RELATION BETWEEN INDOOR THERMAL ENVIRONMENT AND RENOVATION IN LIEGE RESIDENTIAL BUILDINGS

by

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Indoor thermal environment monitoring has been done in 20 residential buildings of Liege city followed by questionnaire based comfort survey amongst the occupants of 85 houses in order to record their preference and expectations about indoor thermal environment in winter and spring season. It is found from the analysis that change of glazing has a minimum or even sometimes an adverse effect on the existing indoor environment due to the absence of proper insulation of the rest of the building envelope. It is observed that in winter there is a sudden drop in indoor temperature and also overheating in summer. This is due to unplanned installation of glazing which actually increases the fenestration area ratio leading to higher indoor temperature fluctuation and causes discomfort. It is also important that the occupant's preference and expectations as well as overall assessment of indoor environment needs to be consider towards energy efficiency improvement.

Key words: *building stock, energy efficiency, building renovation, thermal comfort, Liege*

Introduction

Energy efficiency of buildings is becoming a serious concern for its sustainability [1, 2]. However, there are very limited concerns on the broad spectrum to which a building energy efficiency and indoor thermal environment complimented to each other [3-6]. Indoor thermal environment is a function of occupant's thermal preference and expectations [4-6]. Hence the occupants are always active towards thermal environment and take adaptive actions to restore comfort. Thermal comfort is the essence of any building design and the occupant's behavior and activity determines the energy consumption of the building. The nature of building and occupant's preference and expectations about comfort are governed by occupant's socio-economic status and socio-cultural expectations [4-7]. In Belgium, the residential buildings accounts for 73% and tertiary buildings account for 27% of primary energy consumption [8, 9]. A significant percentage of buildings in the existing building stock of Belgium is relatively old and thus has a huge potential in energy saving [8-11]. The building sector is one of the major sources of greenhouse gas emissions, thus representing a huge potential towards reduction in GHG emissions by energy efficiency improvement [8, 9]. Most of the researcher emphasises the importance of addressing local/regional energy driven issues and policy requirements to improve the energy efficiency. Keeping this in view, European Commission

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(EU) formulated Energy Performance Building Directive, a building regulation with an objective towards harmonization of rules and regulations in all member countries [12]. It adopts a holistic approach in the overall energy performance assessment of both new and old buildings [12].

In this study, it has been tried to address the issue of thermal comfort and energy efficiency in historical houses of Liege city. This study also tries to explore the relationship between the renovation and modification carried out in these building with the indoor thermal environment. These historical buildings are constructed with material and technology when no building energy efficiency norms were in place. Since these buildings are more than 70 years old they went through renovation as well as modifications in last few years to support present life style and energy needs. However, most of the time renovations were partial. Still there is a gap in the understanding these renovations and their effectiveness or influence on the thermal comfort and indoor thermal environment in these buildings. In this study, long term monitoring of indoor environment in 20 houses (10 each in winter and spring) followed by comfort survey in 85 houses (including 20 monitored houses) has been carried out. The results of the monitoring and responses collected during comfort surveys are analysed to understand the impact of renovation on thermal comfort and indoor thermal environment.

Building stock of Liege

Belgium is divided into three regions namely Flemish region, Brussels capital region, and Walloon region. Liege city is in Walloon region and also know as economic capital of Walloon region. A statistical analysis of the information collected through the "General Socio-economic survey 2001" and "Housing quality survey 2006" for Walloon region reveals interesting information about the characteristics of historical buildings in Liege. About 55% of houses have built-up area lies between 51-100 m^2 and 16% and 17% with built-up area of 0-50 m^2 and 101-150 m^2, respectively, [8, 9, 13]. It also needs to mention that 67% of buildings have massive walls and the remaining 33% have composite walls [8, 9, 13]. Most importantly 80.5% of buildings do not have insulated walls and 50% have no roof insulation. It is also observed that windows of 60% of buildings are fully insulated with double glazing, 18% have partially insulated glazing and 22% does not have any insulated glazing [8, 9, 13]. This is reflected in the heating energy consumption per year as it varies from 383 kWh/m^2 (for building constructed before 1863) to 127 kWh/m^2 (building constructed between 2001-2012) [8, 9, 13]. Above reason is also responsible for 70% higher average heating energy consumption in the residential buildings of Belgium than the EU average and stands at 348 kWh/m^2 per year [8, 9, 13]. On positive side, the analysis reveals that 75% of Liege building stock has central heating system and use natural gas as fuel but 74% of boilers are relatively old and need regular monitoring or renovation or need to be replaced to improve the energy efficiency [8, 9, 13].

Methodology

Recent studies show that the growth rate of new construction is only 0.2% per year and the share of relatively old buildings (constructed before 1945) stands at 68.33% of present building stock [8, 9, 13].Buildings constructed before 1945 falls into five different typologies, namely Maison Modeste (Modest house), Maison Moyenne (Average house), Maison De Maitre (House), Maison Historique (Historic house) and Maison apartments (Apartment house). These typologies have distinct building features like height and width, window features and built-up area. These historical houses went through renovation as well as modifications in last few years. Hence, it is important to understand these renovations in the contrast of their effectiveness or influence on the thermal comfort and indoor thermal environment. By carrying out partial renovations through high end technologies to improve the energy efficiency without any firm basis, doesn't resulted the expected results. This argument is firmly supported by number of recent studies highlighting that buildings energy efficiency is not merely a function of advance energy efficient materials and technology but is also influenced by occupants socio-cultural, socio-economic and behaviour in the context of expectations and preferences. In this regard, it is important to know the present functioning of historic houses (before 1945) and preferred indoor thermal conditions of the occupants. Keeping this in mind, indoor thermal conditions of twenty residential buildings of Liege, all built before 1945, have been monitored. This monitoring has been combined with a detailed interview of occupants to record their preference and expectations about indoor thermal environment (closed questionnaire). Figure 1 shows the methodology followed to carry out this study. Various building design parameters like external façade characteristics, materials used for construction, built-up area, type of heating system and renovations carried out were also recorded during visits to the houses. Occupants were also questioned about the various strategies that they follow to make their house comfortable. Measured data along with thermal comfort survey information are used to evaluate the thermal performance of the houses.

