LOW-COST AND NON-INVASIVE ENERGY RECOVERY TECHNIQUES FOR PUBLIC RESIDENTIAL BUILDINGS MADE WITH GREAT PANEL STRUCTURES IN ITALY

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ABSTRACT

In Italy, a large stock of public housing was built during the 1970s and 1980s with industrialized/prefabricated techniques. These buildings have envelopes characterized by the presence of many thermal bridges and low transmittance values. In addition, they feature inefficient single heating systems in residential units and no cooling/ventilation systems. As a result, these buildings require urgent energy retrofitting actions, and it is therefore necessary to define procedures that will guarantee effective results. The possible interventions must be compatible with building construction techniques as well as be minimally invasive and inexpensive. There are only a limited number of technical solutions, considering that residents should not have to move out during the renovations. In most Italian climatic zones, current interventions are usually linked to external insulation and window replacement, leading to an improvement in energy performance and comfort only during winter. Internal comfort conditions tend to worsen in summer months because seasonal temperatures tend to increase by a few degrees. Therefore, solutions should be proposed that will improve both summer and winter conditions. This work proposes an energy recovery procedure applied to a representative building from the abovementioned period located in the Florence area and constructed with an industrialized system named the "tunnel system" (great panels structure). The procedure used in this study provides for the redevelopment of the envelope and the application of a simple mechanical ventilation system to achieve substantial energy savings and improved indoor comfort conditions.

KEYWORDS

social housing, renovation, thermal comfort, mechanical ventilation system, sustainability, overheating.

1. INTRODUCTION

Problems related to residential building renovations particularly impact those in the suburbs of most Italian cities because a large amount of public housing was built from the 1960s to

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the 1980s in response to pressing housing needs, and as a result, construction was conducted quickly and with limited financial resources. These buildings now require significant improvements and upgrades.

During that period, there was a strong impulse towards the standardization of design and construction. As a consequence, there was a search for repeatable architectural models to guarantee the quality of the work at reduced costs and with minimal construction times. Thus, standardized and replicable residential building types were developed (Acocella 1980). This method of building construction led to the use of prefabrication/industrialization systems. One downside of this process was that the use of heavy prefabrication systems led to the construction of undiversified "cookie-cutter" buildings and to apartments with rigid distribution layouts lacking spatial articulation. From a technological point of view, the buildings were also characterized by low energy efficiency and poor quality materials (Dell'Acqua and Ferrante 2009).

This large building stock has therefore many common architectural, structural and plant engineering characteristics. The buildings were often made using industrialized/prefabricated techniques and with heavy reliance on reinforced concrete as a bearing structure which frequently coincided with other building sub-systems, such as the envelope and internal partitions. It is worth noting that the refurbishment of residential buildings built in this specific period is often hampered by economic sustainability, limiting the possibilities of intervention, and is connected to the restricted resources of public ownership of the complexes, the characteristics of the residents when dwellings have been purchased, and the binding construction techniques. Moreover, it is well known that this building stock would benefit from significant renovation and redevelopment in the urban and neighbourhood environment, but those goals often collide with the actual possibility of realizing them. It is therefore essential that the redevelopment objectives be consistent with the construction capacities of the managing bodies. As a consequence, some factors must be considered as "intervention emergencies" such as the high energy consumption of the complexes and poor internal comfort conditions. Improvement of residential living conditions could even lead to social benefits and consequences. As a result, this research has been oriented towards the definition of guidelines that could direct the managing organizations or private owners towards recovery operations that could be concretely realized by economically sustainable interventions and could have real and quantified outcomes. For the definition of the guidelines that contain possible intervention strategies, a significant sample of the public buildings constructed in Tuscany with industrialized/prefabricated techniques during the 1970s-1980s was analysed. This sample represents an example of the Italian building stock built with similar techniques in the same period throughout the country.

The sample of analysed buildings includes 48 public residential complexes with a total of almost 2000 flats built with industrialized and prefabricated techniques by the IACP Institute (Istituto Autonomo Case Popolari–Autonomus institut for public residential buildings) in the provinces of Florence and Prato from 1979 to 1987. For the architectural analysis of the buildings, research was carried out at the CasaSpA. (new name for IACP) archive, the current managing body of the complexes. This research allowed analyses of all the buildings, the exact definition of their components and implants and the building construction processes.

The most commonly used prefabrication/industrialization systems in the two provinces (Florence and Prato) of this study were (Nuti 1984):

- Triedro System: Prebeton Casa-construction company (Montevarchi–AR);
- Elle System: Italcase Prefabbricati-construction company–Bertelli (Brescia);

- K System: Ices-construction company (Cagliari);
- Ca-ab System: Immobiliare Scipione Capece-construction company (Naples);
- Pica System: Unicoop Coarce-construction company;
- Sbs System: Sacep-construction company (Bertinoro–FC);
- Igeco Pontello System: Igeco Pontello–construction company (Vezzano Ligure–SP);
- Tunnel System: Edil Progress–construction company (Prato);
- Prefabricated formworks System: Immobiliare Scipione Capece-construction company (Naples).

Some systems are linear and therefore contain pillars and beams, while others are two-dimensional or three-dimensional, consisting of reinforced concrete large panels (they can have solid or cable walls). Such systems have been widely used to build residential complexes throughout the country.

The buildings were studied and classified according to different types and by identifying sample cases for each type. The analysis of these buildings, prior to defining the recovery hypothesis, demonstrated the common aspects of the construction and issues from an architectural point of view that could limit the possibilities of interventions. From an energy perspective, the conducted analyses on the sample case units highlighted the low energy performance and low comfort levels inside the flats both in summer and winter.

This study considers a group of buildings made with a great panel structure. In this group a majority of the buildings are linear buildings made with solid reinforced concrete walls and slabs; the plan organization is similar, as well as the materials used for the envelope and finishing. Attention was given to the plans, the elevations, and the components and materials used, along with all other technological aspects, to find an intervention solution for recovery. The analyses highlight that some interventions should be avoided, such as the internal re-distribution or the facades re-organization, so as not to interfere with the building structure and to reduce costs. In addition, possible active and passive strategies to achieve better energy savings are reduced. For the improvement of internal comfort, the use of air conditioning systems has been discarded because they are expensive both energetically and economically. This research project also set the goal of allowing tenants to live in the apartments even during renovation. The analysis process carried out on an exemplary case, and the benefits obtained after the application of the planned interventions will be briefly presented below.

2. METHODOLOGY

The research method was developed as follows:

1. Identification and global analysis of buildings. Public residential buildings built using industrialization/prefabrication systems after the 1960s in the provinces of Florence and Prato were identified. The archive documentation of all buildings was analysed, the construction systems adopted most frequently were identified and the buildings considered to be typologically the most significant were chosen (Bazzocchi et al. 2014).
2. Detailed analysis of buildings. For each representative building, the environmental and technological systems were studied to identify all the characteristics of the construction and critical points. Moreover, an energy analysis of these constructs was conducted to evaluate their energy performance during the cold and warm seasons, paying particular attention to the thermal comfort conditions.

This paper analyses only one building as a representative of a building group.

3. Identification of recovery interventions and energy checks on all the analysed buildings as a result of their adoption. In this phase, some possible interventions were planned, congruent with the initial objectives, and the building response was verified in terms of energy consumption after their application (Bazzocchi et al. 2016). The paper shows this phase applied to the building being analysed.
4. Validation of the retrofitting protocol by applying it to other buildings of the same group.

3. THE CASE STUDY

The intervention area is located in Iolo, a district in the city of Prato, and consists of two linear buildings (building A and building B) situated on a secondary street perpendicular to the main road connecting the suburb to the city centre.

Building construction began on 23/06/1980 and ended on 29/10/1982. The structural system adopted is the tunnel system, consisting of vertical septa and slabs in reinforced concrete cast in place.

The climate of Prato can be classified as a Mediterranean climate (typical of coastal areas on the Mediterranean Sea) with mild winters and with very high solar radiation in summer, and with rains concentration especially in winter since the summer is warm and almost dry. Only building A will be shown in this work.

3.1 Analysis of the building

The study of the building from the architectural and technological point of view and from its energy performance is presented here.

