Monitoring the change of indoor environmental conditions of refurbished buildings in Milan.

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Abstract. The energy performance gap, i.e. the difference between measured and predicted behaviour of buildings, is one of the main challenges for the building simulation community and it is highly relevant due to the increasing number of building renovations fostered by recent European Directives. In fact, occupants have a high influence on the building energy use for space heating and cooling, especially in refurbished buildings. The user behaviour may be indirectly investigated by monitoring the indoor environmental conditions before and after the refurbishment. However, in the literature there is a lack of monitoring studies that study the impact of user habits on the predicted energy savings for retrofitted buildings. This study contributes to filling this gap by analysing the air temperature and relative humidity monitored in twenty apartments in the city of Milan (Italy) during two consecutive years. Among them, eight were refurbished during the spring/summer period between the two monitored heating seasons. The analysis of the measured data shows that there is a slight increase in the average indoor air temperature of refurbished apartments. Moreover, the application of a simple hygrometric balance show that users are likely to increase air change rate in naturally ventilated buildings after their refurbishment. Finally, Energy Plus simulations of two monitored apartments showed that such changes in the indoor environmental conditions lead to significant variation in the energy needs for space heating.

Keywords. Building retrofit, indoor environment, energy performance gap, thermal comfort, monitoring.
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1. Introduction

The Energy Performance of Building Directive [1] stated that buildings are responsible for 40% of the final energy use; among the different sectors, residential housing covers 60% to 85% of the national building stock within the European countries [2]. In the last decades, governments promoted building retrofit interventions to reduce energy use and CO_2 emissions associated with space heating and cooling.

However, buildings' renovation rates are meagre; thus the highest energy reduction can be achieved by a deep retrofit of the existing building stock [3] that belong to a large extent to the period after the World Wars. Ruggeri et al. [4] reviewed the crucial steps leading to energy retrofit planning, avoiding phenomena such as overheating or cooling or plant oversize. The energy use of buildings is supposed to decrease after refurbishment due to the reduction of transmission losses. Still, several cases show increased energy use compared to the expected one [5-6]. The resulting energy performance gap between the estimated and the real energy savings is linked to an increased demand for user comfort, also known in literature as *rebound effect*.

Galvin et al [7] recalled four different types of rebound effect previously defined as direct, indirect, economy-wide and transformational; the present paper focused only on the direct effect that is the increase of energy used by a retrofitted building, although it is supposed to have higher energy performance. An analysis of the Danish residential building stock based on energy performance certificates (EPC) investigated how the heat consumption can change due to energy improvements, finding a pseudo-rebound effect for a sample of 134.000 buildings with different characteristics [8]. However, even if data belonging to EPC can be used to describe the energy performance of a building stock, there may be data quality issues to be handled [9] when evaluating the potential energy saving. In fact, the available level of information is often not sufficient, thus requiring merging several sources and increasing the number of assumptions.

As demonstrated by Sunikka-Blank et al. [10] the rebound effect occurs when a fraction of the energy savings achievable after refurbishment is consumed by additional energy use because the user expects more indoor comfort and changes his behaviour accordingly.

From a physical point of view, insulating the building should lead the users to accept a lower indoor air temperature due to the increase in temperature of the internal surfaces. However, calculating the performance of the upgraded building with the same thermal comfort can be misleading. Strictly related to the tendency of the user to increase the comfort level after an energy upgrade, the attitude of people that accept a poor indoor environment in poorly insulated buildings is named *prebound effect,* which is another variable responsible of the energy performance gap. Corrado et al. [11] pointed out that the rebound effect occurs when the users modify their behavior to obtain higher thermal comfort as a consequence of the renovation, increasing the energy demand by 35% to 55%.

Since national and international policies on building retrofit are based on the estimated energy savings after refurbishment actions, further research is needed to investigate the user behaviour and the related motivations and practices in households that could offset the estimated saving. Tackling behavioural change has a key role to develop effective strategies integrated to the improvement of thermal characteristics.

