is double-glazed. The living room received sunlight until late in the afternoon because of its orientation. There is no external shading device to block the afternoon sunlight. According to CIBSE-2006 guidelines, the threshold temperatures in summer for the bedroom and living room should be 23 °C and 25 °C, respectively [8]. If the temperature exceeds the relevant threshold, it may become uncomfortable for the occupants [8]. For the revised EN 15251 standard and ASHRAE 55-2013 (where the adaptive thermal comfort concept is incorporated), the acceptable temperature range for the living environment is 20 °C–24 °C in winter and 23 °C–26 °C in summer [13,14]. The analysis in the present study indicates that the bedroom temperature could reach 28 °C in May (beginning of summer). Therefore, it can be concluded that the bedroom temperature in summer can be outside the comfortable range. Fig. 8 shows the temperature ranges between 22:30 h and 07:30 h for bedrooms and living rooms, respectively. The dominant ranges for the bedroom are 15.1 °C–18 °C and 18.1 °C–21 °C. Moreover, for a significant number of hours, the temperature is in 21.1 °C–24 °C range. For the living room, the dominant ranges are 18.1 °C–21 °C and 21.1 °C–24 °C. For house S_4, constant temperatures are maintained in both the living room and bedroom during the entire monitoring period. The family in this house has a child. Furthermore, the owner's work involved the restoration of historic paintings, with his workshop being attached to the house. Such work requires the maintenance of a constant temperature.

5.3. *Thermal comfort assessment*

5.3.1. *Clothing characteristics*

Comfort is a subjective and context dependant response influenced by past experiences and the socio-economic and socio-cultural setup of the occupant [18,24,25]. It is also related to energy consumption and the occupant's behaviour in the built environment [25]. A thermal comfort survey was carried out amongst 85 households to characterize the occupants' comfort preferences. Clothing level adjustment is usually considered the dominant and most effective personal adaptation process available to restore comfort at various indoor and outdoor temperatures [25]. From the comfort survey, it is found that clothing values (0.3–1.12 clo) are scattered with respect to outdoor temperatures in the range of 6.9 °C–8.9 °C (comfort survey is carried out in winter and early spring season). A regression analysis showed that the relationship between the occupants' clothing preferences against both outdoor and indoor temperatures is weak (Fig. 9). This result is expected based on previous studies, which have shown that the relationship between preferred clothing levels and temperatures is weak for occupants living in heated or cooled environments [25]. The occupants of historical houses are less tolerant towards variations in temperature. At both ends of the regression line, the trend bent inwards, suggesting a wide deviation in clothing patterns with a slight change in temperature, confirming the lower tolerance level of these occupants (Fig. 9). This behaviour by occupants is contrary to what is observed in naturally ventilated buildings, where occupants are more likely to adjust clothing levels with changing temperatures [25]. It is observed from the analysis that people tended

