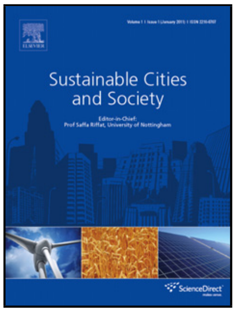

Title: Investigating energy saving potential in a big shopping center through ventilation control

Authors: Domenico Curto, Vincenzo Franzitta, Sonia Longo, Francesco Montana, Elenora Riva Sanseverino

PII: S2210-6707(19)30264-1
DOI: https://doi.org/10.1016/j.scs.2019.101525
Article Number: 101525

Reference: SCS 101525

To appear in:

Received date: 29 January 2019
Revised date: 22 March 2019
Accepted date: 28 March 2019

Please cite this article as: { https://doi.org/

Investigating Energy Saving Potential in a Big Shopping Center through Ventilation Control

Domenico Curto[1], Vincenzo Franzitta, Sonia Longo,
Francesco Montana, Elenora Riva Sanseverino
Department of Engineering
University of Palermo (UNIPA), Palermo, Italy
e–mail: domenico.curto@unipa.it, vincenzo.franzitta@unipa.it, sonia.longo@unipa.it, francesco.montana@unipa.it, eleonora.rivasanseverino@unipa.it

HIGHLIGHTS

1) Economic and energy analysis in Do It Yourself shopping centers ventilation systems is presented, comparing three different stores with different HVAC plants and climatic regions;
2) A brief review on retrofit solutions in non-residential building sector is performed;
3) The economic profitability of three new different retrofit hypotheses for each store and is evaluated;
4) A comparison between the less attractive retrofit solution and most widely adopted retrofit solution is provided;
5) A comparison between international standards for ventilation systems design is provided.

ABSTRACT

This paper investigates energy saving measures for the ventilation system of large shopping centers. This kind of buildings is characterized by high yearly energy consumptions, because of the high level of operating hours and the frequent use of obsolete technologies. In the analyzed case studies, three big Do It Yourself (DIY) shops, located in Italy, are considered. Two different approaches are considered, they are aimed at reducing the annual energy consumption for the indoor air exchange of the sales area. The first considered retrofit solution consists in the installation of heat recovery exchangers, reducing the energy demand for the air thermal treatment without changing the airflow value. In the second scenario, smart air quality sensors are inputs for the modulation of the air exchange rate according to the actual requirement for indoor air quality. In a third scenario, the application of both retrofit

---

[1] Corresponding author

solutions is considered. For each scenario, the paper reports the yearly energy savings, the avoided CO_2 emissions and cost saving indicators. Furthermore, as the three shops are equipped with different heating systems and are located in different parts of Italy, a technological and climatic comparison is provided.

KEYWORDS

Buildings; Energy saving; Indoor Air Quality; Shopping Center; Ventilation Control.

1 INTRODUCTION

The building sector is one of the most impacting on energy consumptions of a developed country (European Commision, 2010). Buildings are indeed responsible for 40% of the energy consumption of the EU member states and 36% of their CO_2 emissions. Furthermore, about 35% of buildings in EU are over 50 years old, so these may represent the main target for future energy efficiency policies. ‘Energy saving’ is one of the means suggested in the Kyoto Protocol for getting a reduction of environmental pollution and global warming (Beccali, Cellura, & Mistretta, 2007). ‘Energy saving’ can be defined as a reduction of primary energy consumptions in final uses only by the utilization of more efficient equipment, without compromising the quality of service (Retail Forum for sustainability, 2011).

More in detail, different examples of ‘energy saving’ measures can be found in the literature, divided by sector (ICF Consulting Ltd, 2015):

- in the primary and secondary sectors, the substitution of obsolete equipment with more modern and efficient ones, in order to reduce the energy consumption, is often adopted;
- in the transport sector, a spreading solution is the implementation of public transport vehicles supplied by hydrogen, electrical energy or biomass-derived fuels (Cotana et al., 2014), so as to reduce the dependence from fossil fuels, greenhouse gas emissions as well as environmental pollutants (Volpe, Bermudez Menendez, Ramirez Reina, Messineo, & Millan, 2017);
- in the buildings sector, many different techniques can be adopted (Ferrari & Zanotto, 2016), ranging from the improvement of thermophysical properties of the building envelope to the adoption of building automation systems both in tertiary and residential buildings (Ingrao, Messineo, Beltramo, Yigitcanlar, & Ioppolo, 2018). In this way, the energy demand can be met efficiently, while reducing the energy consumption for air conditioning/ventilation and lighting (Naik, Dhamankar, & Karve, 2015; Pan, Xu, & Li, 2012).