This paper used real data provided by a monitoring system installed in twenty apartments in two consecutive winter seasons, eight of which straddle a retrofit intervention on the building envelope. Data have been provided by TEICOS Group, as partner of the SPICA project to implement the study on living comfort and facilitate intelligent energy management through HEMS (Home Energy Management System). The aim of the SPICA project was to propose an innovative service for citizens to contain energy costs and to improve environmental comfort conditions. Therefore, the condominiums participating in the project have given the availability to install in some housing units, the “Valorizzami” monitoring kit consisting of a set of environmental sensors, native LoRaWAN class A. The objective of the analysis is to determine whether there is a change in indoor thermo-hygrometric conditions attributable to the intervention, and to estimate the impact of this possible change on the energy demand of the building. The influence of the user behaviour on energy savings has been investigated also by dynamic simulations carried out with EnergyPlus, simulating different combinations of envelope retrofit and indoor environmental conditions.

2. Case study

2.1 Monitoring program

The monitoring campaign was carried out in twenty apartments from 11 November 2018 to 31 December 2019. In this work, we aim to investigate the impact of building retrofit on user behaviour, whose habits can have a significant effect on the energy use of buildings as highlighted in the Introduction.

The monitored apartments are located in three apartment blocks in the suburbs of Milan, named M, B and F (Table 1). Eight apartments were monitored before and after refurbishment, while the other twelve did not undergo the retrofit in the same period. Two sensors were installed in each apartment, generally located in the living room, bedroom or entrance door.

Tab. 1 - Number of apartments per condominium

	M	B	F
Num. of apartments	10	142	47
Num. of monitored apartments	6	2	12

Sensors monitored indoor air temperature and pressure, relative humidity (RH), indoor illuminance and volatile organic compounds concentration (VOC) through the operation. Although measures were collected on an hourly basis, the percentages of non-available data range between 2.3% and 9.3% depending on the starting date of the monitoring campaign. Hourly profiles of dry-bulb temperature and relative humidity of the outdoor air were taken from the regional agency for environment protection (ARPA Lombardia) [12] and used to estimate the air change rates as explained in Section 3.1.

2.2 Simulated building

Dynamic simulations were performed with the software Energy Plus [13] to simulate the thermal behaviour of the building with the average indoor environmental conditions both ante and post retrofit. Weather data were simulated according to the .epw file of Milano Linate [14], which is the most similar to the weather conditions of the considered location. Information regarding the buildings were taken from the energy report required by the national standards according to the Decree of the 26/06/2015 [15-16]. The main characteristics of the three blocks M, B and F are summarized in Table 2.

Tab. 2 - Building retrofit interventions

	M	B	F
Retrofit actions on the building envelope (if any)	External wall and roof insulation	External wall insulation and blowing of insulating materials.	No actions on the envelope
HVAC system	Centralized heating system supplied by a heat pump	Centralized heating system supplied by a heat pump	Centralized heating system supplied by 3 condensing gas boiler
Emission system	High-temperature radiator	High-temperature radiator	Aluminium radiators
PV system	No	Yes	No

Block M had the most detailed information to perform a detailed energy model among the three buildings. External and internal walls are made of solid bricks, while floors and ceilings have a traditional brick-concrete structure. The retrofit actions include 14 cm of rock wool panels for both envelope structures on the external side. The stratigraphy of the building envelope components are shown in Table 3.