3.1.1 Analysis of the environmental and technological system

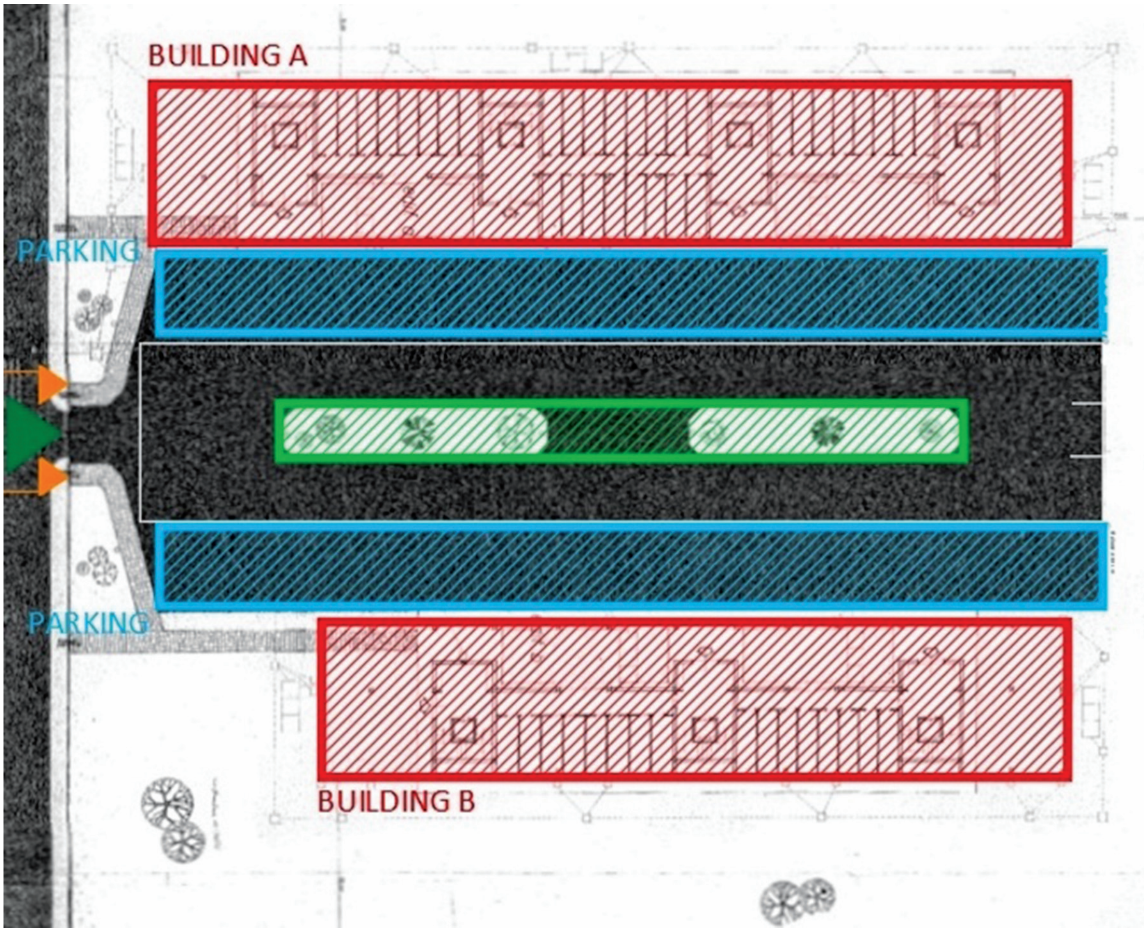
The building type factor classification (Nuti 2010) for the analysis of the chosen building can be summarized in five (5) classes according to distinctive features: land use/environmental factors, morphological/dimensional factors, distributional/functional factors, formal/aesthetic factors, and technical/technological factors.

The two constructions (A and B) are located at the same site and are oriented mainly along an east-west axis, perpendicular to the main roads (Figure 1). Buildings are linear with a classical rectangular shape, placed symmetrically relative to a central axis. The entrances to the buildings are located on central courtyards, in which two strips of parking spaces are placed along both buildings and a private road marked by two green spaces that separate vehicular and pedestrian lanes. The areas behind the buildings are reserved for private green areas. The main housing access occurs through the stairwells situated on the main front of both buildings.

The ground floor is characterized by the presence of porches and cellars, which create a direct link between the area and the appurtenant central green area located at the back. This layout is possible due to the opening of large passages on the transverse walls made of reinforced concrete, which constitute the main structure of the buildings.

Building A is the larger of the two (65x11 m). It contains 32 apartments distributed over four floors with eight units per floor. The areas with the arcades are located at the ends of the building and at the main front, corresponding to two blocks of eight cellars each accessed through passages created on the lateral septa of the staircases. The other two blocks of cellars are located in the central area of the building. Analysed by distributional and functional characteristics, the building follows a modularity in plan organization (AA.VV 1980). Indeed, the

FIGURE 1. General plan showing building site organization (buildings A and B, the parking area, the green area, the driveway and the walkway).



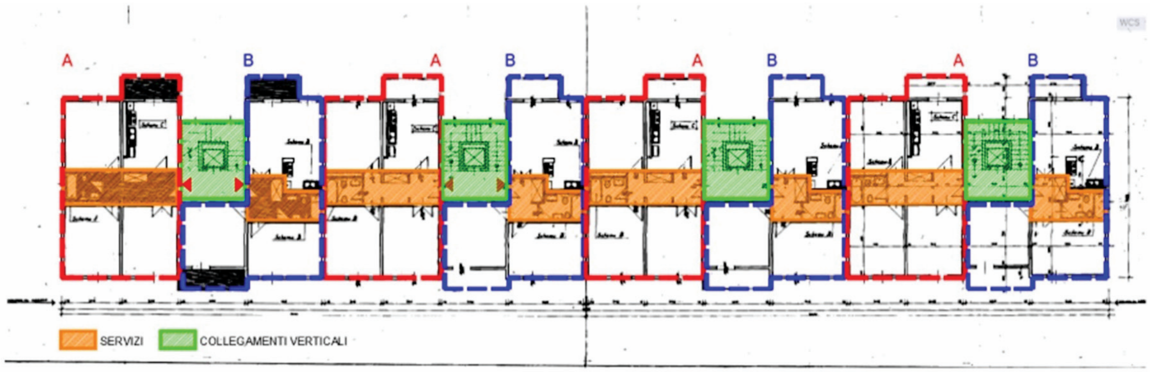
plan consists of an aggregation of four modular blocks; each block contains a central stairwell and one flat on each side of the stairs. The type of structure used allows an easy distribution of units. Each stairwell is used by two units of different sizes:

- Type A (four units, approximately 70 m^2);
- Type B (three units, approximately 60 m^2).

Both units are organized in functional bands: the main bands are the living area and night area, separated in the middle from a secondary band consisting of a distributional area and a service area. In the larger accommodation, this secondary band position is placed in the middle in terms of building depth, while in the smaller one is shifted with respect to the axis (Figure 2). This displacement is possible because the supporting septa of the structure are only in the transverse direction and there are no constraints inside the apartments in the longitudinal direction.

The building presents regular and simply plastered facades. The elevations present a modularity depending on the structural system. The openings are placed in the same position depending on the modules with a width of 1.10 m. The south façade (Figure 3) has a "loggia" 1.20 m

FIGURE 2. Typical floor plan—Building A: Service areas are highlighted in orange, flat Type A and flat Type B in red and blue, respectively and the stairwells are highlighted in green.