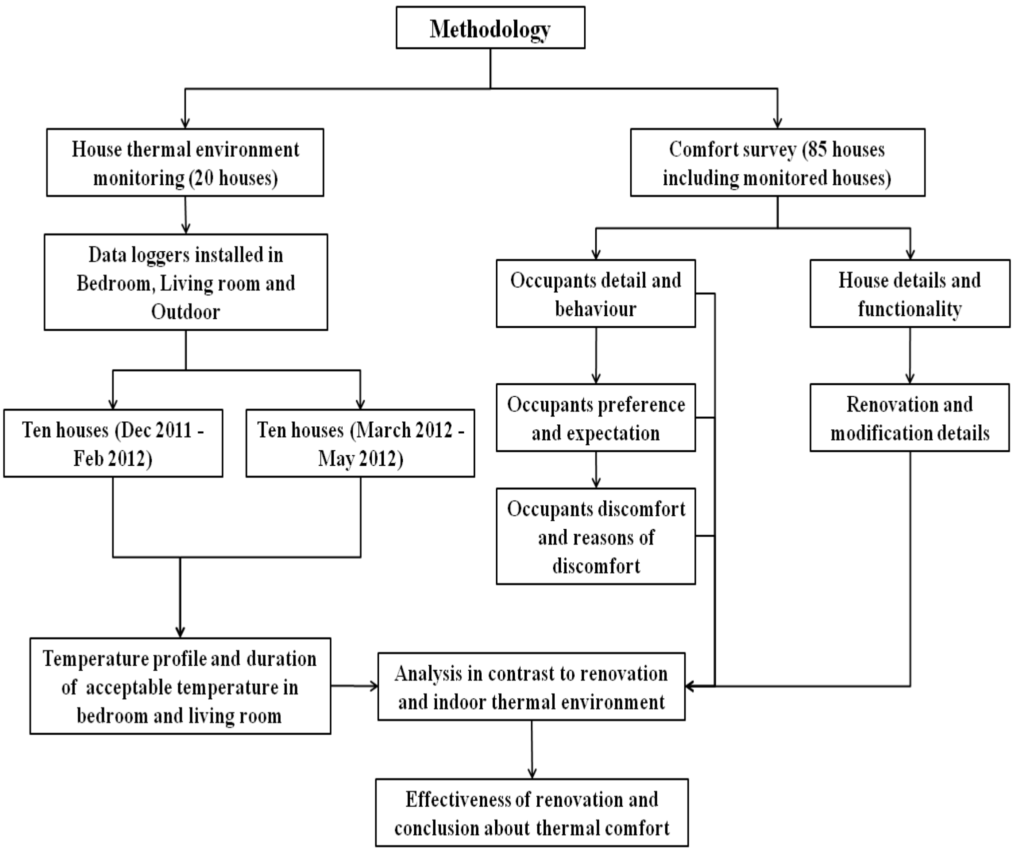

Figure 1. Methodology of the study

Thermal monitoring and comfort survey

Table 1. Details of houses monitored in winter and spring with indoor temperature swing

House number	Typology of houses and year of construction	House arrangement	Insulation (wall and roof)	Magnitude of average swing in temperature during monitoring period [°C]			
				Bedroom		Living	
				Start	End	Start	End
W_1	a, 1919-1945	Terraced	No, No	1-3	2-4	6-8	4-8
W_2	a, 1875-1918	Terraced	Yes, Yes	1-2	1-2	3-4	4-6
W_3	b, 1875-1918	Terraced	No, Yes	4-5	2-3	4-5	4-5
W_4	b, 1875-1918	Terraced	Yes, Yes	3-4	3-4	3-4	3-4
W_5	c, 1875-1918	Terraced	No, Yes	0.5-1	0.5-1	2-3	2-3
W_6	c, 1875-1918	Terraced	No, Yes	2-3	2-3	3-6	3-6
W_7	d, 1919-1945	Terraced	No, No	2-6	1-7	2-5	2-5
W_8	b, 1875-1918	Terraced	No, Yes	2-6	2-7	4-8	4 -9
W_9	c, 1875-1918	Terraced	No, Yes	2-4	0.5-1	2-4	2-4
W_10	c, 1875-1918	Terraced	Yes, Yes	2-4	3-4	4-5	4-7
S_1	c, 1875-1918	Terraced	No, Yes	1-2	2-3	3-4	1-2
S_2	c, < 1875	Terraced	Yes, Yes	0.5-1	0.5-1	4-5	0.5-1
S_3	c, 1919-1945	Terraced	Yes, Yes	3-4	1-2	4-5	2-3
S_4	c, 1919-1945	Terraced	No, Yes	0.5-1	0.5-1	2-3	1-2
S_5	c, 1919-1945	Terraced	No, Yes	1-2	2-3	2-3	1-2
S_6	c, 1875-1918	Terraced	Yes, Yes	0.5-1	1-2	1-2	1-2
S_7	c, 1875-1918	Terraced	No, Yes	1-2	1-2	1-2	1-2
S_8	c, 1919-1945	Terraced	No, Yes	n.a.	n. a.	2-3	2-3
S_9	c, 1875-1918	Terraced	Yes, Yes	n.a.	n. a.	2-4	1-2
S_10	d, 1919-1945	Terraced	No, No	n.a.	n. a.	1-2	1-2