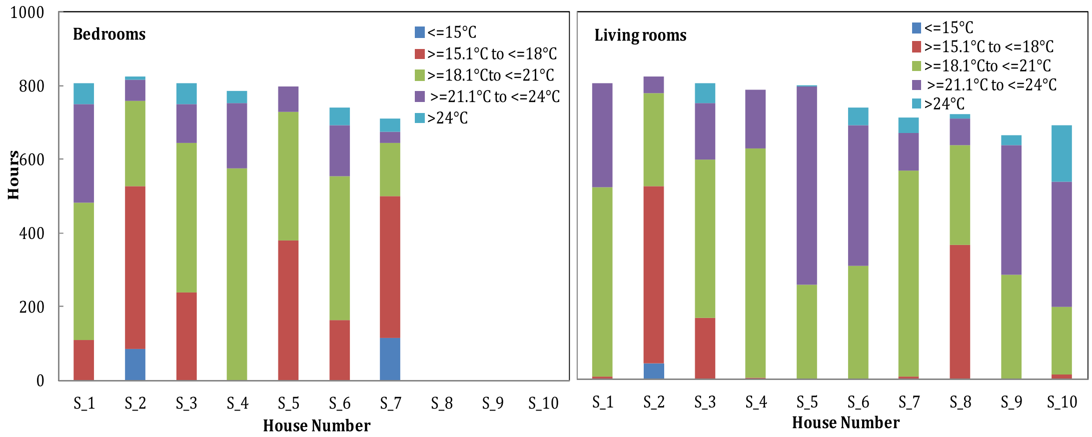


Fig. 8. Temperature ranges and their durations between 22:30 h and 07:30 h in spring in the monitored houses.

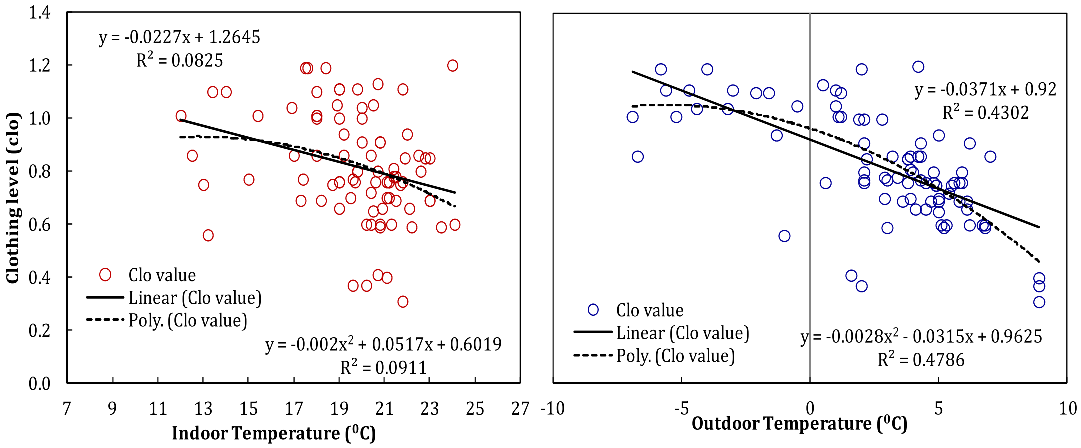


Fig. 9. Clothing characteristics with respect to outdoor and indoor temperature in monitored houses.

to have high clothing levels despite the high temperatures prevailing in the indoor environment. This may be related to the existence of an important radiant temperature asymmetry in the houses. Probable reasons for the phenomenon include un-insulated walls and large glazing areas on external façades [11]. An earlier study showed that clothing level variation is an effective mechanism for overcoming the discomfort caused by radiant temperature asymmetry [11]. The high clothing level found in this study should not be misunderstood as a form of adaptation by the occupants. Even though indoor temperatures are in the 18 °C–23 °C range, occupants in these houses preferred to adopt higher clothing levels.

5.3.2. *Comfort temperature analysis*

Fig. 10 present the relation between TSV (thermal sensation votes) and indoor temperature. The regression coefficient value suggests that the TSVs are influenced by the indoor thermal environment and are more sensitive to indoor temperatures. This finding is supported by the discussion of the radiant temperature issue in the previous paragraph. It also reflects the same (less tolerant to change in indoor temperature) from the clothing pattern analysis. The temperature range corresponding to ±1 TSV is 17 °C–24 °C. This range of temperatures obtained from the comfort survey is consistent with the new EN 15251 standards, which states that, for existing buildings, the range of comfortable temperatures should lie within ±4 °C across winter and summer [8]. The occupants' lower tolerance towards temperature fluctuations makes them more sensitive towards radiant temperature asymmetry from un-insulated walls and large glazing areas. This argument is further supported by the preference of occupants for relatively high clothing levels in these old houses. It is observed from Fig. 2b that the daily maximum and minimum temperatures for the spring monitoring period can exceed 24 °C during May. This temperature range can therefore be expected to be dominant for an even longer time in summer, causing considerable discomfort to the occupants.

