In-situ analysis of thermal performance of dwellings of the medieval center of Cahors befor thermal rehabilitation

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IN-SITU ANALYSIS OF THERMAL PERFORMANCE OF DWELLINGS OF THE MEDIEVAL CENTER OF CAHORS BEFORE THERMAL REHABILITATION

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Abstract *As other historical centres in Europe, the centre of Cahors – in the south west of France - is characterized by its historical heritage, but also by its high level of degradation, high vacancy rate of the dwellings and fuel poverty of its inhabitants. Consequently, the energy retrofit of the old housing stock is urgent and relevant. For this, the city council of Cahors had created several partnerships with Universities, craftsmen, and architects in order to elaborate sustainable technical solutions. The energy retrofit solutions have to preserve historical details, to be sustainable, to create a healthy indoor climate and also to preserve the building from pathologies.*

In-situ measurements have been running in two medieval apartments to study indoor comfort in the main room (room and wall temperatures, indoor relative humidity) and also some parameters in the outer wall such as humidity, temperature variations and heat transfer (U value). A large masonry brick and a timber frame wall have been monitored in summer and winter conditions, before retrofitting.

Large thickness of wall, inhomogeneity of construction, aging of materials and uncontrolled indoor environment - in part due to natural ventilation - make difficult obtaining accurate and relevant results by computer simulations. The onsite campaign, offering more realistic boundaries, permits to offer a better understanding of thermal behaviour of historical buildings.

1. INTRODUCTION

Nowadays, the rising energy price causing more fuel poverty and the awakening to the ecological emergency explained the growing interest toward energy saving and efficiency of buildings. Buildings, due to their high energy needs, mainly due to winter heating and summer cooling, represent one of the sectors most involved in the reduction of energy consumption. In France, new buildings represent only 1% of the building stocks. For this reason, low carbon retrofitting of existing buildings is an important factor in the energy transition. The centre of Cahors is characterized by its historical heritage, so it’s subject to specific regulations and needs adapted methods of intervention for refurbishment. Indeed, rehabilitations modify hygrothermal equilibrium of the walls and rooms and may can provoke pathologies as dew point between wall and insulation or mould growth. [1]. That’s why, a good understanding of old building behaviour is a pre-requisite for building rehabilitation work.

Two basic approaches are used to access building long-time performance. Commonly, the thermal performance is studied through a computational modelling combined with experimental assessment of material properties that are used as input data. However, most of the models were calibrated on modern buildings and do not to represent historical buildings. Numerous factors affect the accuracy of computational modelling, as the inhomogeneity of historical masonry that is usually formed by different walling materials and mortars, the accuracy and availability of measured material parameters [2]. The natural ventilation is also hardly well-simulated. Furthermore, the dense urban morphology of historical centre generates a microclimate; the available climate data to run a simulation with computational models usually come from airport weather stations which are reliable indicators of regional weather patterns, but not necessarily representative of microclimatic conditions. [3]

The second approach is the setting up of onsite campaign. This process is often more expensive and more time consuming than computer simulation, but when considering the multitude of factors affecting the computational modelling of historical buildings, an in-situ analysis represents a relevant method to access building thermal behaviour. On this account, two buildings of the centre of Cahors have been monitored in summer and winter conditions, before retrofitting. Final objective of the campaign will be to compare measured thermal comfort pre and post retrofits.

2. CASE STUDY BUILDINGS AND MONITORING CAMPAIGN

2.1. Studied dwellings

Two buildings have been chosen as being representative of the dwellings of the historical centre of Cahors. Different criteria as the implantation, the rate of adjoining, the constructive typology and the construction materials have been taken into account. The two dwellings are respectively built with large masonry brick walls (40 cm thickness) and timber frame fulfilled with brick walls (14cm thickness) (see Picture 1) representing two of the three main constructive typologies present in the historical centre.

Studied buildings are located in a dense district with high level of adjoining buildings and surrounding shading buildings and so correspond to the urban morphology of the historical centre of Cahors, in term of density, compacity, contiguity and solar admittance as morphologic indicators. [4]

Occupants having significant impact on energy consumption and ambiance, monitored dwellings are chosen without occupant in order to understand intrinsic physic characteristics of buildings.

In order to focus on the opaque envelop study, shutters of the windows remained closed during the whole monitoring period.