W – winter, S – spring; Typology of houses: a – Maison De Maitre; b – Maison Modeste; c – Maison Moyenne; d – Apartments; n. a. – not available

Monitoring of indoor conditions within the first ten houses was carried out during the winter season (November 2011 to February 2012), when the heating system was ON in most of the houses. Monitoring of second set of ten houses was carried out in spring season (March to May 2012), when heating system in most of the houses was switched OFF. Thermal comfort surveys were carried out in 85 houses (including monitored houses) between 17:00 and 20:00 hours on week days and from 11:00 to 20:00 hours on weekends so as to ensure enough time to collect information from the occupants. For comfort surveys, a hand held data acquisition system (Environmental meter, Omega instruments, UK) was used to measure local temperature and relative humidity at body height (1.1 m from ground). An average of 5 measurements was considered for analysis in order to minimize the errors. The long term monitoring of indoor conditions includes the measurements of temperature (inside and outside house), relative humidity (inside and outside house) and illumination level (inside and outside house). All these parameters were measured through data loggers (HOBO-U12 RH/Temp/ Light/External Data Logger, USA). The temperature sensor accuracy is ± 0.35 °C, the humidity sensor accuracy is ± 2.5% RH and the light intensity measurement accuracy is ±2 lumen/ft^2, respectively. All these parameters were recorded at an interval of 30 minutes. The selected houses for this study were kept under normal operation throughout the monitoring period. No restrictions were imposed on the occupants and were advised to carry out their as usual living conditions. This was necessary to get the monitoring results close to real situation. Table 1 provides the type, construction period and main characteristics of the twenty houses monitored during this study. It can be observed from tab. 1 that most of the houses are over 100 years old. The questionnaire for comfort survey was designed in such a way that it addresses the objective of the study as well as to provide enough specific and subjective information to draw meaningful conclusions. Data collected during comfort survey and through data loggers were further processed and analyzed in order to evaluate the status of comfort prevailing in these houses.

Results and discussion

In the present study both thermal comfort survey and indoor thermal environment monitoring are being carried out simultaneously. In the following sections data collected during monitoring of houses and comfort surveys are analysed in a systematic manner to draw the meaningful conclusions.

Renovation in houses

This study is focussed on thermal performance and thermal comfort of the historical building stock (constructed before 1945) in Liege city. These houses are quite old (tab. 1) and are constructed with material and technology when no building energy efficiency directive were in place. It is also a fact that there has been a drastic change in socio-economic status, lifestyle and accessible technology over the last 50 years. So to meet the present day lifestyle needs and also due to rising constraints on energy economics and awareness about energy efficiency and environmental concerns, these houses went through partly modifications and renovations [14-16].

It is found from the analysis that the most common interventions in these houses are installation of double glazing and insulating roofs. It is also found that renovation or replacement of heating system is only in 30% of houses whereas in 50% of houses the heating system is more than 15 years old. It means that a significant number of houses are still operating with relatively old heating systems. High level of renovation work is concentrated on glazing because of low cost and less complexity supported by tax incentive by government on renovation of windows with double glazing. Renovation of roofs and walls are less frequent because insulating roof and walls is financially intensive and is a complex process when applied in occupied houses. The energy bills of the monitored houses are analysed to look into the effectiveness of renovations in terms of energy savings. However, it has been found that the energy savings is not reflected in the energy bills. This reveals that an integrated approach in renova ting the houses to improve the energy efficiency was not adopted. Especially indoor thermal comfort was not duly considered by these renovations thus nullifying the energy saving. Four prominent discomfort reasons are found from the analysis, namely low lighting level, existence of low temperature in winter, difficulty in regulating temperature and cold sensations from glazing.

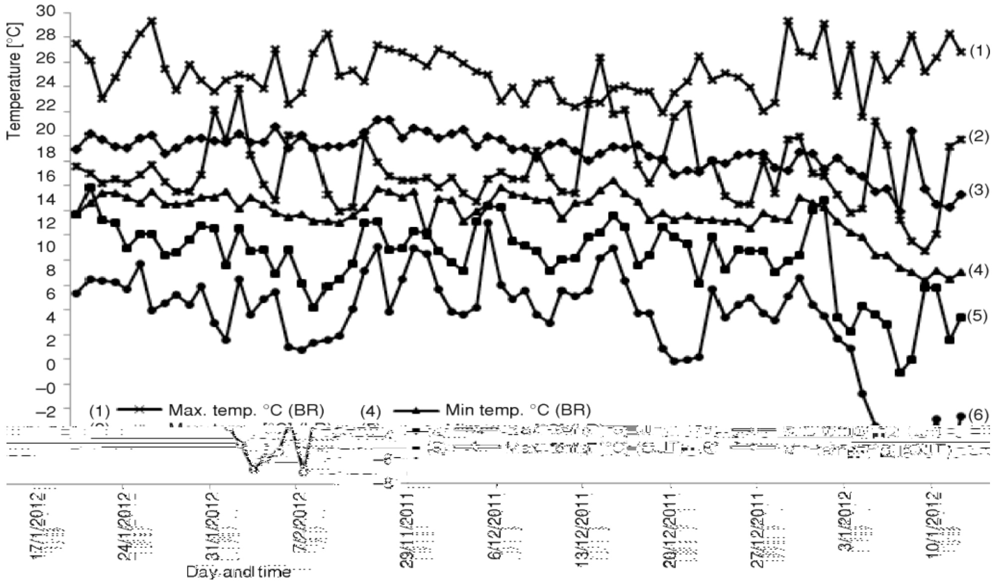

Figure 2a. Temperature profile in winter season (house W_8)