Tab. 3 - Thermal properties of the building envelopes ante- (a) and post-retrofit (b)

(a)	Original structure	U value [W/(m² K)]
External wall	Internal plaster (2cm) Solid bricks (37.5 cm) External plaster (2 cm)	1.40
Internal wall	Internal plaster (1.5 cm) Solid bricks (12 cm) External plaster (1.5 cm)	1.43
Internal Floor/Ceiling (towards the basement)	Ceramic tiles (1.5 cm) Concrete screed (7 cm) Brick-concrete layer (20 cm) Internal plaster (1.5 cm)	1.39
Windows	Double-glazed	2.71

(b)	Retrofitted structures	U value [W/(m² K)]
External wall	Internal plaster (2cm) Solid bricks (37.5 cm) Rock wool panels (14 cm) External plaster (2 cm)	0.21
Internal Floor/Ceiling	Ceramic tiles (1.5 cm) Concrete screed (7 cm) Brick-concrete layer (20 cm) Rock wool panels (14 cm) Internal plaster (1.5 cm)	0.21

Two apartments were selected for the simulation considering representative configurations within the buildings investigated in terms of heated areas and surfaces bounded by the external environment, since the latter have a significant influence on the energy needs for space heating. Figure 1 (top) represents a typical small apartment of 66.8 m² (M5 bordered by the basement (yellow), other apartments on the top and two sides (pink), and has only two sides facing outside (blue).

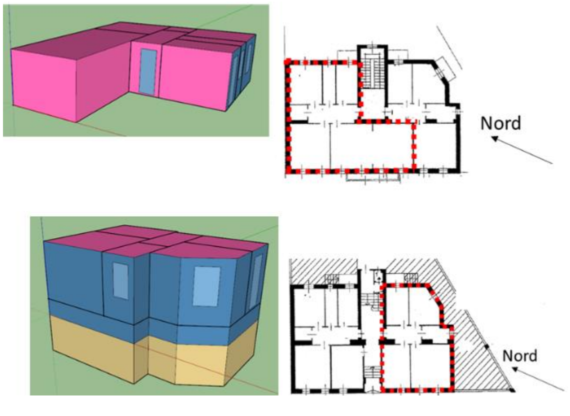

Figure 1 - 3D geometrical model and floor plan of the simulated apartments

The second configuration shown by Figure 1 (bottom), represents a typical large apartment (M2) of 98.5 m² with only one side facing the outdoor environment and the others adjacent to other heated apartments.

Since the main focus of the analysis is the real behaviour of the building, simulations used the net heated area, not considering the influence of thermal bridges. Internal loads and related schedules were estimated from BS ISO 18523 [17] for typical residential buildings, considering a family of 3 (M5) and 4 (M2) people, with a laptop, a TV and typical kitchen loads for a total peak load of 11.9 W/m² for M5 and 9.7 W/m² for M2. Schedule profiles are shown in Figure 2 for occupancy, lights and appliances.

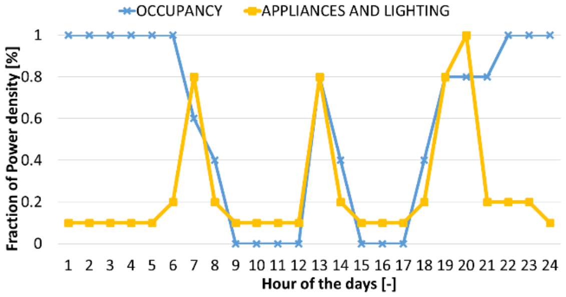

Figure 2 – Schedule profiles of internal loads.

3. Methods

This Section is divided into three parts. The first one describes the procedure to analyse the monitored data, including the estimation of the air change rates before and after the refurbishment. The second part outlines the main assumptions and scenarios for the energy simulations of the selected apartments. The third subsection describes the metrics used to assess indoor thermo-hygrometric conditions before and after the refurbishment based on both data and simulation results.

3.1 Analysis of the monitored data

The analysis of the monitored data was carried out on two subsets of the original dataset: one representing the situation before the refurbishment, and one after. In both periods, the analysis was conducted for 8 refurbished apartments and for 12 unrefurbished apartments separately. Periods of the same duration have been compared, with similar climatic conditions and similar expected activities in the daylife of the occupants. According to these criteria, two periods of five weeks before the Christmas holydays were identified as the most suitable ones, i.e. from 14/11/2018 to 21/12/2018 and from 14/11/2019 to 21/12/2019.