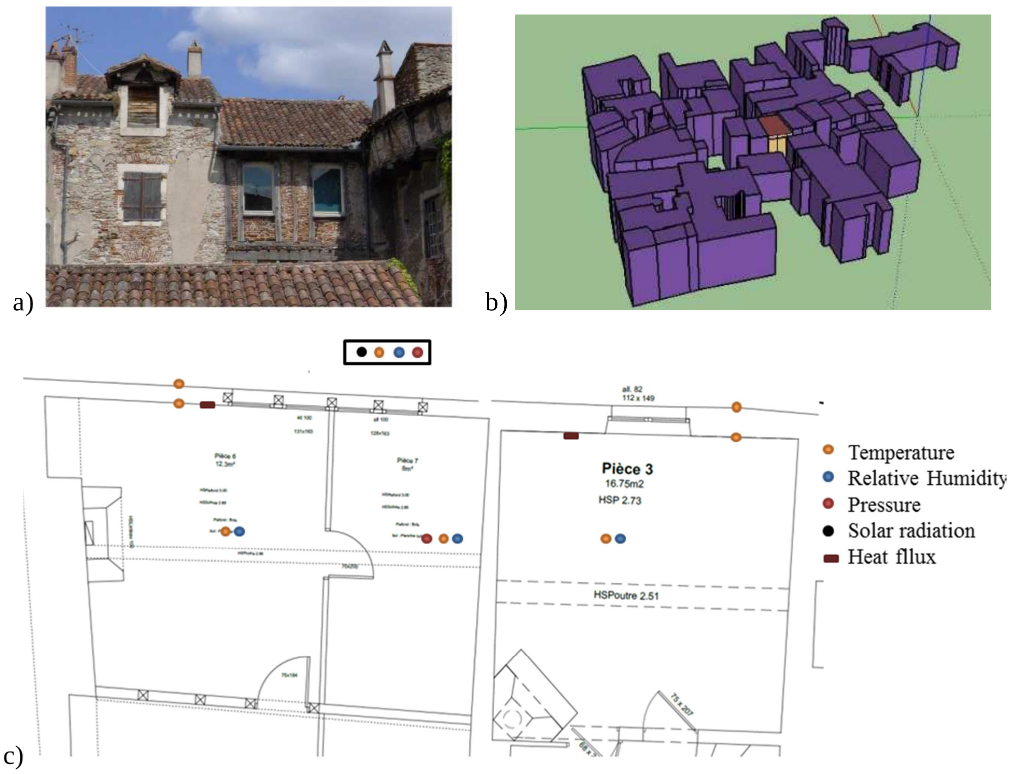


Figure 1 : Characteristics of monitored dwellings: a) Massive brick and timber framed constructions b) Urban morphology c) Monitoring description

In order to work with a non-destructive approach, the historical bricks studied in laboratory come from already dismantled walls (see Table 1). Thermal properties were determined using the commercial devices lambdameter EP500e for thermal conductivity and DesProtherm for thermal capacity.

Table 1: Material properties of historical bricks

Material	Density (kg/m^3)	Thermal Conductivity (W/(m².K))	Thermal Capacity (J/(kg.K))
16^{th} century brick	1616	0.39	746
18^{th} century brick	1795	0.52	800

2.2. Data collections

Monitoring results were collected between July and August 2015 for summer conditions and between December 2015 to April 2016 for winter conditions. Data were recorded every 10 minutes.

2.2.1. Hygrothermal monitoring of indoor climate

In order to evaluate the thermal comfort, two KIMO® data loggers, monitoring indoor air temperature and relative humidity, were placed in each room and located in middle of the room with the height of 1.5m above ground. Surface temperatures from walls, floor and ceiling were recorded thanks to 18 thermocouple sensors.

2.2.2. Monitoring of exterior wall

Exterior walls have a west orientation where the effect of solar radiation can't be neglected.

Wall heat transfer measurements were collected in accordance with ISO 9869:1994 (ref). The walls were instrumented with a heat flux meter (Captec® sensor). Heat flux meter were placed on the inside surface of the walls, for timber framed wall, the captor is located on the infill part and not the wood part. Silicon grease was used to achieve good thermal contact between the sensor and the wall surface. Thermocouples were placed on the internal and external surfaces of the wall.