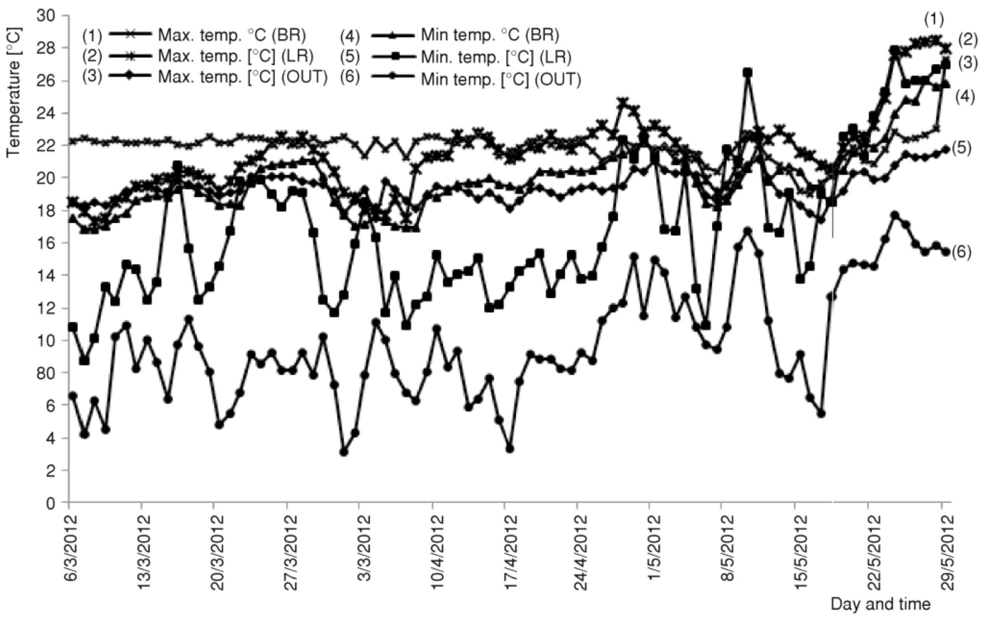

Figure 2b. Temperature profile in spring season (house S_1)

To overcome discomfort, occupants take various adaptive measures at personal level as well as to modify the existing indoor environment. It is found that the most prominent adaptive action is changing clothing level (putting warm clothing) and moving to different room (warmer room). It is also found that in winter, operation of window and curtains, heating system and use of portable heaters are prominent. In spring, only operation of window and curtains are the major opportunities used by the occupants to modify the indoor environment.

High percentage of use of portable heaters suggests the existence of a non-uniform heating in the living space. It is found that high glazing area on rear and front facade of the houses are responsible for cold sensations in the living space in winter and excess direct solar radiation in the living space in spring. During the comfort survey occupants also reported that the non-existence of financial incentive and high renovation costs are the major hurdles to improve the energy performance of the buildings. This conclusion is also supported by the high heating energy consumption in these houses [8, 17, 18].

Thermal performance of monitored houses

Thermal performance study of houses is an important way to evaluate their performance with respect to persistent indoor temperature and thermal comfort against outdoor temperature variation. Figures 2a and 2b present the typical temperature profile in a house at winter and spring seasons. Table 2 present the indoor and outdoor mean temperature profile and comfort status in 20 houses where detailed monitoring are carried out. Ten houses are first monitored in the months of December 2011 to February 2012. These house number starts with a prefix 'W' denoting 'winter' season. Next ten houses monitored in the months of March 2012 to May 2012 and house numbers start with a prefix 'S' denoting 'spring' season. Mean temperature of bedroom, living room and outdoor over the monitoring period is presented in tab. 2. It is found from tab. 2 that temperature in bedroom and living room in all houses is maintained at different level. It can also conclude that the occupants in the age group of 40-60 years and above prefers relatively high temperature in both the bedroom and living rooms and also prefers less difference between bedroom and living room temperatures.

The difference between living room and bedroom temperature is more in winter compared to spring. It can be concluded from the temperature profile that living room in all the monitored houses is functionally more active (occupied for more hours in a day) and preferred to be at higher temperature in winter. It is found from winter recorded data that the decay in the temperature of living room is rapid compared to bedroom in all houses. This implies that living room is losing more heat in the winter months. It is observed from the tab. 2 that the occupant of house number W_2 and W_5 consider the house indoor thermal environment as comfortable. It is found that the temperatures in both these houses are well maintained though the effect of low outdoor temperature in the month of February 2012 on indoor temperature is visible. This phenomenon was common in all the monitored houses. It can also be concluded that in these houses radiant temperature asymmetry is quite prominent due to the presence of non-insulated walls and large glazing areas. This conclusion is supported by the high indoor clothing level of occupants and temperature corresponding to thermal sensation vote. It can be concluded that the heating system in the houses is not working effectively. This problem is related to the presence of non-insulated walls and large glazed area on front and rear facades of the houses. It can also be concluded that the glazing is an important cause of discomfort in winter season (cold sensation).