5.3.3. *Thermal comfort and occupant behaviour analysis*

Thermal monitoring analysis has revealed that high temperature swings occur in pre-1945 residential buildings. Occupants must therefore take certain kinds of adaptive actions to modify the indoor environment and improve the thermal conditions. Fig. 11 presents the principal reasons for discomfort in these houses. There are four main reasons identified from the analysis, namely low lighting levels, temperature being too low in winter (even though the heating system is ON), difficulties in regulating the temperature and cold sensations from glazing. Two personal adaptive actions are putting on warm clothes and moving to a different room. Fig. 12 shows the frequency of the various adaptive and behavioural actions by occupants that modify the indoor thermal environment in both summer and winter. These actions are in addition to personal adaptations and must be viewed in combination with them. In winter, using window curtains, turning on the heating system and using portable heaters are prominent strategies. In spring, the opening and closing of windows and the use of window curtains are the major adaptive actions. The frequent use of portable heaters in winter raises questions about

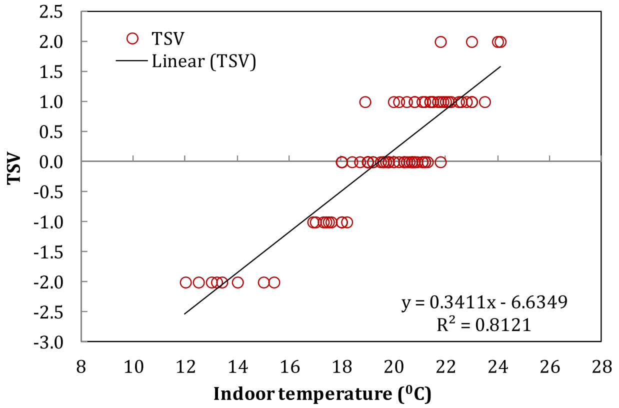


Fig. 10. Relation between TSV and indoor temperature.

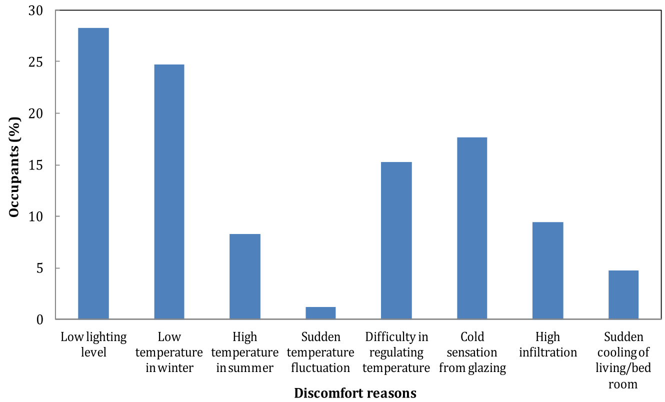


Fig. 11. Reasons for discomfort in monitored houses.

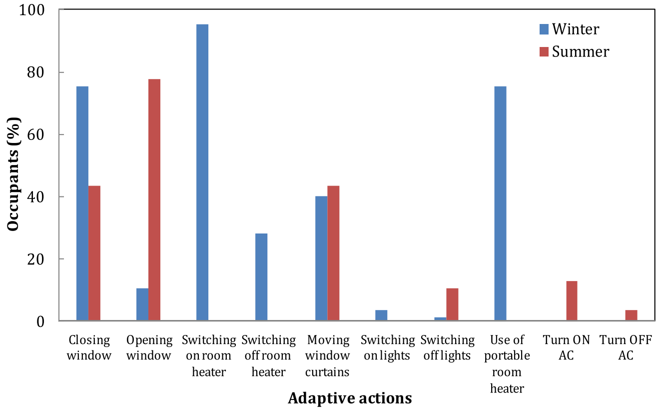


Fig. 12. Adaptive and behavioural actions to modify the indoor environment in monitored houses.

the efficient functioning of heating systems and suggests the existence of non-uniform heating in the living space. The cold sensations in winter and excess direct solar radiation in spring can be attributed to the presence of large glazing areas on the rear and front façades.