Solar radiation is measured with a calibrated solarimeter KIMO® CR110. Air pressure differences between indoor and outdoor climate were also measured with calibrated KIMO® CP110 differential pressure meter, giving the dynamic effect of the wind on the exterior wall.

Air temperature and relative humidity of the outside climate were also recorded.

3. STUDY OF THE HEATING PERIOD

3.1. Thermal transmittance

Evaluating how much heat is lost through external walls is a key requirement for building energy retrofitting. Several studies in recent years have focused on the measure of in situ U-values of solid walls in order to study the potential impact of insulation on their thermal performance. [5] [6]

3.1.1. Method

The thermal transmittance of the wall was obtained through heat transfer measurement according to the standard ISO 9869 [7]. Because of heterogeneity of ancient building walls, a preliminary thermographic analysis is normally required to avoid structural abnormalities.

$$U = \frac{\sum_{i=1}^{n} Q_{in,i}}{\sum_{i=1}^{n}(T_{in,i} - T_{ext,i})} \quad (W.m^{-2}.K^{-1}) \qquad (1)$$

U : thermal transmittance
Q : heat flux
T_{in} , T_{ext} :internal and external surface temperature

To ensure that the hypothesis of steady-state conditions is met, and therefore that the effects of the thermal mass are zero on average, sufficiently long data series have to be analysed and whole days have to be sampled in order to capture the full diurnal cycle [7]. The standard states that monitoring campaigns have to last from a minimum of three days up to more than seven days. Baker [5] recommends to extend the monitoring period to two weeks or more to achieve satisfactory results and stable conditions.

North wall is commonly preferred to avoid the effect of solar radiation, but configuration of the building doesn't always permit it.

3.1.2. Results and discussion

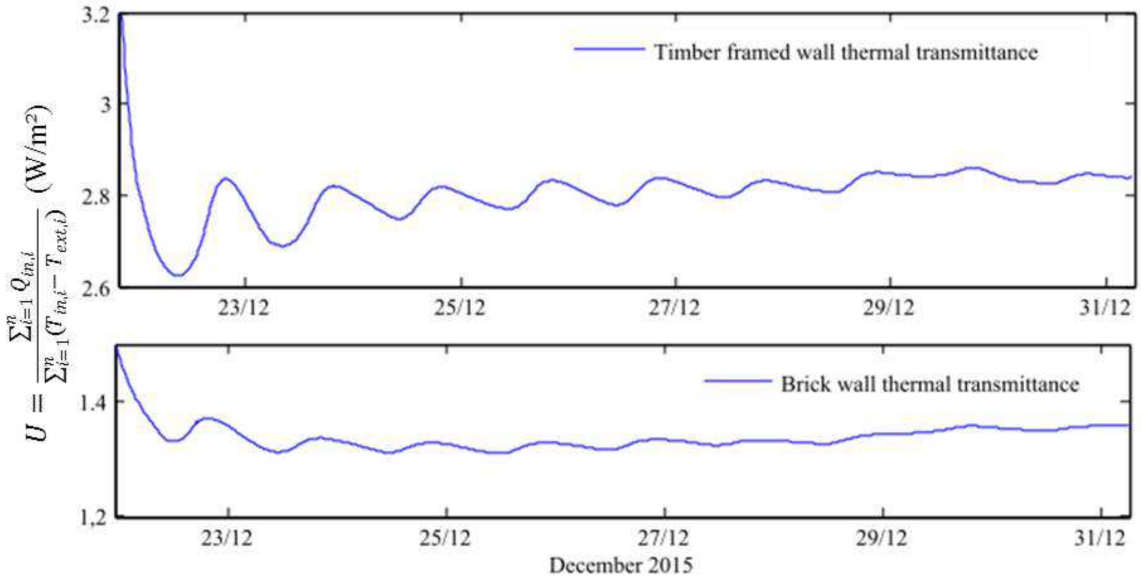


Figure 2 : Monitoring of the thermal transmittance of two wall typologies

Figure 2 shows the evolution of the calculated U-values from 22 December 2015 to 31 December 2015. It varies for solid brick wall between 1.3 and 1.5 W.m-2.K-1 with an asymptotical value of 1.35 W.m-2.K-1. The lower thickness of timber framed wall induces a higher variation from 2.65 to 3.3 W.m-2.K-1 due to the direct impact of solar radiation on internal heat flux; the final value tends to 2.85 W.m-2.K-1.