It is found from temperature profile of the monitored houses that there is a sharp increase in bedroom maximum temperature at the end phase of monitoring period (fig. 2b). Looking at the trend, it can be concluded that there must have been an overheating scenario in bedroom during the last week of May 2012 in most of the houses. This may be because in most of the houses living room is in ground floor and its façade are less exposed to sunlight whereas the bedrooms are on the top floor of the house and receives sunlight throughout the day till late afternoon in both spring/summer season. In most of the houses an interesting pattern is observed where the difference between the maximum temperature and minimum temperature of living room goes on decreasing from start to end of monitoring period but for bedroom it remained constant. It also found that rise and decay of temperature in bed room is at higher rate than that of living room and this phenomenon is just opposite to the observation of winter months. It is found from the indoor temperature profile that 24 hrs average temperature of the living room is almost at constant level whereas bed room is showing fluctuations. This fluctuation in bedroom increases as it gradually moves towards summer season. In most of the cases the average temperature does not represent the actual thermal environment as averaging of temperature over 24 hours suppress the actual swing of temperature over 24 hours. So in this study, due consideration has given to daily maximum and minimum temperature variation over the monitoring period to evaluate the daily temperature swing (tab. 1). The extent of swing in indoor temperature defines the level of comfort in the house and its functioning (lower the minimum temperature the more is the heating energy consumption in winter).

Table 2. Temperature profile and comfort status in monitored houses in winter

House number	Mean indoor temperature [°C]		Mean outdoor temperature [°C]	Clo	Indoor temperature corresponding to TSV]°C]	Overall comfort*	TSV	Met (20 min before voting)	Age of occupants (years)
	Bed-room	Living room							
W_1	16.76	17.23	4.87	0.86	12.5	b	-2	2.4	20-40
W_2	18.56	22.00	3.03	1.11	21.8	a	2	1.6	40-60
W_3	11.17	13.16	3.82	1.1	13.4	b	-1	2.4	20-40
W_4	14.19	13.92	3.92	1.01	12.8	b	-1	1.2	20-40
W_5	14.34	18.16	5.74	1.01	15.4	a	0	2.4	40-60
W_6	17.16	19.06	5.46	0.31	19.6	b	1	2.4	20-40
W_7	14.37	15.96	6.08	0.56	13.2	b	-2	1.6	20-40
W_8	13.90	20.57	4.94	1.04	16.9	e	2	1.6	40-60
W_9	15.06	19.39	4.96	1.19	18.4	b	0	1.6	20-40
W 10	17.70	17.77	6.51	1.19	17.6	b	0	1.6	20-40
S_1	20.63	20.94	13.38	0.94	19.2	b	0	1	40-60
S_2	17.56	17.88	13.34	1.05	18.2	b	1	1.2	60-70
S_3	19.65	20.64	13.39	0.77	15	b	-2	1.6	40-60
S_4	20.59	20.69	13.58	0.86	18	a	-1	1.6	40-60
S_5	18.61	21.61	12.26	0.69	17.3	b	1	1.6	60-70
S_6	19.65	21.56	13.06	1.11	19.8	b	0	1.6	40-60
S_7	17.29	20.18	13.01	1.19	17.5	c	-1	1.2	40-60
S_8	n. a.	18.74	12.02	0.81	21.4	a	1	1.2	40-60
S_9	n. a.	21.75	14.03	0.77	19.6	b	0	1.2	40-60
S_10	n. a.	22.54	13.46	0.69	21.5	b	1	1.2	20-40

W – winter; S – spring; *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 – n. a. – not available

Comfort status in residential houses of Liege

Comfort is a subjective and contextual response of the people. It is governed by the past and present experiences, socio-economic and socio-cultural setup of the occupant [3, 5].

It also determines the occupant's acceptance, behaviour in a built-environment and the energy consumption of the building [4, 7, 19]. It is now an established fact that range of comfort temperature for occupants; exposed to different climates are different [3-5]. In other way, the occupants living in buildings which are being heated or cooled have different expectations and perception about comfort than the occupants living in free running buildings [3-5]. Residential houses of Liege city are heated/cooled and above all the houses selected in this study are more than 100 years old with high heating energy consumption. So it becomes necessary to study the status of comfort in these houses. Table 3 presents the comfort survey parameters of the study. Questionnaire based thermal comfort survey is carried out from January 2012 to May 2012 covering 85 occupants in 85 houses (including 20 monitored houses), falling under five building typologies.

Table 3. Comfort survey parameters

Clothing level (clo)		0.3 to 1.11		
Metabolic rate (met)		1 to 1.4		
Number of subjects		85		
Number of houses under different typology				
Maison Modeste	Maison Moyenne	Maison De Maitre	Maison Historique	Maison Apartments
19	37	16	5	8
Survey time		January 2012 to May 2012		
Subjects age (years)				
20 > age	20 < age < = 40	40 < age < = 60	60 < age < = 70	70 < age
6	20	37	10	12
Subjects gender				
Male		50		
Female		35		
Construction year of houses				
Before 1875	1875 < age < 1918		1919 < age < 1945	
2	41		42	

Thermal comfort monitoring has been carried out in ten houses during the period from December 2011 to February 2012 and another ten houses in the months of March 2012 to May 2012. From the recorded data, the duration (in hours) of a range of temperature existed in living room and bedroom in all these houses are analysed. Figures 3a to 3d represents the duration (in hours) for which different temperature ranges existed in bedroom and living room respectively during the monitoring period. It can be concluded from fig. 3a and fig. 3b that in most of the houses, for maximum duration, bedroom temperature is less than 15 °C and lies in the range between 15.1 °C to 18 °C during winter period monitoring. However, in the case of living room, it is found that for maximum duration temperature is in the range of 15.1 °C to 18 °C and 18.1 °C to 21 °C.