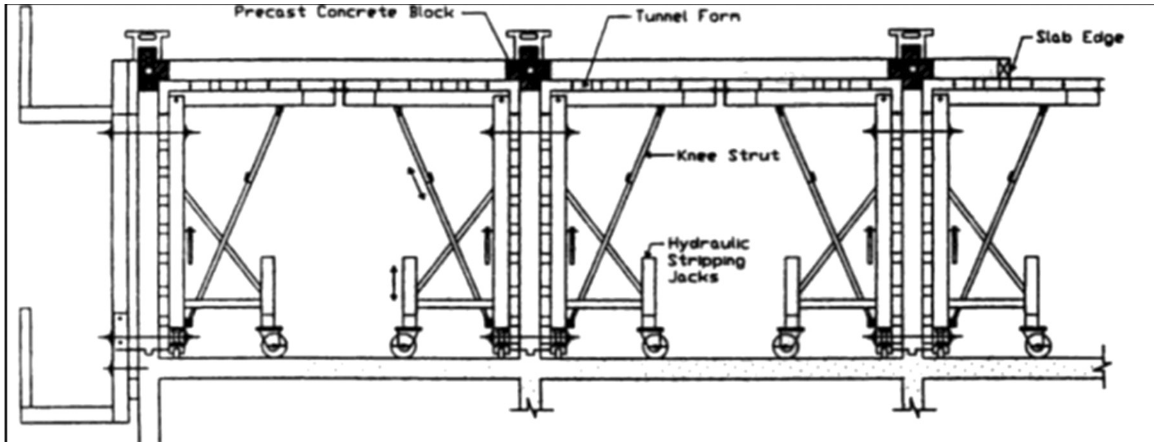


deep. In addition to the presence of these overhangs that characterize this elevation, another element to be highlighted is the distinction of different plaster colours. The north elevation has the same characteristics of modularity as the previous one and the same differentiation in terms of the use of different paint colours on the front.

The most relevant technological system is the structural system. The structure adopted for the building being assessed was constructed with the tunnel forming method (I.C.I.E 1978), which consists of vertical partition walls and casting concrete slabs with an industrialized system of formworks with a "reversed U" shape (entire tunnel) or even a "reversed L" (middle-tunnel) that are then coupled to form a U (Figure 4). The components of the tunnel are two vertical flat elements and one horizontal metal element. All these elements are reinforced on the internal

FIGURE 3. South elevation of building A.

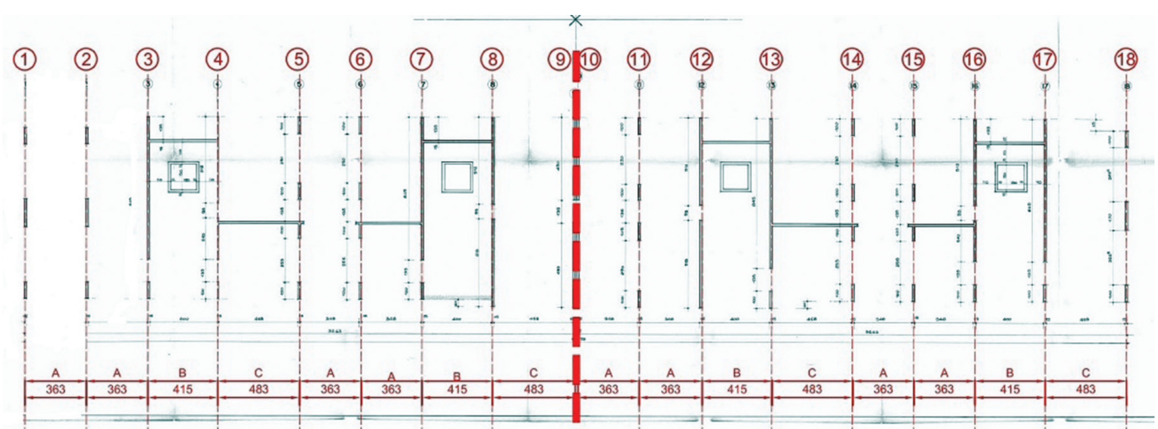
FIGURE 4. Tunnel System (I.C.I.E. 1978).



side with folded plates that contain concrete casting. The basic modules generally have a depth of 1.25 m and are juxtaposed to one another to form the depth of the tunnel with the necessary measure required to cover the entire body of the building. The height of each element is equal to the useful gross height of the room to be built, and the span depends on the structural calculation and on the size of the project rooms. The tunnel elements are then placed on the floor side by side and with a distance of approximately 14–16 cm from one another to achieve the thickness of the structural septa. This set of tunnel elements, which constitutes the core of the whole building, is completed by a set of accessories needed for the casting phases or to interface the structure with the completions. These elements are the "banches," special metal formworks for the walls that give them the external finishing, special structural fixtures for the stairwells and lifts, horizontal jet restrictors for the slab plans and vertical ones placed in the spaces between the various pipes, and vertical and horizontal mobile formworks for obtaining openings in walls and floors.

The building presents the frames organized according to a variable wheelbase distance following the sequence AABC, where A = 3.63 m, B = 4.15 m (stairwell) and C = 4.83 m (Figure 5). The sequence is repeated in the same way for the whole building development.

FIGURE 5. Concrete frames. Distinct "ground floor" septa with frame numbers.



This structural system affects the flats' internal distribution: internal partition walls in the transversal direction (bearing walls of the tunnel system) mark the division between the rooms. The external walls, as a direct consequence of the type of structure, are made up of reinforced concrete that is 15 cm thick and an internal counter-wall 5 cm thick of "Placomur" (polystyrene insulation glued to the supporting wall and plasterboard panel coating). The interior plasterboard partitions, used to divide rooms along the longitudinal axis, are 10 cm thick, and all interior plaster surfaces are made up of gypsum. The slabs are made up of reinforced concrete as well. The lower surface of the reinforced concrete slab (15 cm thick) between the first and ground floor consists of "Eraclit" panels (mineralized wood wool insulation panel) with a thickness of 5 cm and scratched plaster finishing glued to the intrados of the slab. The windows and door windows of the apartments are made of Swedish pine wood and have plastic blinds. The technical implants consist of autonomous heating systems with gas-fired boilers for each single apartment and a simple distribution of radiators generally without thermostatic valves and with a single chronothermostat. Kitchens are usually set against a false gypsum plasterboard wall with a thickness of 8 cm separating the services duct area that is approximately 17 cm deep from the load-bearing wall or from another plasterboard wall when there is a bathroom on the other side.

Chimneys and pipes pass through slots made on the slabs. The shafts are placed in the same position for all levels, down to the pillar floor and up to the roof covering.

The analysed building can be considered representative of one of the building groups analysed in the research; the building techniques used have created constraints in terms of the internal distribution of the flats (partitions walls in reinforced concrete), the possibility of interventions on the façade and plant maintenance or installation operations. Because of its monolithic configuration, many interventions would be invasive.

3.1.2 Energy analysis (BASE CASE)

This phase of the analysis (named BASE CASE) was fundamental to understanding building weakness and finding possible recovery strategies compatible with the building type and constraints derived from the previous analysis. This study was carried out both in semi-stationary and dynamic conditions. The global energy performance index (EP_{gl}) was evaluated, according to the National Legislative Standards D.lgs. 192/2005 (2005) (UNI/TS 11300-1:2014 2014; UNI EN ISO 52016-1:2018 2018) to establish the energy class of the building. The analysis under dynamic conditions is necessary to understand the more well-founded, thermodynamic behaviour of the building, which is closely dependent on the variability of the environmental conditions (Ferrari 2009). The simulation software used for this purpose is TRNSYS-Trnbuild.[5] Table 1 lists the energy performances of the building envelope elements by the evaluation of the thermal transmittance (U-values) and a comparison with the legislative standards values (D.lgs. 192/2005 2005) as well as the surface mass, the periodic thermal transmittance (Yie-values), the time lag (Ø), and useful parameters to evaluate their thermal inertia in summer.

Table 1 shows that the building presents good thermal inertia due to the building elements of the envelope (Evangelisti et al. 2014).

The building can be divided into three different thermal zones: the stairwells, the flats and the cellars/attic. (Table 2)

5.The software was developed at the University of Wisconsin and distributed in Europe with IISiBat interface, developed by CSTB (Sophia Antipolis-France).

TABLE 1. Energy performance of the building envelope elements.