Measured U-values are compared with calculated U-values with simple steady state method. The calculated values are respectively for bricks and timber framed from 0.84 to 1.06 W/m².K-1 (16th and 18th century bricks) and from 1.89 to 2.28 W/m².K-1. These values are obtained using the dry thermal conductivity of bricks shown in Table 1. Measured U-values are higher than calculated ones, from 1.3 to 1.6 times.

The difference can be explained by the following limits of the method:

- Ancient bricks special feature are high variation in their intrinsic properties, the brick samples recovered in dismantled walls of Cahors and studied in laboratory do not necessarily represent exactly the bricks of studied dwellings. Furthermore, moisture content of the wall impacting on the thermal conductivity is not taken into account.

- The quality of the thermal contact of the heat flux sensors with the walls impacts results and in ancient buildings rough internal surfaces are commonly found.

- In urban configuration with high rate of adjoining buildings, dwellings don't always present a North exterior façade.

- The average method considers that over a sufficiently long period, the thermal mass effects are on average zero and gives an estimation of steady state response of the walls. Changes to the direction of the heat flow violate the assumption of steady state behaviour [8], therefore the average is typically only used during the winter heating season. The results presented here show that on west wall, solar radiation can't be neglected and highly accentuates outside variation.

3.2. Time lag

3.2.1. Method

Commonly, when studying the improvement of thermal comfort of a dwelling, the thermal transmittance is the main parameter controlled. However, the envelope thermal inertia should be also considered. Several authors report that actually thermal inertia is one of the most important parameters for improving thermal comfort conditions as well as for reducing heating and cooling energy demands of buildings [9] [10]. This phenomenon is related to two important parameters, the time lag (TL) that is the time required for heat wave to propagate through a wall from the outside to the inside and the decrement factor (DF) that is the decreasing ratio of its amplitude during this process.

Few authors studied how outside wall temperature, determined by absorption coefficient, azimuth and external loads (sky temperature, air temperature, solar radiation) impact on TL and DF [11] and demonstrated that simplified methods using constant decrement factor and time lag values have poor accuracy in a significant number of cases [12].

3.2.2. Results and discussions

In-situ TL values for brick wall presented in Figure 3, highlight the non-constant condition of TL and differ from calculated values. Furthermore a different value for TL_{day} (heat wave from the outside to inside) and TL_{night} (from inside to outside) can be observed.