It is found in the house W_3 and W_4 that the temperature in living room is less than 15 °C because during the monitoring period living room in these two houses was under renovation. It is also found that in the house number W_2 relatively high temperature is maintained in living room and bedroom because owner of the house was ill and preferred relatively high temperature. It is found from fig. 3c that the bedroom temperature lies in the range of 15.1 °C to 18 °C and 18.1 °C to 21 °C. It is also observed that there are instances when bedroom temperature reaches the range 21.1 °C to 24 °C and even exceeds 24 °C for certain period of time. However, according to CIBSE-2006 guidelines, the threshold temperature for bedroom is 23 °C during daytime and for living room the threshold temperature is 25 °C. Hence, if the temperature exceeds 23 °C or 25 °C in bedroom or living room respectively, then it becomes uncomfortable for the occupants [19]. It is found in fig. 3d that the temperatures in the living room of most of the houses are in the range of 18.1 °C to 21 °C and 21.1 °C to 24 °C. It is observed that the temperature in the living room crosses 24 °C. House S_2 and S_8 operate air conditioner so for significant duration living room temperature lies in the range of 15.1 °C to 18 °C.

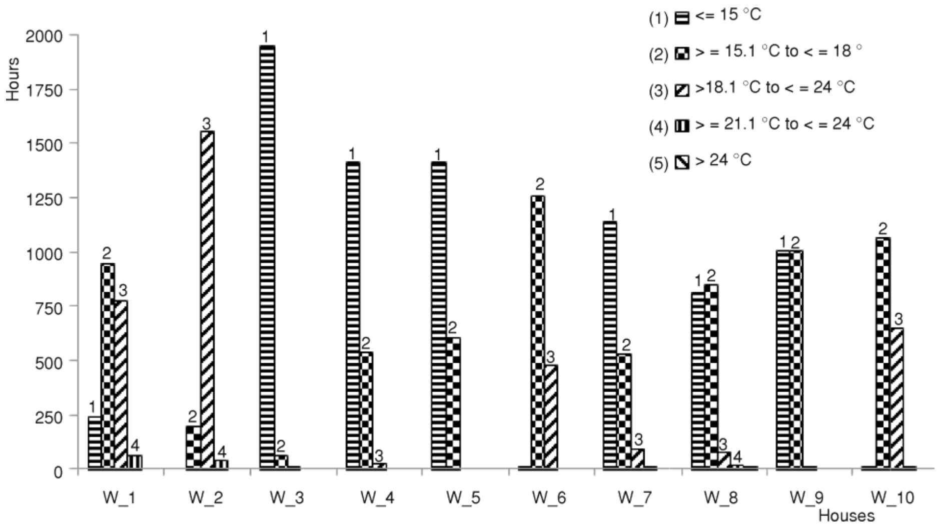

Figure 3a. Temperature range and duration of various houses: bedroom (winter monitoring)

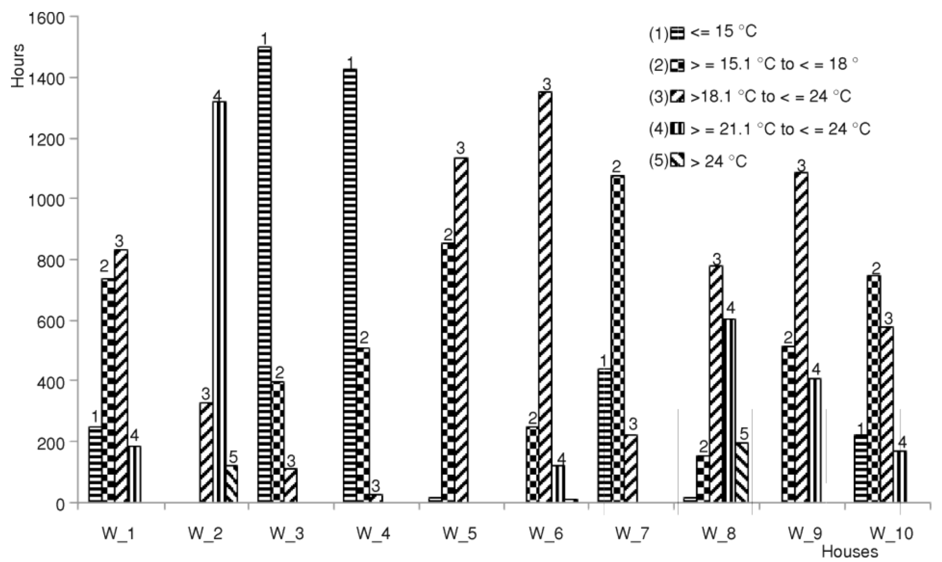

Figure 3b. Temperature range and duration of various houses: living room (winter monitoring)