The study also collected information about various renovations carried out in buildings over time to support the changing lifestyles and energy requirements and to provide higher comfort levels. The most common interventions are insulating roofs and installation of double-glazing. A significant number of renovations concentrated on glazing, probably because it is the easiest and cheapest intervention that can be made in an occupied building. The other options, such as roof and wall insulation, are less frequent because they are expensive and complex processes for occupied houses. It is also found that renovation or replacement of the heating system occurred in only 30% of houses, whereas 50% of houses have heating systems more than 15 years old. This means that a significant number of houses are still operating with relatively old heating systems.

6. Discussion

The indoor thermal environment can be judged effectively by studying the indoor temperature profile of the house over a long period of time. In this study, indoor and outdoor temperatures are monitored in winter (December 2011 to February 2012) and in spring (March to May 2012) at 10 houses during each season. It is found that different temperature ranges are dominant in bedrooms and living rooms at different times of the day and in different seasons. The analysis clearly shows that, for almost all houses, occupants are mainly concerned about the temperature of the living room in winter and early spring and the temperature is maintained consistently higher than the bedroom. This is related to the living room being a more active space, which deserves consideration when renovating or designing a house. The conclusions of this study are similar to the findings of Lomas and Kane [13], Vadodaria et al. [14] and Rudge and Gilchrist [22]. However, this study goes a step further by conducting a comfort survey and recording the occupants' adaptive actions to support its conclusions. Table 4 shows the dominant temperature matrix. It shows that, in winter, the occupants kept the indoor temperature of the house quite low, in contrast to the recommended temperature range in modern comfort standards. In spring, the indoor temperature could exceed 24 °C and summer temperatures may go even higher. Table 3 shows that, across the two seasons studied, the range of indoor temperatures for both bedrooms and living rooms are 9 °C. This is much higher than the recommended limit in the EN-ISO 15251 and EN-ISO 7730 standards for existing buildings [7]. The analysis also shows that the bedroom temperature fluctuation in winter is less than that for the living room. In winter, the difference between the maximum temperatures for the living rooms and bedrooms remained almost constant throughout the monitoring period. However, during spring, this phenomenon is reversed. The average bedroom temperature fluctuated more as the summer months approached. This study also concludes that a more rapid rise and fall in temperature occurred in bedrooms than in living rooms. The difference between the maximum and minimum temperatures for living rooms decreases from the beginning to the end of the spring monitoring period while remaining time it is constant for bedrooms. At the beginning of the spring monitoring period, the maximum living room temperature is higher than that for bedrooms. However, by the end of the monitoring period, the maximum bedroom temperature could be above that for living rooms, with bedroom temperatures exceeds 24 °C. This could be a cause of considerable discomfort for the occupants in the summer months [8,13]. Fig. 6 reinforces this point by indicating the hours for which the bedroom temperature was higher than 24 °C.

The thermal comfort survey is carried out to record the direct and indirect secondary parameters that influence occupants' perceptions of thermal comfort. It is found that the occupants in pre-1945 buildings are less tolerant towards changing indoor and outdoor temperatures. It is observed that people prefer to adopt relatively high clothing levels despite high indoor temperatures. This supports the existence of issues involving radiant temperature asymmetry. It is also indicated by the use of portable heaters in a large number of houses. The temperature range corresponding to ±1 TSV is found to be 17 °C–24 °C. It is interesting that, despite large fluctuations in indoor temperature and other issues causing discomfort, about 88% of people reported being ‘comfortable’. However, the range and values of comfort parameters observed in these pre-1945 residential buildings would be considered unacceptable according to existing standards [8,13,14]. This shows that the existing standards will tend to underestimate the level of comfort perceived by occupants of historic buildings. Thermal comfort criteria for historical/old residential buildings need to be accommodated in these standards. Functionality analysis shows that the heating cycle in these buildings is highly dependent on family configuration, occupants' preferences and ages. It implies that actual energy consumption is usually far lower than hypothetical assumptions derived from present-day standards.