The weather conditions including outdoor air temperature, relative humidity (RH) and global solar irradiance (GHI) on the horizontal plane were collected from Lombardy's Regional Office for

Environmental Protection (ARPA) using data from Milan (Piazza Zavattari) weather station [12]. Table 4 shows a summary of weather conditions in the selected periods. It can be observed that in the monitored period after refurbishment the outdoor air was slightly warmer (+2.4°C on average) than in the previous period. In principle, this increase could affect user behaviour, thus introducing an external disturbance to the analysis. However, the air was also more humid and there was less solar radiation, thus partially compensating the feeling of cold during the post-retrofit period.

Tab. 4 – Summary of weather conditions in the selected periods

Scenario	Ante (2018)	Post (2019)
T_e	6.0±3.3°C	8.4±2.5°C
RH_e	81.6±13.5%	91.9±12.4%
GHI	1.36±0.57 kWh/(m^2 day)	0.83±0.59 kWh/(m^2 day)

Concerning indoor air conditions, hourly values of temperature and relative humidity were calculated by averaging measurements from all sensors. While the average internal humidity and the air change rate are calculated considering the full-day average (00:00-23:59), the indoor air temperature was calculated excluding night hours, i.e. only daytime. This operation allows to exclude the periods when the central gas boiler is off (22:00-7:00), i.e. when the occupants have no possibility to control their indoor temperature through the thermostatic valves.

Since the position and number of sensors changed from flat to flat and over time, no weighting factor was applied. Instead, data were filtered by considering only those days with a minimum number of hourly measurements. This lower acceptability threshold was set to 12 hours in the full-day data pre-processing, and 7 hours in the daytime data pre-processing.

The average ventilation rate was estimated for each apartment from the hygrothermal balance assuming a constant internal vapour generation of 0.375 kg$_v$/h, as shown in Eq. (1).

$$G_a = \frac{G_v}{x_i - x_e} \tag{1}$$

The air mass flow rate (kg$_a$/h) was then converted into air change rate (volumes per hour) by normalizing the data with respect to the building net heated volume, as shown in Eq. (2).

$$ACR = \frac{G_a}{\rho_a V} \tag{2}$$

The air change rate was then averaged over time to get daily values. In fact, the objective of this estimation is to compare ventilation rates before and after the refurbishment rather than calculating actual values, which would require either knowledge on the internal vapour generation or different monitoring methods. Outliers were filtered out using barrier functions to exclude negative air change rates or values higher than 2.0 h^{-1}.

3.2 Simulation scenarios

The analysis described in the previous Section allowed to determine the indoor environmental conditions before and after refurbishment. These conditions have been later used to simulate the buildings in the following three scenarios:

- Ante-Ante (AA): Both indoor environmental conditions and building envelope ante-intervention (i.e. before refurbishment).

- Ante-Post (AP): Retrofitted building envelope (i.e. after refurbishment) with the same indoor environmental conditions monitored ante-intervention.

- Post-Post (PP): Both indoor environmental conditions and building envelope post-intervention (i.e. after refurbishment).

3.3 Key Performance Indicators

The main objective of the present work was to determine whether the change in the buildings indoor environmental conditions is responsible for a significant change in the energy needs for space heating E_{SH} (kWh/m^2) based on the monitoring campaign and on the results of the mentioned simulations. To this end, the energy needs were calculated using EnergyPlus for two reference housing units (M5 and M2), as explained above. The resulting operative temperature profile were used to calculate the thermal discomfort index TDI (°C h) as follows:

$$TDI = \begin{cases} \int (T_{i,min} - T_{op})\, dt\,, & T_{op} < T_{i,min} \\ \int (T_{op} - T_{i,max})\, dt\,, & T_{op} > T_{i,max} \end{cases} \tag{3}$$

Where $T_{i,min}$ and $T_{i,max}$ were assumed to be 20°C and 25°C, respectively. These values were chosen based on ISO 16798 [18] Standard.