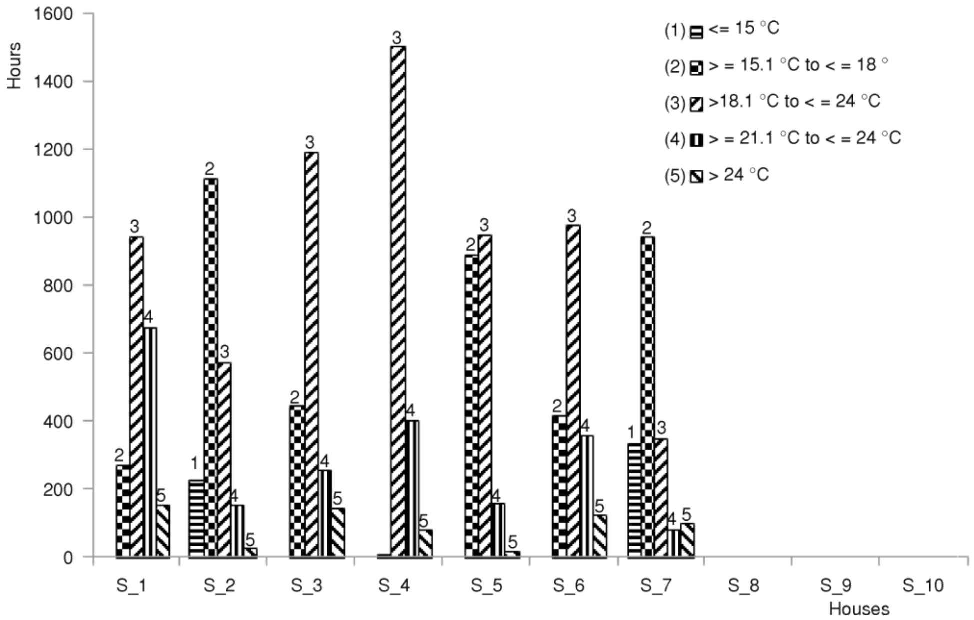

Figure 3c. Temperature range and duration of various houses: living room (spring monitoring)

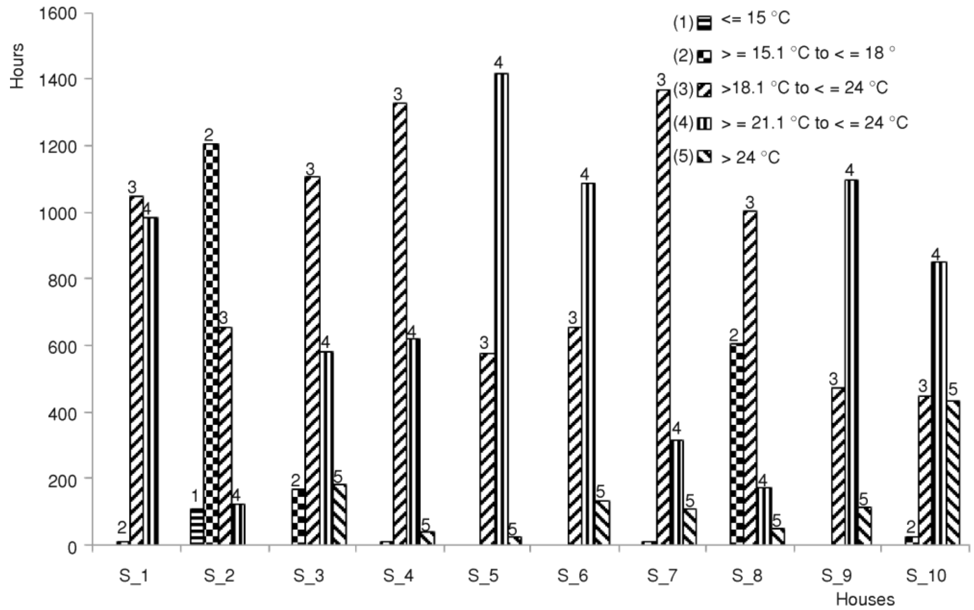

Figure 3d. Temperature range and duration of various houses: bedroom (spring monitoring)

As per revised EN 15251 standard and ASHRAE 55-2010 (adaptive thermal comfort concept is incorporated) the range of acceptable temperature range in the living environment in winter is 20 °C to 24 °C and in summer the range is 23 °C to 26 °C [20, 21]. The analysis in this study reveals that the temperature in the bed room reached 28 °C in May month (start-