Building Elements	Components	U-values W/m²K	Standards U-values W/m²K	Surface mass kg/m²	Yie-values W/m²K	Time lag (Ø)
External walls	1. External plaster (1 cm) 2. Reinforced concrete wall (15 cm) 3. Glass wool (4 cm) 4. Gypsum internal cladding (1 cm)	0.698	0.29	324.60	0.245	6 h26'
Arcade slabs	1. Ceramic (1 cm) 2. Reinforced concrete slab(15 cm) 3. Eraclit Panel (5 cm) 4. Smoothing with plaster (0.2 cm)	0.83	0.29	326.30	0.273	6 h19'
Attic slabs	1. Leca concrete (10 cm) 2. Reinforced concrete slab (15 cm) 3. Smoothing with plaster (0.1 cm)	0.92	0.29	361.40	0.195	9 h4'
Windows	1. Wooden frames 2. Simple double glass	2.83	1.80	—	—	—

For each thermal zone, internal gains, set-point temperatures (the set-point temperature is applied only for the winter season –20°C because there is no air conditioning system) and the ACH number were defined. The ACH number represents the number of air change rates to be considered in a room. Standards give 0.5 h^{-1} for residential buildings and this is the value considered in the dynamic simulations of this work. This value represents a mean value that takes account of both the infiltrations through the envelope and the air changes due to window openings.

TABLE 2. Input data according to the different thermal zones.

Thermal zones	Heating system	Internal gains (W/person)	Lighting gains (W/m²)	ACH (h^{-1})
Stairwells	NO	/	0.5	0.2
Flats	YES	100	5	0.5
Cellars/Attic	NO	/	0.5	0.2

FIGURE 6. Classification scale on the basis of $EP_{gl,nren}$. (D.lgs.n.192/2005 2005, appendix 1).

	Classe A4	≤ 0,40 $EP_{gl,nren,rif,standard\ (2019/21)}$
0,40 $EP_{gl,nren,rif,standard\ (2019/21)}$ <	Classe A3	≤ 0,60 $EP_{gl,nren,rif,standard\ (2019/21)}$
0,60 $EP_{gl,nren,rif,standard\ (2019/21)}$ <	Classe A2	≤ 0,80 $EP_{gl,nren,rif,standard\ (2019/21)}$
0,80 $EP_{gl,nren,rif,standard\ (2019/21)}$ <	Classe A1	≤ 1,00 $EP_{gl,nren,rif,standard\ (2019/21)}$
1,00 $EP_{gl,nren,rif,standard\ (2019/21)}$ <	Classe B	≤ 1,20 $EP_{gl,nren,rif,standard\ (2019/21)}$
1,20 $EP_{gl,nren,rif,standard\ (2019/21)}$ <	Classe C	≤ 1,50 $EP_{gl,nren,rif,standard\ (2019/21)}$
1,50 $EP_{gl,nren,rif,standard\ (2019/21)}$ <	Classe D	≤ 2,00 $EP_{gl,nren,rif,standard\ (2019/21)}$
2,00 $EP_{gl,nren,rif,standard\ (2019/21)}$ <	Classe E	≤ 2,60 $EP_{gl,nren,rif,standard\ (2019/21)}$
2,60 $EP_{gl,nren,rif,standard\ (2019/21)}$ <	Classe F	≤ 3,50 $EP_{gl,nren,rif,standard\ (2019/21)}$
	Classe G	> 3,50 $EP_{gl,nren,rif,standard\ (2019/21)}$

According to the energy performance classification scale (Figure 6), the building presents energy class E (EP_{gl} = 111.36 kWh/m^{2}y).

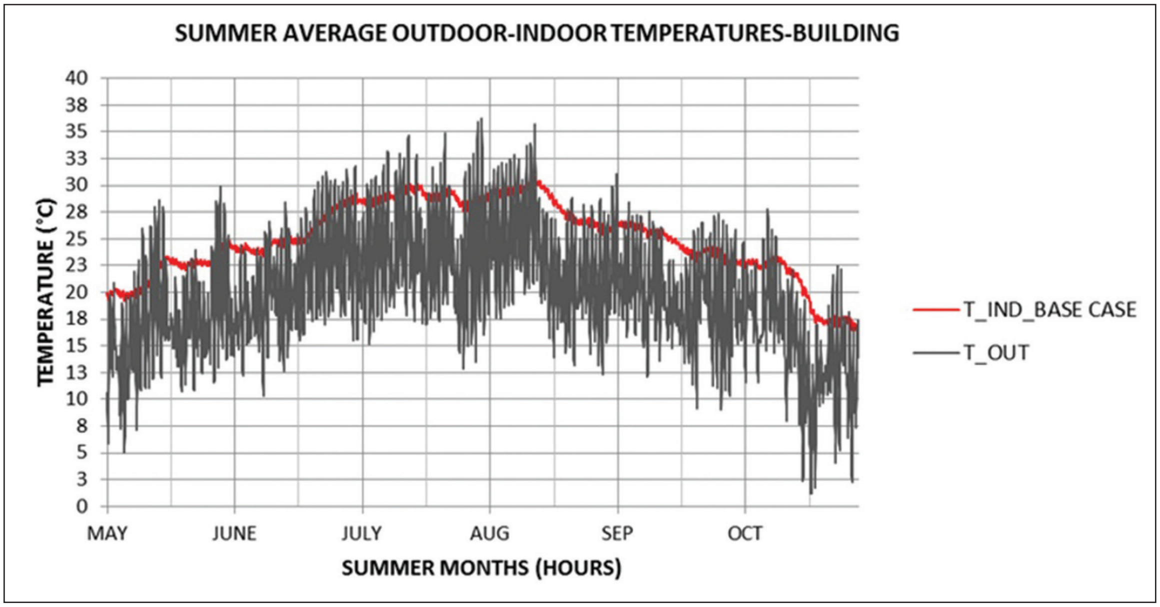
The dynamic simulations allow evaluation of the indoor temperatures (T_IND), the relative humidity (RH), and the humidity ratio (absolute humidity-HR) hourly, in order to assess thermal comfort conditions.

One method for the evaluation of thermal equilibrium conditions and well-being was developed by Fanger (Fanger 1970). It is based on the determination of the predicted mean vote (PMV) index. Fanger established a physical/emotional scale expressed through a vote of comfort from –3 (cold) to +3 (hot). The ISO Standard 7730:2006 (2006) recommends staying within the range of –2 to +2. Fanger proposed another statistical index predicted percentage of dissatisfied (PPD). Three different ranges of PMV correspond to three different values of PPD: **1**) –0.2 < PMV < +0.2 → PPD < 6%; **2**) –0.5 < PMV < +0.5 → PPD < 10%; and **3**) –0.7 < PMV < +0.7 → PPD < 15%. This work was used in this model for the evaluation of thermal comfort levels.

Through the dynamic simulation, the mean indoor temperatures of the entire building were evaluated. Figure 7 shows the comparison among the indoor temperatures (T_IND), averaged across all the flats, and the outdoor temperatures (T_OUT) in summer months. The temperatures in winter are always consistent to 20°C because that is the set-point temperature for the heating system. October is included in the summer period because the heating system is turned off according to the national standards. Otherwise, this month would be considered as a "shoulder month" along with September and May.

Furthermore, the number of hours during each summer month exceeding 26°C and 28°C (#hoursT > 26–28°C), was evaluated. The first value is the threshold for the comfort range, and the second one was chosen considering the mean temperatures in July and August (above 28°C). Figure 8 (on the left) highlights that July and August present almost all the monthly temperatures above the comfort limit value, and in August, more than half the month has hours with temperatures above 28°C. The same considerations have been made for the relative humidity values (RH). The RH comfort range threshold is set at 60%; the study analysed the number of hours with a RH above 60% and above 70%, another threshold used when addressing humidity issues (#hoursRH > 60–70%). Figure 8 (on the right) shows that May, June, September

FIGURE 7. Hourly trend of mean temperatures during the year and the outdoor temperature hourly trend. These values are averaged across all the flats.



and October present higher levels of relative humidity, and July presents almost half the month with RH above 70%.

Until now, the entire building has been considered because the evaluations are referred to as averaged values. Thermal comfort conditions must be evaluated by analysing thermal zones. However, averaged values across all the flats do not give thorough results. The flat per floor with the worst indoor comfort conditions (indoor temperatures and relative humidity) was then studied. Figure 9 summarizes the number of flats per floor (corresponding to the thermal zones) and the table below the figure highlights the worst flats/floor.

The results of the worst flat in the building (flat 6 on floor 4) will be presented in this work. Table 3 shows the significant indoor air temperature values of the flat.