Therefore, the expected key performance indicators for the refurbished buildings were calculated using the simulation results of AP scenario: $E_{SH,AP}$ and TDI_{AP}. The actual performance indicators –i.e. considering varied indoor environmental conditions were calculated, instead, using the simulation results of PP scenario: $E_{SH,PP}$ and TDI_{PP}. Usually, the Energy Performance Gap measures the difference between measured and predicted energy consumption. Here, the simulated energy performance gap EPG_{SH} (kWh/m^2) was calculated as the relative difference between actual and expected energy performance:

$$EPG_{SH} = \frac{E_{SH,PP} - E_{SH,AP}}{E_{SH,AP}} \quad (4)$$

4. Results

Section 4.1 is focused on the difference between the indoor environmental conditions in the monitored apartments. The latter constitute the boundary conditions for the building simulations, whose results are reported in Section 4.2.

4.1 Analysis of the monitored data

Figure 3 shows the difference in the indoor air temperature before and after retrofit in one of the monitored apartments of condominium B. The profiles show that there is not a clear increase or decrease in the average temperature that lasts for the entire period. For instance, during 19-21/11/2019 the indoor air temperature was higher than that recorded in the same days of the previous year, while during 23/11/2019 the temperature was clearly below compared to the same day of 2018. This is most likely due to the diverse human activities, that are also affected by daily and weekly cycles. Predicting such occupant-related patterns is not among the objectives of the current work, that rather tries to discover significant year-to-year differences in the average indoor air measurements assuming to have similar internal heat and water vapour gains. A careful observation of the temperature profiles reveals that, on average, the daily oscillations are more pronounced during 2018, i.e. before building retrofit. Indeed, in the period considered, the difference between maximum and minimum indoor air temperature drops from 2.0°C to 1.4°C. The lower temperature decrease occurring in 2019 is likely caused by the higher thermal insulation of the building envelope.

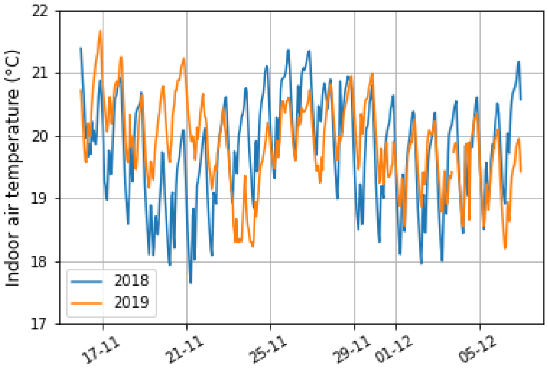

Figure 3 - Example of average indoor air temperature profiles over three weeks ante and post retrofit.

Table 5 and Table 6 report the average indoor thermos-hygrometric conditions in the refurbished and unrefurbished apartments, respectively. One may see that in the refurbished flats there is a clear increase in the indoor air temperature (+0.4°C) during daytime, that goes from 21.3°C to 21.7°C. The same increase does not occur in the unrefurbished flats. However, a reduced increase in temperature (+0.2°C) is still present. This means that the temperature increase after building retrofit should not be entirely explained with the rebound effect, but is likely due to individual preferences/activities of the occupants that cannot be considered as a general trend. Indeed, a more careful analysis of the data reveals that only four apartments out of eight experience an increase in the indoor temperature (+0.97°C on average) while the other four show a limited yet significant reduction (-0.19°C), as shown in Figure 4(a). These discrepancies may also be due to other factors, such as a different size and orientation of the external walls and windows. Repeating the same analysis on a bigger sample of apartments could provide more statistically significant, representative trends.