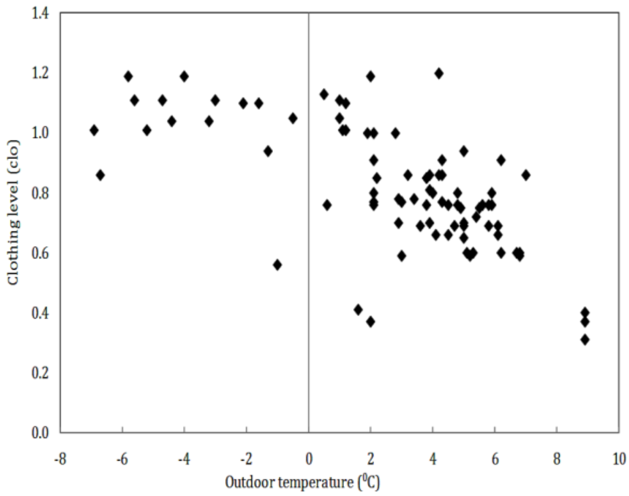

Figure 4a. Clothing level against outdoor temperature

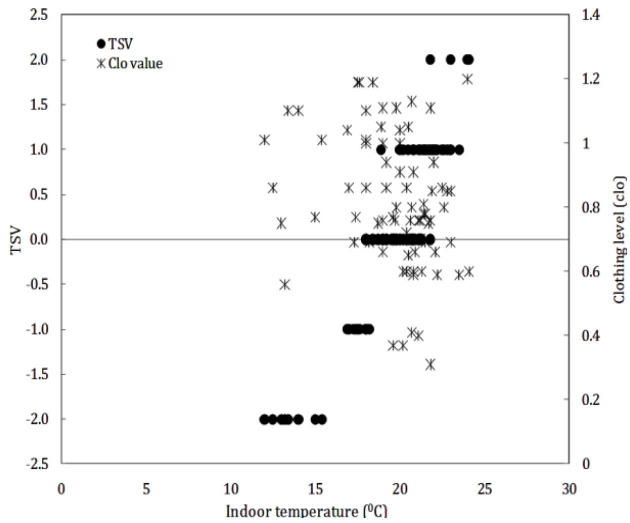

Figure 4b. Thermal sensation vote and clothing level against indoor temperature

ing of summer). So it can be concluded that in summer months bedroom temperature crosses the comfortable range. It is found during the survey that in most of the houses 60% to 80% of rear and front facade area is glazed so in summer direct sun light entering inside the living space responsible for drastic rise in indoor temperature. It can be concluded that preferred temperatures in living room and bedroom are different during different seasons of the year. This also supports the conclusions of previous section.

Figures 4a and 4b represents the preferred clothing level against outdoor temperature and clothing level and thermal sensation vote against indoor temperature. Clothing level adjustment is an important adaptation process to restore the comfort at different temperatures [3-5]. It has been found that clothing values are scattered from 0.3 to 1.12 clo with the outdoor temperature range from 6.9 °C to 8.9 °C. It is found from clothing pattern profiles that the relationship between clothing values and outdoor or indoor temperature is weak. This suggests that occupants in the houses are less tolerant to clothing value with increase or decrease in temperature. This finding is contrary to what observed in case of free running buildings [3-5]. It is found from fig. 4b that there is a large variation in clothing level (0.3 clo to 1.12 clo) corresponding to Thermal Sensation Votes (TSV). This is very interesting phenomenon and supports the argument of existence of radiant temperature asymmetry in the houses (existence of non-insulated wall and large glazing areas on external facade) and clothing level adjustment is one of the prominent adaptive actions to overcome the discomfort caused by radiant temperature asymmetry.

Figure 4b represents the influence of indoor temperature on thermal sensation and clothing pattern of the occupants. This analysis also found that occupant's thermal sensation is strongly influenced by the indoor environment temperature but very weakly related with the outdoor temperature. This supports the argument that occupants of mechanically heated and cooled environment shows less adaptation towards outdoor temperature fluctuation.

Temperature range corresponding to ±1 TSV is 17 °C to 24 °C. This result is being validated by new EN15251 standard where it states that in existing buildings the range of comfort temperature ±4 °C across winter and summer season [20]. Occupant's lower tolerance towards temperature fluctuation also makes them more sensitive towards radiant temperature asymmetry from non-insulated walls and large glazing area. This argument is further supported by the relatively high clothing level of occupants in these historical houses.

It can be concluded that occupants in these houses prefer higher clothing level even though indoor temperature is in the range of 18 °C to 23 °C (fig. 4b). Though the occupant's shows low clothing level related adaptation but prefer high clothing level because of high indoor temperature fluctuations (tab. 1). It is also found form the analysis that occupants are not satisfied with the existing lighting level in the house. They wish brighter light in the indoor environment. In daytime when only natural light is used then the depth of the room plays an important role. So the rooms with large glazing area and less depth shows better natural lighting level.

Conclusions

The conclusions are based on the analysis of data collected from monitored houses and comfort survey. Analysis of the collected data shows that different types of renovation were being carried in houses at different years showing a lack of integrated approach. Though the occupants of the houses are quite aware about benefits of energy efficiency and benefits of insulation but high renovation cost and non-existence of financial incentive is the major hurdle in adopting integrated approach in renovation of the houses. This lack of integrated approach is also preventing occupants from realizing full benefits of renovation in terms of improved energy efficiency and thermal comfort.

It has been found that existence of large glazing area on rear and from façade is responsible for cold sensation in the living space. Thermal performance study of the monitored houses shows that occupants in the houses prefer different temperature in bedroom and living room. It has been found that living room in all the monitored houses are functionally more active and preferred to be at higher temperature in winter. It is found that in spring season rise and decay of temperature in bedroom is at higher rate than that of living room and this phenomenon is just opposite to what has been observed in winter months. Age of the occupants also influenced the indoor thermal environment. Occupants in the age group of 40-60 years or more preferred warmer indoors compared to occupants in the age group of 20-40 years. In summer, it has been observed high fluctuations and sharp increase in bedroom temperature leads to the overheating. Also in summer living room temperature has less fluctuation compared to bedroom. In this study, it has been found that occupants of these houses are less tolerant to clothing level against varying temperature but prefer higher clothing level because of higher indoor temperature fluctuation. It is found that thermal sensations of occupants are weakly related to prevailing outdoor thermal environment and strongly related to prevailing indoor temperature. It can also conclude that large number of occupants uses portable heaters to overcome the discomfort caused by non uniform heating in living space (radiant temperature asymmetry). Though most of the occupants reported overall comfort level in the house as moderate but are found not to be satisfied with the indoor lighting level and preferred brighter lighting level. This study provides a deep understanding on the complex functioning of the building and parameters that affects the thermal performance and comfort of these houses.

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