Regarding the indoor comfort conditions, the PPD index was the studied parameter with its three varied percentages of dissatisfaction (PPD < 6% = -0.2 < PMV < +0.2; PPD < 10% = -0.5 < PMV < +0.5; and PPD < 15% = -0.7 < PMV < +0.7). The number of hours with PPD <

FIGURE 8. On the left #hoursT > 26–28 °C. On the right #hoursRH > 60–70%. Values averaged across all the flats.

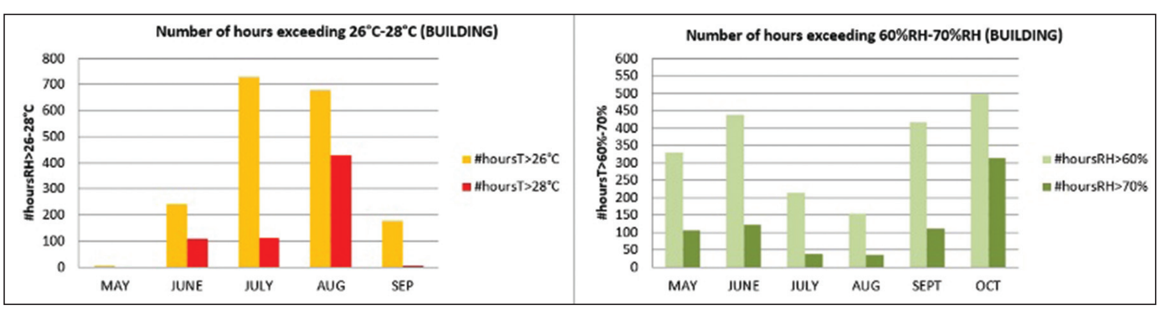
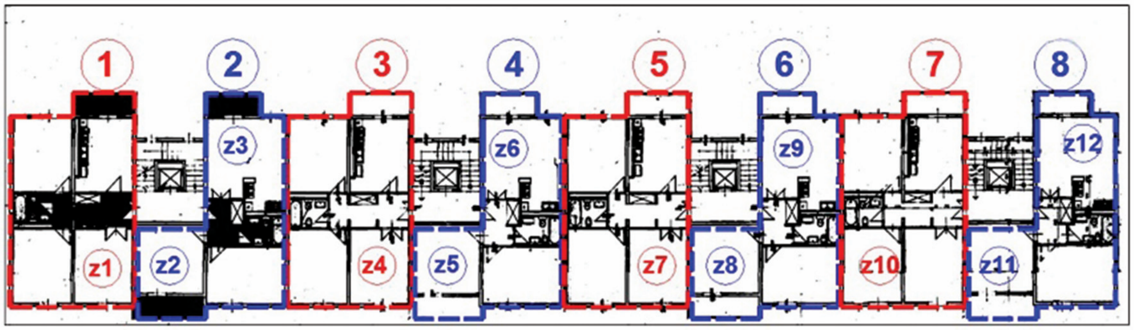


FIGURE 9. Thermal zones and worst flats/floor in Building A.



FLOOR 1	FLOOR 2	FLOOR 3	FLOOR 4
FLAT 8	FLAT 6	FLAT 2	FLAT 6

6–10–15% (#hours < 6–10–15%PPD) was then calculated for each summer month. The higher the number of hours with PPD < 6%, the better the comfort level is inside the flat. Figure 10 shows that in July and in August there are no PPD < 6–10–15%, meaning that the percentage of dissatisfaction is high and that there is a substantial discomfort level. The other months present higher values, meaning that the flat presents a good compromise between indoor temperatures and RH values. The analysed results show that the presence of large mass building elements is not sufficient to guarantee good indoor comfort levels.

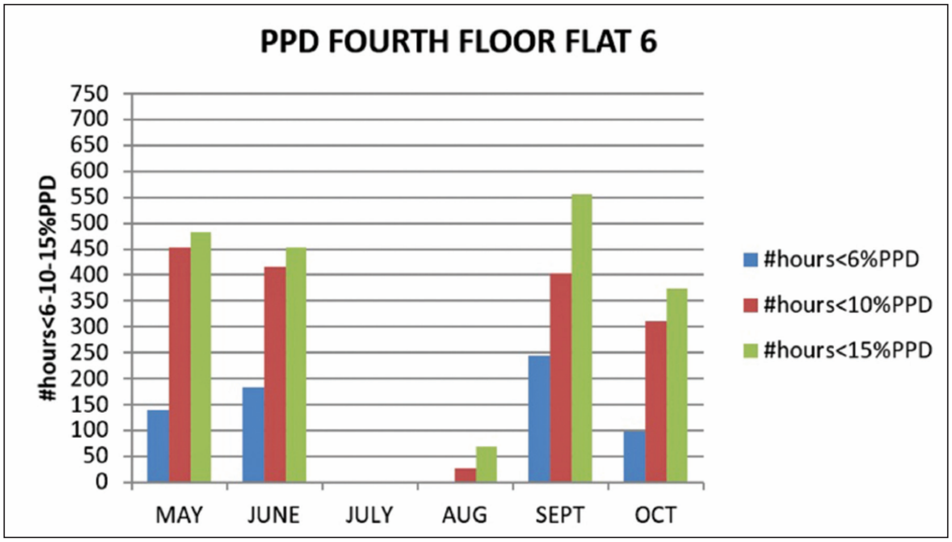
According to the previous results, the most suitable strategies in relation to the building type are as follows:

- *During the winter season:* minimize heat loss due to both transmission through the envelope (for example, due to poor insulation or windows with low performance) and ventilation (natural opening of the windows and air leakage as a result of poor tightness of the buildings);

TABLE 3. Temperature values during the central months in summer and during the shoulder season (MAY-SEP-OCT).

FLAT 6-FLOOR 4			
	JUNE	**JULY**	**AUG**
MEAN T (°C)	26.30	29.67	28.83
MAX T (°C)	30.39	31.14	31.40
	MAY	**SEP**	**OCT**
MEAN T (°C)	22.48	25.17	20.34
MAX T (°C)	25.69	27.30	23.88
MIN T (°C)	19.25	22.29	16.20

FIGURE 10. #hours < 6–10–15%PPD in flat 6-floor 4.



- *During the summer season:* ensure good cooling to improve thermal-hygrometric internal comfort.

3.2 Envelope Recovery Hypothesis (STEP A)

The first step (STEP A) was the application of an insulation layer on the facades, on the attic and arcade/cellar slabs and a substitution of the windows. These were the most suitable strategies (Ma et al. 2012; Boeri and Longo 2012; Carraretto 2008) according to the building type and with the aim of the work (best solution at lower costs). The insulation chosen for the external walls and for the arcade/cellar slabs was an expanded polystyrene (EPS) panel that was 8 cm thick. This material is the most commonly used insulation in residential housing recovery because of its good energy performance results and low-cost relative to other insulation materials. For the attic floor, mineral wool insulation (10 cm thick) was chosen. The thickness of the insulation on the walls/slabs and the windows type were chosen according to actual legislative standards (D.lgs.n.192/2005 2005).

The number of air change rates (ACH) considered in the model is 0.5/h, taking into account an average value for good indoor air quality inside the apartments (according to UNI EN 15251:2008 2008).

According to the energy performance classification scale (Figure 6), the "recovered" building presents energy class B (EP_{gl} = 55.69 kWh/m^{2}y).

Considering the behaviour of the whole building, the addition of the insulation layer on the facades led to an increase in summer indoor temperatures of almost 2°C and a consequent decrease in relative humidity. Despite the improvement of the thermal inertia of the building elements, due to the increase in the surface mass and the increase in the time lag of the thermal wave (Table 4), the accumulated heat during the warmer hours of the day is not able to leave the flat during the cooler hours, further increasing the indoor temperatures.

The envelope recovery led to an increase in the number of hours exceeding 26°C and 28°C in all months (in October the mean temperature values are still under 26°C).

TABLE 4. Energy performance of the building envelope elements before and after the recovery interventions.