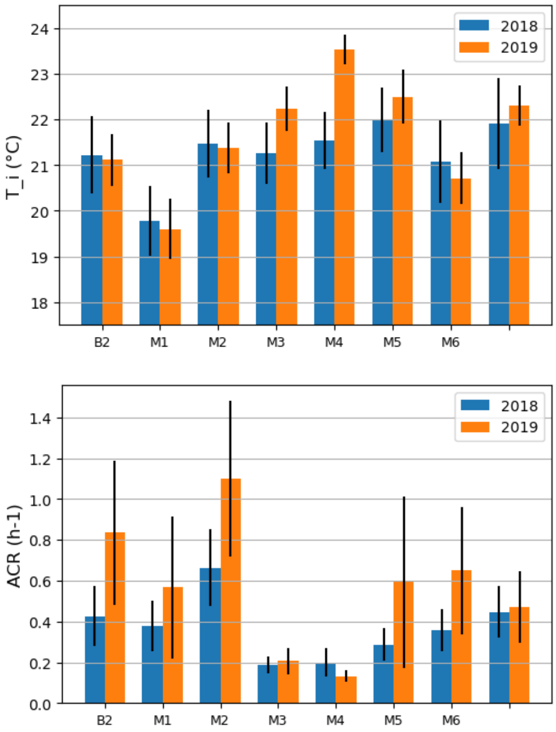

Figure 4 – Indoor environmental conditions ante and post retrofit in the refurbished apartments: average air temperature (top) and air change rate (bottom).

The daily air change rates show a notable increase after building retrofit. In fact, they go from 0.37 to 0.57 volumes/hour (+55%). Such variation is also confirmed by the fact that 7 apartments out of 8 have the same increasing trend, as shown in Figure 4(b). However, differently from the indoor temperature, the air change could not be measured directly. Therefore, these values should only be interpreted as an estimation of the relative change in the ventilation rates after the retrofit. This result relies on the assumption that internal water vapour generation was the same in the monitored periods. Although being a strong assumption, it is deemed as reasonable due to the duration of the periods considered (five weeks). In the flats of block F, the increase in the air change rates was less pronounced, going from 0.53 to 0.64 volumes/hour (+21%). Here, 8 flats out of 12 experience an increase. The analysis therefore shows that the increase in the air change rates cannot be explained simply with a change in the user behaviour linked to the request of a more comfortable indoor environment. Instead, it is more likely that this change is, at least in part, due to the different weather conditions in the periods compared. This hypothesis is confirmed by the fact that in the five weeks of 2019, there was a higher external air temperature. This could have been a driver to increase ventilation for both refurbished and non-refurbished buildings.

A similar consideration holds true for the internal relative humidity, that increases from 48% in 2018 to 53% in 2019 despite the higher indoor air temperature and increased estimated air change rates. These trends can be physically explained with the inflow of warmer and more humid outdoor air occurring during the five weeks of 2019.

Tab. 5 – Summary of indoor thermo-hygrometric conditions ante and post retrofit.

Scenario	Ante (2018)	Post (2019)
$T_{i,avg}$	21.3±0.8°C	21.7±0.5°C
$RH_{i,avg}$	47.9±5.6%	53.2±4.9%
ACR	0.37±0.11 hr^{-1}	0.57±0.26 hr^{-1}

Tab. 6 – Summary of indoor thermo-hygrometric conditions in non-refurbished buildings.

Scenario	2018	2019
$T_{i,avg}$	21.2±0.7°C	21.4±0.7°C
$RH_{i,avg}$	48.1±5.8%	55.4±5.2%
ACR	0.53±0.16 hr^{-1}	0.64±0.24 hr^{-1}

4.2 Simulated buildings

Simulations belonging to scenario AP, that simulated the refurbished apartments maintaining the previous thermo-hygrometric indoor conditions, should highlight the expected energy demand for space heating, i.e. the energy demand without a change in the user behaviour. Scenario PP, instead, simulated the refurbished apartments with the changed user behaviour, thus shading light on the effect of user behaviour on the final energy demand of the buildings. The degree-hours of thermal discomfort were also calculated for the same scenarios in order to quantify the possible gain in thermal comfort linked to the rebound effect. For each scenario, both the energy demand and thermal discomfort index were calculated for both simulated apartments (M2 and M5), thus finding the ranges shown in Table 7.