One of the major limitations of this study is the small number of participants in the thermal comfort surveys, which is caused by time constraints and limited access to pre-1945 houses. However, the study has established that pre-1945 residential houses cannot be considered functionally similar to modern houses. These houses should have a different set of assessment regulations and standards. There is an urgent need for a detailed large-scale study on pre-1945 houses to address the occupants' interaction with their built environment and energy efficiency. The authors assume that the findings of this study will assist policy makers in addressing the complex issue of renovation and energy efficiency in these old houses.

7. Conclusions

This study is carried out to evaluate the thermal performance and thermal comfort status of pre-1945 residential buildings in the city of Liège, Belgium. The study is divided into two parts. The first part involved long-term monitoring of indoor environments and the second part involved a questionnaire-based comfort survey. Indoor environment monitoring enables an understanding of the functionality of pre-1945 houses and the dominant thermal environment at different times of the day during different seasons. In this study, different houses are monitored during the winter and during the spring. The study also collected information concerning adaptive actions by occupants in winter and summer, indoor illumination levels and overall comfort levels. The houses selected for detailed analysis showed that occupant behaviour and family composition greatly affect the functioning and occupant preferences about indoor thermal environments. The occupants' adaptations to the indoor thermal environment of the house and its functioning greatly affect their energy consumption and govern the overall energy efficiency of the house.

The study stresses that occupants behave differently when compensating for the difficulty of maintaining comfortable thermal conditions in their house throughout the day, by adjusting temperatures differently in different rooms at different times of the day, thereby economizing on energy use and optimizing comfort. It is found that occupants of all the monitored houses are functionally more active in their living rooms, which they preferred to be at higher temperatures in winter (socio-culturally important). It is found that occupants are less concerned about matching clothing levels to actual temperatures but preferred a higher clothing level because of higher indoor temperature fluctuations. This study provides a deep understanding of the complex functioning of pre-1945 buildings and the parameters that affect the thermal performance and comfort of these houses. This flags the idea that different houses in the building stock should be treated differently when designing initiatives for energy efficiency improvements. The study argues that the present-day comfort standards fail to estimate the comfort levels in pre-1945 residential buildings accurately and, if applied incorrectly, they may underestimate the actual comfort levels. It is desirable to use present-day comfort standards only with great care if doing economic feasibility studies concerned with the energy-saving potential of these houses.

Acknowledgement

The first author gratefully acknowledges financial support for this work, received in the form of a postdoctoral research grant from the University of Liège.

References

[1] Nicol JF. Comfort and energy use in buildings – getting them right. Energy Build 2007;39(7):737–9.

[2] Georgiadu MC, Hacking T, Guthrie P. A conceptual framework for future-proofing the energy performance of buildings. Energy Policy 2012;47(8):145–55.

[3] Anisimova N. The capability to reduce primary energy demand in EU housing. Energy Build 2011;43(10):2747–51.

[4] Halawa E, Van Hoof J. The adaptive approach to thermal comfort: a critical overview. Energy Build 2012;51(8):101–10.

[5] EN 15251. Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics. Brussels: CEN; 2007.

[6] Nicol JF, Wilson M. A critique of European Standard EN 15251: strengths, weaknesses and lessons for future standards. Build Res Inf 2011;39(2):183–93.

[7] European Parliament and Council. Directive 2010/31/EU of the European Parliament and of the council on the energy performance of buildings. Official J Eur Communities 2010. L 153/13, 18/6/2010.

[8] Olesen BW, Parsons KC. Introduction to thermal comfort standards and to the proposed new version of EN ISO 7730. Energy Build 2002;34(6):537–48.