Building Elements	Components after the recovery		U-values W/m^2K	Surface mass kg/m^2	Yie-values W/m^2K	Time lag (Ø)
External walls	1. External plaster (1cm) **2. EPS panel (8 cm)** 3. Reinforced concrete wall (15 cm) 4. Glass wool (4 cm) 5 Gypsum internal cladding (1 cm)	Before	0.698	324.60	0.245	6 h26’
		After	**0.25**	**325.47**	**0.013**	**8 h13’**
Arcade slabs	1. Ceramic (1 cm) 2. Reinforced concrete slab (15 cm) 3. Eraclit Panel (5 cm) **4. EPS panel (8 cm)** 5. Smoothing with plaster (0.2 cm)	Before	0.83	326.30	0.273	6 h19’
		After	**0.28**	**327.10**	**0.083**	**6 h44’**
Attic slabs	**1. Mineral wool panel (10 cm)** 2. Leca concrete (10 cm) 3. Reinforced concrete slab (15 cm) 4. Smoothing with plaster (0.1 cm)	Before	0.92	361.40	0.195	9 h40’
		After	**0.28**	**377.90**	**0.028**	**13 h40’**
Windows	1. PVC windows 2. Climaplus Saint Gobain glass	Before	2.83	—	—	—
		After	**1.70**			

This increase is represented by the following Equation 1:

$$R_{T,26-28} = \%h_{bc,26-28} - \%h_{A,26-28} \tag{1}$$

where

$R_{T,26-28}$ = percentage variation in hours exceeding 26°C or 28°C during the month;

$\%h_{bc,26-28}$ = percentage of hours exceeding 26°C or 28°C in BASE CASE ($\%h_{bc,26-28} = \#h_{26-28}/H_m$) in the month;

$\%h_{A,26\text{–}28}$ = percentage of hours exceeding 26°C or 28°C in STEP A ($\%h_{A,26\text{–}28} = \#h_{26\text{–}28}/H_m$) in the month;

$\#h_{26\text{–}28}$ = number of hours exceeding 26°C or 28°C in the month; and

H_m = number of hours in the month.

The negative signs of the percentages in the table (Figure 11) represent the increase in temperatures.

The same evaluation was performed for the RH values (Equation 2). In this case, the increase of temperatures led to a decrease of RH values (positive values):

$$R_{RH,60\text{–}70} = \%h_{bc,60\text{–}70} - \%h_{A,60\text{–}70} \quad (2)$$

FIGURE 11. Comparison between the number of hours exceeding 26–28°C in STEP A and BASE CASE during summer months.

$R_{T,26\text{-}28}$ (%)		
STEP A/BASE CASE		
	$R_{T,26}$	$R_{T,28}$
MAY	-	-
JUNE	-12%	-12%
JULY	-2%	-12%
AUG	-8%	-33%
SEP	-42%	-21%
OCT	-	-

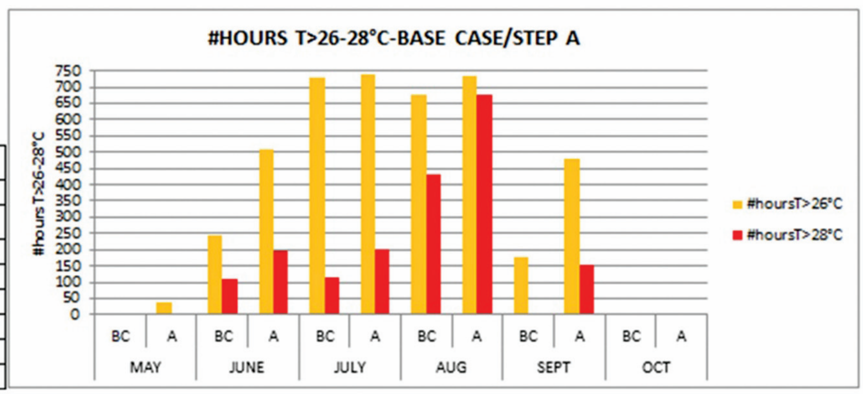
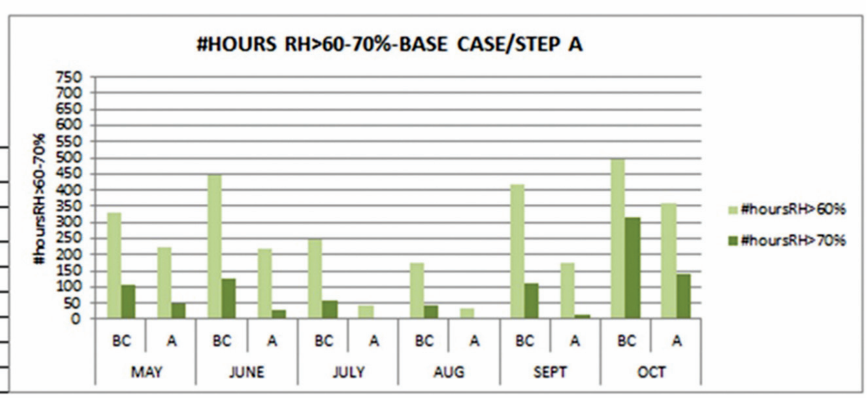


FIGURE 12. Comparison between the number of hours exceeding 60%–70% of relative humidity in STEP A and BASE CASE during summer months.

$R_{RH,60\text{-}70}$ (%)		
STEP A/BASE CASE		
	$R_{RH,60}$	$R_{RH,70}$
MAY	15%	8%
JUNE	32%	13%
JULY	28%	7%
AUG	19%	6%
SEP	34%	13%
OCT	18%	23%



where

$R_{RH,60–70}$ = percentage variation in hours with RH exceeding 60% or 70% during the month;

$\%h_{bc,60–70}$ = percentage of hours with RH exceeding 60% or 70% in BASE CASE ($\%h_{bc,60–70} = \#h_{60–70}/H_m$) in the month;

$\%h_{A,60–70}$ = percentage of hours with RH exceeding 60% or 70% in STEP A ($\%h_{A,60–70} = \#h_{60–70}/H_m$) in the month;

$\#h_{60–70}$ = number of hours with RH exceeding 60% or 70% in the month; and

H_m = number of hours in the month.

Hours exceeding 70% RH are almost completely eliminated in June, July, August and September.

The answer in terms of thermal comfort after the envelope recovery is presented by the analysis of indoor temperatures, RH values and PPD index in flat 6 on floor 4 (Table 6).

Directly considering the evaluation of the PPD index, the variation in terms of percentage of hours with PPD < 6–10–15% between BASE CASE and STEP A was calculated with the following Equation 3:

$$R_{PPD,6–10–15} = \%h_{bc,6–10–15} – \%h_{A,6–10–15} \quad (3)$$

where

$R_{PPD,6–10–15}$ = percentage reduction in hours with PPD < 6–10–15% during the month;

$\%h_{bc,6–10–15}$ = percentage of hours with PPD < 6–10–15% ($\%h_{bc,6–10–15} = \#h_{6–10–15}/H_m$) in the month;

TABLE 6. Temperature values during the central months in summer and during the shoulder season (MAY-SEP-OCT).

FLAT 6-FLOOR 4						
	JUNE		JULY		AUGUST	
	BASE CASE	STEP A	BASE CASE	STEP A	BASE CASE	STEP A
MEAN T (°C)	26.85	28.24	30.33	31.95	29.52	31.27
MAX T (°C)	31.02	32.18	31.85	33.14	32.10	33.34
	MAY		SEPTEMBER		OCTOBER	
	BASE CASE	STEP A	BASE CASE	STEP A	BASE CASE	STEP A
MEAN T (°C)	23.07	24.18	25.80	27.48	20.84	22.55
MAX T (°C)	26.36	27.42	28.15	29.65	24.59	25.75
MIN T (°C)	19.45	20.13	22.69	24.54	16.45	18.31

$\%h_{A,6\text{–}10\text{–}15}$ = percentage of hours with PPD < 6–10–15% in STEP A ($\%h_{A,6\text{–}10\text{–}15}$ = $\#h_{6\text{–}10\text{–}15}/H_m$) in the month;
$\#h_{6\text{–}10\text{–}15}$ = number of hours with PPD < 6–10–15% in the month; and
H_m = number of hours in the month.

The intervention on the envelope led to an increase in the internal temperatures and a consequent decrease in relative humidity. The comfort conditions (Figure 13) improved during the "shoulder" months (May and October) because of the increase in the mean temperature values (too low values, especially in October) along with the decrease in RH values, while in September, temperatures reached values considered too high. During the central months, the indoor comfort conditions suffered a significant decrease, despite the decrease in indoor humidity, demonstrating that temperature is the most important factor that influences the indoor comfort in these months.