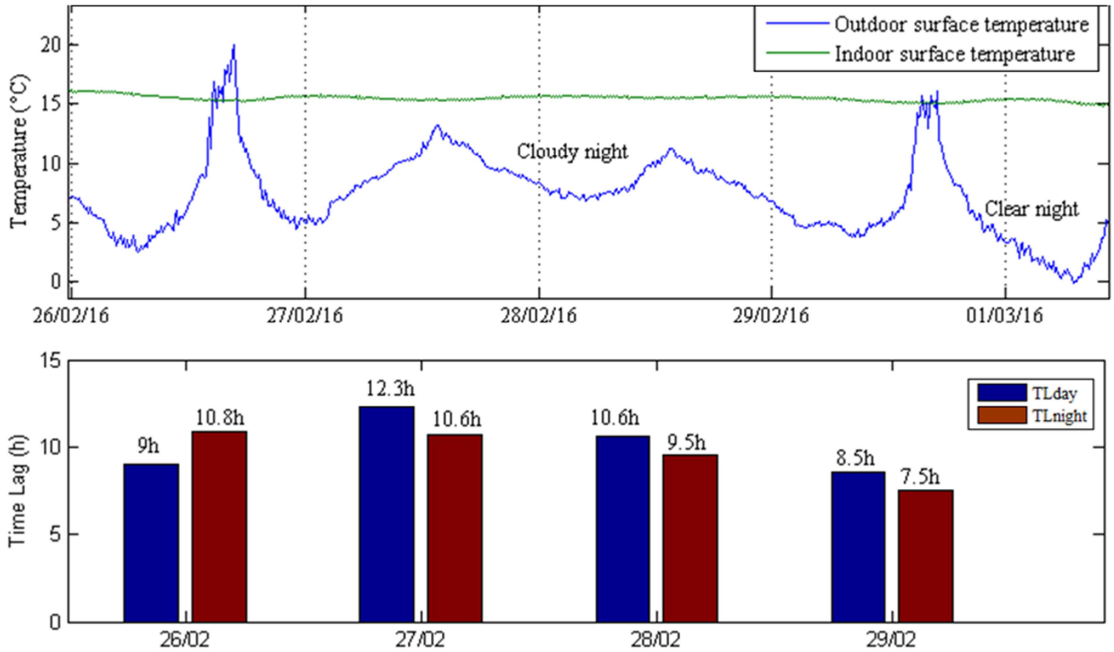


Figure 3: Observation of a non-constant time lag

The time lag variations can be explained as follow:

- As suggested by Chuan Sun [13], the non-sinusoidal periodic fluctuation of the outside sol–air temperature (surface temperature in our study) leads to a variation between night and day time lags, increasing stage being different from decreasing stage of the periodic fluctuation.

- When outdoor environment is schematized using a sinusoidal oscillation of the sol–air temperature, the dynamic behaviour of the walls depends only on the thickness, the position and the thermo-physical properties of the layers [11], this simplification do not take into account the variation of thermal external loads. It can be observed that two main parameters are in competition. TL will follow mean outside temperature variation, which means that when the outside temperature is steadily increasing from one day to the next, TLday will be later and TLnight sooner. In competition with this phenomenon, TL is also dependent from sudden temperature variation, which means that a clear night (for TLday) cooling the wall with sky temperature or sunny day (for TLnight) warming the wall with solar radiation, will inverse the heat wave and shorten the TL.

In typical case, it would be unrealistic to simplify the time lag of an exterior wall with a constant value.

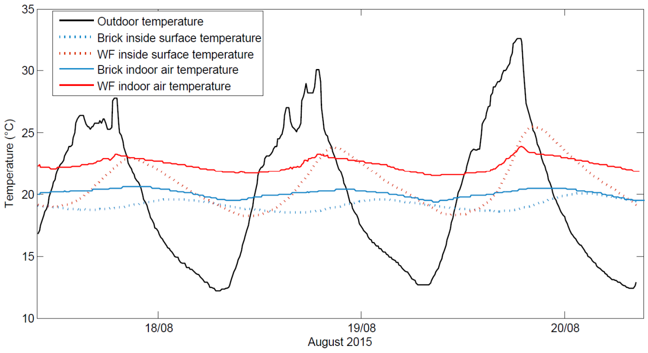
4. STUDY OF THE COOLING PERIOD

Increasing thermal resistance of wall with thermal insulation can induce over heating phenomena during the warm season. That's why, summer behaviour of ancient buildings in Cahors is studied with a special attention to avoid that the thermal rehabilitation causes the installation of air conditioning systems.

4.1. Room and wall thermal inertia

The thermal inertia of a wall directly affects the indoor air temperature and the thermal comfort. However, it does not always reflect the effective thermal inertia of the whole building. [14]

Here, TL_{wall} and DF_{wall}, designed thermal inertia parameters of the wall, determined with indoor and outdoor surface temperatures. TL_{room} and DF_{room} are determined with indoor and outdoor air temperature. A period of three days of August 2015 is studied, presenting similar variations. The mean values of TL and DF are used.



	Brick wall	Timber Framed wall
TLwall (h)	7.05	1.3
DFwall	0.0561	0.2910
TLroom (h)	1.32	0.27
DFroom	0.0483	0.0963

Figure 4 : Observation of time lag and decrement factor in summer conditions

The study of in-situ values can lead to various observations. Firstly, in both typologies, a lower TL_{room} than TL_{wall} is obtained. In dwellings with high rate of adjoining buildings the exterior wall plays a minor role than in other constructions. Furthermore high air permeability of old buildings also impacts indoor air temperature. Both typologies also present a lower DF_{room} than DF_{wall}, but in case of timber framed dwelling attenuation between room and wall is factor 3 whereas in massive brick dwelling the attenation is only of 1.2. This result shows that in case of timber framed dwelling even if exterior wall strongly reacts with exterior variation, the indoor air temperature is prevented from these variations thanks to mass of the rest of the adjoining buildings.

Last observation is the lower value of TF in summer than in winter. The higher variation of thermal internal loads can partially explained it.