[9] Wright A. What is the relationship between built form and energy use in dwellings? Energy Policy 2008;369(12):4544–7.

[10] Singh MK, Mahapatra S, Teller J. An analysis on energy efficiency initiatives in the building stock of Liège, Belgium. Energy Policy 2013;62(11):729–41.

[11] Singh MK, Mahapatra S, Teller J. Relation between indoor thermal environment and renovation in Liège residential buildings. Therm Sci 2014;18(3):889–902.

[12] Roberts S. Altering existing buildings in the UK. Energy Policy 2008;36(12):4482–6.

[13] Lomas KJ, Kane T. Summertime temperature and thermal comfort in UK homes. Build Res Inf 2013;41(3):259–80.

[14] Vadodaria K, Loveday DL, Haines V. Measured winter and spring-time indoor temperatures in UK homes over the period 1969–2010: a review and synthesis. Energy Policy 2014;64:252–62.

[15] De Meester T, Marique AF, De Herde A, Reiter S. Impact of occupant behaviours on residential heating consumption for detached houses in a temperate climate in the northern part of Europe. Energy Build 2013;57(2):313–23.

[16] Mlecnik E, Attia S, Van Loon S. Net zero energy buildings: a review of current definitions and definition development in Belgium. In: The proceedings of passive house; 2011 [Brussels, Belgium].

[17] Nicol F, Humphreys M. Derivation of the adaptive equations for thermal comfort in free-running buildings in European standard EN15251. Build Environ 2009;45(1):11–7.

[18] Humphreys MA, Nicol JF. Understanding the adaptive approach to thermal comfort. ASHRAE Trans 1998;104(1):991–1004.

[19] De Dear RJ, Brager GS. Developing an adaptive model of thermal comfort and preference. ASHRAE Trans 1998;104(Pt 1A):145–67.

[20] Nicol JF, Humphreys MA. Adaptive thermal comfort and sustainable thermal standards for buildings. Energy Build 2002;34(6):563–72.

[21] Humphreys MA, Hancock M. Do people like to feel 'neutral'? Exploring the variation of the desired thermal sensation on the ASHRAE scale. Energy Build 2007;39(7):867–74.

[22] Van der Linden AC, Boerstra AC, Raueb AK, Kurvers SR, de Dear RJ. Adaptive temperature limits: a new guideline in The Netherlands: a new approach for the assessment of building performance with respect to thermal indoor climate. Energy Build 2006;38(1):8–17.

[23] Rudge J, Gilchrist R. Measuring the health impact of temperature in dwellings: investigating excess winter morbidity and cold homes in the London Borough of Newham. Energy Build 2007;39(7):847–58.

[24] Auliciems A. Towards a psycho-physiological model of thermal perception. Int J Biometeorology 1981;25(2):109–22.

[25] Fanger PO. Thermal environment – human requirements. Environ 1986;6(4):275–8.

[26] Milne M, Givoni B. Architectural design based on climate. In: Watson D, editor. Energy conservation through building design. New York: McGraw Hill; 1979. p. 96–113.

[27] Becker R, Paciuk M. Thermal comfort in residential buildings – failure to predict by standard model. Build Environ 2009;44(5):948–60.

[28] De Dear RJ, Brager GS. Thermal comfort in naturally ventilated buildings: revisions to ASHRAE Standard 55. Energy Build 2002;34(6):549–61.

[29] Singh MK, Mahapatra S, Teller J. Study on indoor thermal comfort in the residential buildings of Liege, Belgium, CISBAT. 2013. p. 481–6. Lausanne 4-6 September 2013, Switzerland.

[30] ISO 7730. Moderate thermal environment – determination of PMV and PPD indices and specifications of the conditions for thermal comfort. Geneva, Switzerland: International Organization for Standardization; 1994.

[31] Thermal environmental conditions for human occupancy. American Society of Heating, Refrigerating and Air-conditioning Engineers Inc; 2013. ASHRAE Standard 55.