In summary, if STEP A (envelope recovery) increased the energy performance of the building by decreasing the energy demand for heating, it also worsened the indoor comfort conditions by increasing the indoor temperatures by almost 2°C compared to the BASE CASE during the central months in summer.

The next section examines the effort to improve the indoor comfort levels by decreasing internal temperatures and by maintaining acceptable RH values by exploiting the free-cooling technique and without introducing air conditioning systems into the building. The construction presents a good thermal mass, but this characteristic is not sufficient to ensure good comfort levels. A further increase in thermal inertia, by using, for example, different insulation materials or by inserting new layers into the building's elements, would contrast with the characteristics of the building structure and the research aim (low-cost and non-invasive strategies).

3.3 Application of the mechanical ventilation system (STEP C1–STEP C2)

The introduction of fresh air into a house could help to decrease indoor temperatures (Artmann et al. 2007). To do so, it is necessary to increase the number of ACH when outdoor temperatures present useful values (outdoor temperatures < indoor temperatures). The introduction of outdoor air can be accomplished by natural or mechanical ventilation systems or hybrid systems. The exploitation of natural ventilation techniques in this building is difficult because

FIGURE 13. Comparison between the PPD index values in BASE CASE and STEP A.

$R_{PPD,6\text{-}10\text{-}15}$ (%)			
STEP A/BASE CASE			
	$R_{PPD,6}$	$R_{PPD,10}$	$R_{PPD,15}$
MAY	-18%	5%	-3%
JUNE	25%	56%	38%
JULY	-	-	-
AUG	-	3%	9%
SEP	30%	36%	38%
OCT	-15%	-10%	-5%

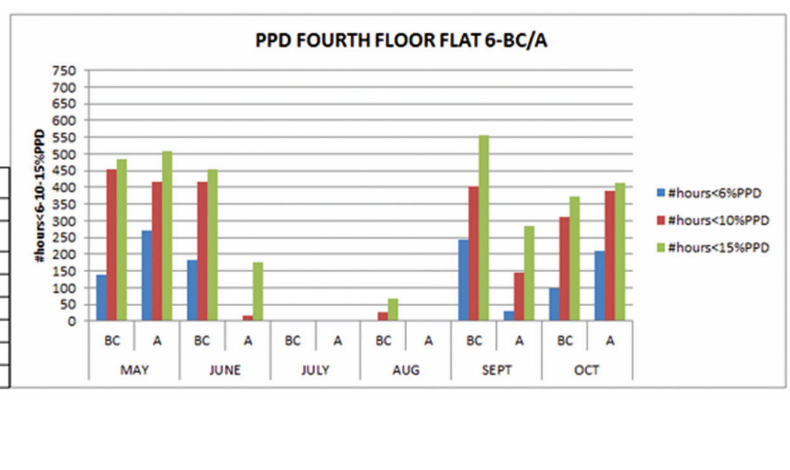


TABLE 7. Monthly schedule of the ACH and switching control on the MVS.

MONTH	ACH (h^{-1})
MAY	**0.5**
JUNE	**1:** when T_out < T_ind **0.5:** when T_out > T_ind
JULY	**1:** when T_out < T_ind **0.5:** when T_out > T_ind
AUGUST	**1:** when T_out < T_ind **0.5:** when T_out > T_ind
SEPTEMBER	**1:** when T_out < T_ind **0.5:** when T_out > T_ind
OCTOBER	**0.5**

the façades are already configured. Mechanical ventilation systems (MVSs) are useful both to improve the indoor air quality and to decrease the higher temperatures by using the ventilation system for cooling (Artmann et al. 2007). In general, these systems use fans to move the air, and thus, they consume only the electricity necessary to make them work. These systems do not condition the air,[6] they simply "change" the air according to the objective they are required to satisfy. Unlike natural ventilation systems based exclusively on temperature gradient and wind power, the correct ACH number can be guaranteed through the use of an MVS by setting it on the mechanical ventilation handling unit. In addition, with the use of MVSs, air cleaning through filtration might be applied (it depends on the mechanical system), avoiding the introduction of pollutants into the building as well as a reduction in outdoor noise, a common issue in a naturally ventilated building. Various configurations of mechanical ventilation are in use (Santamouris and Wouters 2006). They can be divided into two groups: single stream and double stream. The hypothesis is to use the single stream MVSs because of the low costs (Liddament 1996; Coydo et al. 2016) and the simplicity of the installation. These systems are divided into two groups: in the mechanical extract ventilation (MEV) system, a fan is used to mechanically remove air from a space, and in the mechanical supply ventilation (MSV) system, fresh outdoor air is introduced into the house with a fan. The MSV is the supply system used because it can work in summer by providing fresh air during cooler hours of the day by setting the required air flow rate.

The system needs openings on the envelope, which can be realized on the window frame to facilitate air recirculation inside the flat, along with openings on the internal walls to make the air pass from one room to another.

STEP C-1

This section analyses the effect of doubling the ACH up to 1/h during the central months in summer. In this system, the temperature of the inlet air into the house is equal to the external

6. The primary function of mechanical ventilation systems is to ensure the right number of air change rates, but they can include additional units and be able to condition the inlet air or dehumidify it.

TABLE 8. Temperature values during the central months in summer and during the shoulder season (MAY-SEP-OCT). Comparison between STEP A and STEP C-1.

FLAT 6-FLOOR 4						
	JUNE		JULY		AUGUST	
	STEP A	STEP C-1	STEP A	STEP C-1	STEP A	STEP C-1
MEAN T (°C)	28.24	26.18	31.95	29.40	30.28	28.63
MAX T (°C)	32.18	30.37	33.14	31.21	32.33	31.49
	MAY		SEPTEMBER		OCTOBER	
	STEP A	STEP C-1	STEP A	STEP C-1	STEP A	STEP C-1
MEAN T (°C)	24.18	23.47	27.48	24.83	22.55	21.24
MAX T (°C)	27.42	26.80	29.65	27.32	25.75	24.21
MIN T (°C)	20.13	19.80	24.54	21.70	18.31	17.30

temperature because of the absence of any conditioning treatment and the choice to not include the heat recovery. All flats have their own system depending on the outdoor/indoor temperature differences, which increase the air change rates when conditions are appropriate. It will be necessary to install two sensors: one measuring outdoor temperatures and the other measuring indoor temperatures. The input data are summarized in Table 7, according to the different months.

Concerning May and October, it was decided to maintain ACH = 0.5/h for all the months because the results in terms of RH and indoor temperatures were acceptable.

Analysing flat 6 on floor 4, the decrease in the mean temperature values in May and in October (Table 8), despite the maintenance of ACH = 0.5/h, depends on the fact that the total number of air change rates is higher than 0.5/h because ACH_{INF} = 0.2/h[7] (infiltrations through the envelope) must be taken into account. As widely expressed already, ACH = 0.5/h is a mean value that takes account of both the infiltration through the envelope and the air changes due to a window opening. If a mechanical ventilation system is introduced into the flat, then the air change rates for infiltration must be taken into account.

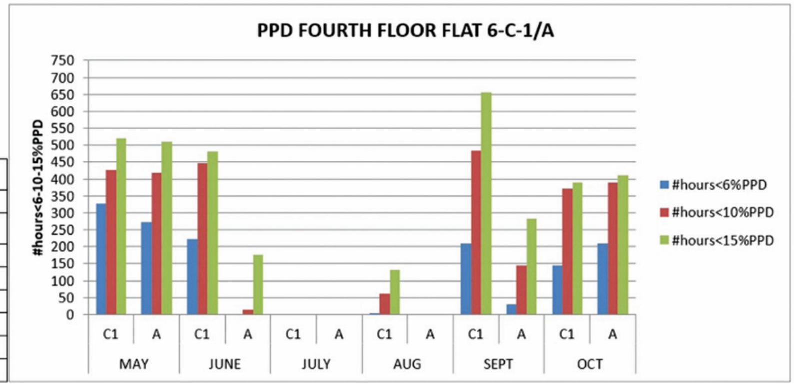
To understand the results in terms of thermal comfort, a comparison of PPD values between STEP A (envelope recovery) and STEP C-1 (ACH = 1/h) was performed (Figure 14).