Results of scenario AP showed that the energy saving obtainable with the retrofit goes from 50% (M2) to 58% (M5) in the monitored period, and are even higher if the same indoor conditions are considered for the whole heating season (53-61%).

The difference between scenario AP and PP is consistent, confirming the existence of a rebound effect. Indeed, the energy savings drop to 32-40% considering the monitored period only, and to 33-43% considering the whole heating season.

As a consequence, the energy performance gap EPG_{SH} calculated from the simulation outputs was found to be 36-41% in the monitored period and 42-47% assuming the same user behavior holds true for the entire season. These values are very high and reflect the importance of user behavior in achieving the desired energy savings after a technical intervention on the building envelope. However, they must not be interpreted as actual gaps but rather as an upper limit to the rebound effect. In fact, they are based on simulations that rely on several assumptions reported in the Methods Section. The main assumption is that occupancy and human activities do not change after retrofit and that the effect of a different weather does not influence indoor conditions significantly.

Looking at thermal comfort, the increase in energy use after retrofit is strictly related to the need of the user for a higher indoor comfort, which corresponds to a lower amount of time where with an operative temperature lower than 20°C (TDI low). The lower indoor temperatures are not entirely linked to user preferences, but also to physical constraints such as the inertia required to heat up the apartments before the building refurbishment. The higher ACR obtained from the hygrometric balance led to lower overheating, with few periods with operative temperatures higher than 25°C (TDI high).

Tab. 7 – Comparison on energy need and thermal discomfort obtained with building simulations.

Scenario		AA	AP	PP
		M2-M5	M2-M5	M2-M5
Seasonal E_{SH} (kWh/m^2)		85.1-97.5	40.3-38.1	57.1-56.0
Monitored period E_{SH} (kWh/m^2)		20.6-23.4	10.4-9.9	14.1-14.0
TDI (°C h)	Low	532.3-760.8	19.3-16.8	17.6-18.1
	High	0-0	44.9-66.3	0-1.4

5. Conclusions

The present work investigated a dataset reporting temperature and humidity profiles recorded in twenty apartments in Milan in two consecutive winter seasons, eight of which were refurbished during the summer in between. The research question was whether there is a significant change in the indoor conditions that could be linked with the so-called rebound effect, i.e. a demand for increased comfort that typically occurs after energy efficiency measures such as the thermal insulation of residential buildings.

The study shows that, on average, a slight increase (+0.4°C) in the indoor temperature that occurs as a result of a significant increase in half of the refurbished flats. This change must not be attributed entirely to a behavioural change, since a slight increase (+0.2°C) occurs also in non-retrofitted buildings. Therefore, the increase could be more likely linked to lower transmission losses at night and different weather conditions in the monitored periods. An hygrothermal balance based on measurements of indoor and outdoor humidity reveals that the air change rates increase significantly after the intervention (+55%). The same increase is lower in non-refurbished apartments (+21%), thus confirming the hypothesis of the behavioural cause to increased ventilation.

Overall, a rebound effect seems to occur and to be due to higher ventilation requirements rather than to higher indoor temperatures. In absence of measured energy consumption data, simulations of two representative apartments were carried out to estimate the energy performance gap linked to this behavioural change. The latter ranged from +36% to +47% depending on the simulated apartment and on the duration of the period considered.

The small number of the analysed sample hinders the generalization of the results. However, the analysis points out that a rebound effect occurs. Therefore, estimating the energy-saving potential based only on improved thermal characteristics can lead to a significant overestimation of the heat saving potential in residential buildings and more attention should be put on the behaviour of the final users. Future work will try to extend these findings using a larger dataset.

6. Acknowledgement

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Data Statement

The datasets generated during and/or analysed during the current study are not available because of privacy agreements but the authors will make every reasonable effort to publish them in near future.