4.2. Summer thermal comfort analysis

Different current comfort standards are intended to optimize the thermal acceptability of indoor environments. For naturally ventilated buildings R.Dear and G.Brager [15] suggest that the conditions for an acceptable thermal environment shall be based exclusively on the adaptive model (linear regression) approach because occupants in naturally ventilated buildings are tolerant of a significantly wider range of temperatures than in HVAC buildings.

The monitoring of the month of August 2015 reveals that the indoor air temperature of the timber framed dwelling was on average 2°C higher than the masonry dwelling and from the linear regression proposed in the ASHRAE 55 standard [15], we observed that the timber framed dwelling overpassed the level of acceptable comfort 7.5 times more than the second building (see Figure 5) (respectively 246 hours and 32 hours.). This result confirms that low thermal inertia of light buildings (timber framed) can contribute to the over-heating [16]. On the other hand, Diaz [17] shows that even if peak loads in light buildings are higher, overheating can be prevented using good ventilation, that is more effective in light buildings than in massive ones because of the rapid answer of the construction to temperature variation of the outside during the night. The observation the minimal outdoor temperature in regard with indoor temperature confirms that night ventilation is an effective cooling strategy in this climate to avoid overheating.

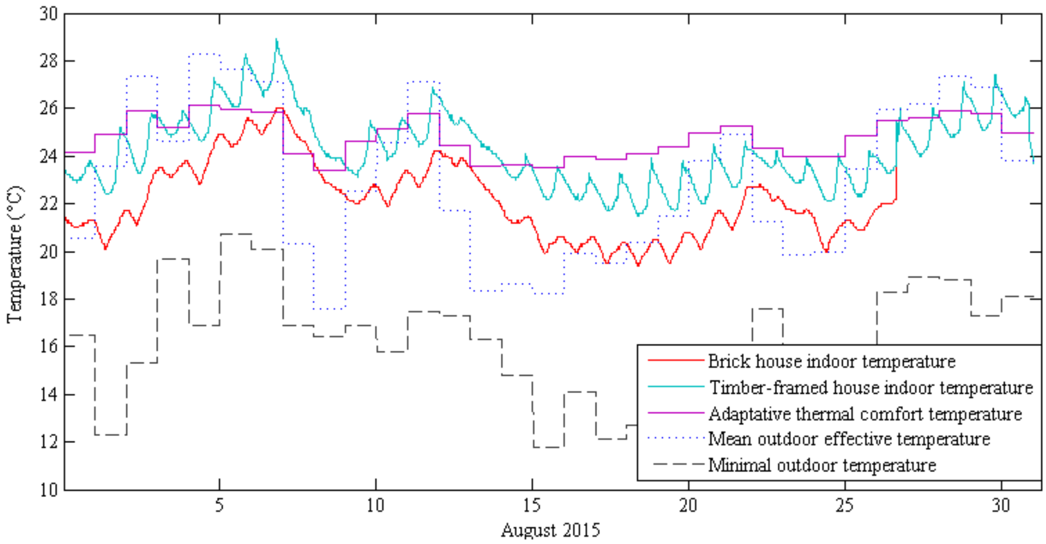


Figure 5 : Study of adaptive summer comfort according to ASHRAE 55

5. CONCLUSIONS

In our case study, ISO 9869:1994 method to determine thermal transmittance seems unadapted. The solar radiation due to west orientation of the wall causes important fluctuation of exterior conditions and obliges a very long monitoring period. Inverse method to obtain thermal transmittance will be test in future.

With real exterior and interior boundaries, time lag presents a non-constant behaviour due to the non-periodical oscillation of thermal loadings and the constant variation of mean exterior temperature.

Massive brick constructions present good characteristics for comfort summer and can be improve with free cooling. Furthermore, the morphological configuration of medieval centre, with high rate of contiguity has a positive impact on the indoor air temperature of timber framed building. Indeed, indoor air temperature, enjoying the thermal mass of adjoining buildings, presents a much lower variations than indoor surface wall temperature.

In situ measurements confirm high complexity of thermal behaviour of old building in a dense urban morphology. Next monitoring campaign, after wall refurbishment, will allow a comparison of measured thermal comfort pre and post retrofits and will validate or not some technical retrofitting solutions.

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