According to the PPD index, the most relevant increase in internal comfort is shown in June and September. In July, ACH = 1/h does not improve the indoor conditions, even if it contributes to a decrease in the indoor temperatures. In addition, the effects on the comfort conditions are negligible in August; although in this case, the mean temperature value decreases by approximately 1.60°C (still above 28°C). In October and May, the decrease in indoor temperatures and the increase in relative humidity worsen the comfort conditions, but the percentage of the variation is negligible.

7. Mean value approved by the Building Regulation Document F (Government H. 2010) for building air infiltration.

FIGURE 14. Comparison between the PPD index values in STEP A and STEP C-1.

$R_{PPD,6\text{-}10\text{-}15}$ (%) STEP C-1/STEP A			
	$R_{PPD,6}$	$R_{PPD,10}$	$R_{PPD,15}$
MAY	-7%	-1%	-1%
JUNE	-31%	-60%	42%
JULY	-	-	-
AUG	-	-8%	-18%
SEP	-25%	-47%	-52%
OCT	9%	2%	3%



STEP C-2

This section analyzes the results after the application of ACH = 2/h. In May and October, the number of air change rates is still ACH = 0.5/h, so comfort level changes will occur mainly in the months between May and October. (Table 9)

Still considering flat 6 on floor 4, the increase in ACH up to 2/h led to a decrease in the mean indoor temperature values, and in August, this value even reached the comfort value (≈26°C).

The increase in ACH = 2/h led to a relevant decrease in temperatures in July and August compared to STEP C-1 (ACH = 1/h) results and led to an increase in relative humidity, especially in June and September (Table 10).

To understand the results in terms of thermal comfort, a comparison of PPD values between STEP C-1 (ACH = 1/h) and STEP C-2 (ACH = 2/h) was performed (Figure 15).

TABLE 9. Monthly schedule of the ACH and switching control on the MVS.

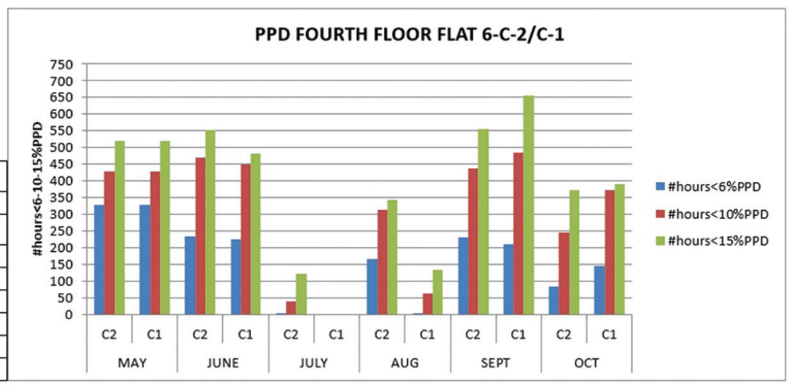
MONTH	ACH (h^{-1})
MAY	**0.5**
JUNE	**2:** when T_out < T_ind **0.5:** when T_out > T_ind
JULY	**2:** when T_out < T_ind **0.5:** when T_out > T_ind
AUGUST	**2:** when T_out < T_ind **0.5:** when T_out > T_ind
SEPTEMBER	**2:** when T_out < T_ind **0.5:** when T_out > T_ind
OCTOBER	**0.5**

TABLE 10. Temperature values during the central months in summer and during the shoulder season (MAY-SEP-OCT). Comparison between STEP A and STEP C-2.

FLAT 6-FLOOR 4						
	JUNE		JULY		AUGUST	
	STEP A	STEP C-2	STEP A	STEP C-2	STEP A	STEP C-2
MEAN T (°C)	28.24	24.61	31.95	27.48	30.28	26.76
MAX T (°C)	32.18	29.01	33.14	29.83	32.33	30.28
	MAY		SEPTEMBER		OCTOBER	
	STEP A	STEP C-2	STEP A	STEP C-2	STEP A	STEP C-2
MEAN T (°C)	24.18	23.47	27.48	23.08	22.55	20.92
MAX T (°C)	27.42	26.80	29.65	25.96	25.75	23.90
MIN T (°C)	20.13	19.80	24.54	19.39	18.31	17.27

FIGURE 15. Comparison between the PPD index values in STEP C-1 and STEP C-2.

$R_{PPD,6-10-15}$ (%)			
STEP C-2/STEP C-1			
	$R_{PPD,6}$	$R_{PPD,10}$	$R_{PPD,15}$
MAY	0%	0%	0%
JUNE	-1%	-3%	-10%
JULY	0%	-6%	-17%
AUG	-23%	-34%	-28%
SEP	-3%	7%	14%
OCT	8%	17%	2%



The simulations results for the flat in June show a moderate improvement in comfort conditions despite the increase in relative humidity. In September, maintaining ACH = 1/h seems to be the best solution to not increase RH values. Instead, in July and in August, the further increase in ACH improves the indoor comfort conditions.

4. CONCLUSIONS

The analysis of the building and its behaviour in terms of energy consumption and thermal comfort led to the definition of its weaknesses and the consequent establishment of compatible strategies for the building type (public residential building built with industrialized techniques and particularly with solid large panels in reinforced concrete) and to the research aim (low-cost strategies and with the aim to maintain the tenants in the flats during the renovation works). The adopted procedure resulted in considerable energy savings and the improvement of indoor comfort conditions in summer and winter. The application of an insulation layer on the façades and window replacement has improved the envelope quality in both summer and winter. During the cold season, this intervention led to a reduction in heat losses and to a related significant reduction in energy consumption (a decrease of almost 40% in total building energy demand for heating). During the warm months, the application of the insulation layer on the facades slowed the incoming heat. Despite the increase in thermal capacity, the dynamic simulations have shown an increase in temperatures of almost 2°C in the flats. Building envelopes with good periodic thermal transmittance do not guarantee indoor comfort levels (Fosas et al. 2018). A ventilation system was then applied by exploiting "ventilative cooling" through the use of the outdoor cooler air (especially during the night). The simple supply system (MSV) was chosen rather than exploiting natural ventilation techniques.

The best fitting of ACH for each summer month was then evaluated. The first step (STEP C-1) led to relevant improvements in the comfort conditions in June and September, while the increase in ACH up to 2/h (STEP C-2) led to relevant improvements in July and August. Analysing the sample flat, the mean temperature value in August was approximately 26°C (comfort threshold) compared to the values in BASE CASE (29.52°C) and in STEP A (31.27°C). Table 11 summarizes the best fitting ACH number according to the different months. In June, ACH = 1/h and ACH = 2/h give similar results in terms of indoor thermal comfort conditions, and the difference between the two steps was approximately the increase in RH levels. In September, in STEP C-2, the increase in RH worsens thermal comfort. However, humidity control along with temperature control could be useful.

These analyses have shown that this control could be more useful during the "shoulder months," but the humidity levels inside the apartments need to be taken into account throughout the year.

The document presents only a part of this research project and the proposed procedure. Subsequent studies will show the integration of relative humidity control in the buildings.

In the study, the procedure was applied first to a sample case considered exemplary for its typological building group and then validated by applying it to four other buildings of the same group, obtaining similar results.

Systematically, the chosen procedure for the buildings retrofitting considers the following interventions:

TABLE 11. Best fitting ACH number per each month.

Summer months	Air change rates ACH (1/h)
MAY	0.5
JUNE	1/2
JULY	2
AUGUST	2
SEPTEMBER	1
OCTOBER	0.5

- application of an insulation layer on the envelope and replacement of windows sills;
- window replacement; and
- installation of a simple mechanical ventilation system without air treatment but with internal temperature and humidity control through sensors.

The final results for the considered group in this paper are a decrease of almost 40% in the total building energy demand for heating a decrease of almost 3°C inside the flats during the central months in summer (July and August) and 1°C in June, and the maintenance of relative humidity inside the flats under 60% during all the summer months and during the shoulder season (May, September and October).

Thus, this method with the recommended interventions is applicable to all buildings with similar characteristics located in similar climate zones as it obtained considerable energy savings and indoor thermal comfort improvements.

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