Figure 1 shows how the primary energy consumptions in Italy has evolved in last sixteen years, by sector: industry, transport and buildings (Eurostat, 2019). As it can be noted, the buildings sector has a great impact on the national energy demand.

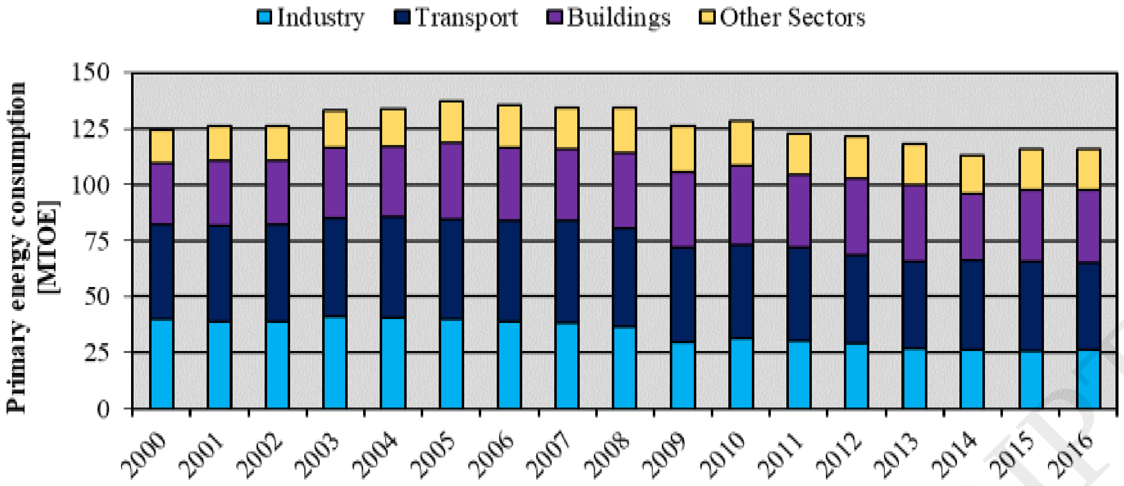

Figure 1. Primary energy consumption in final uses in Italy by sector (Eurostat, 2019)

Figure 2 shows the yearly trend of the primary energy consumption for commercial activities, as a part of the total energy consumption for buildings. Two terms are here considered: electricity and thermal consumptions. A comparison between Figure 1 and Figure 2 reveals that the primary energy consumption for commercial activities is about one sixth of the total primary energy consumption for buildings in Italy.

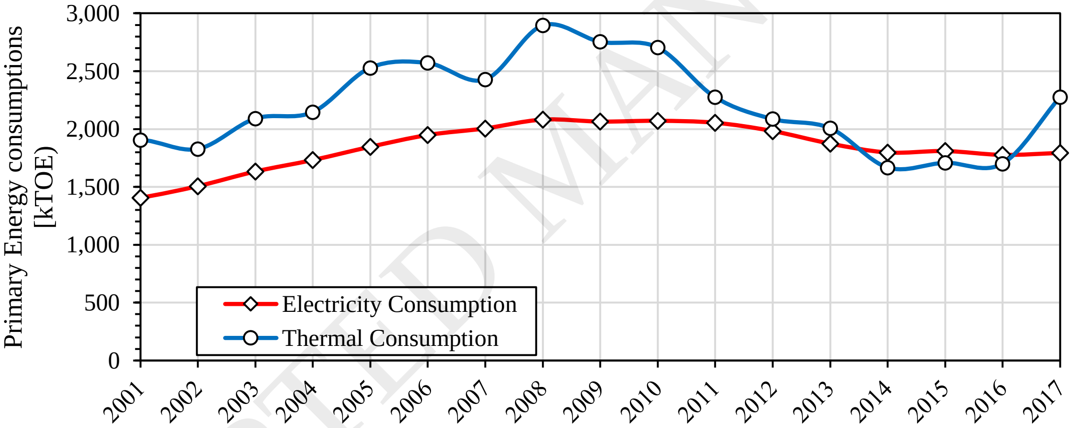

Figure 2. Annual primary energy consumption for commercial activities in Italy (Eurostat, 2019)

In the last two decades, the commercial activities have been growing in Italy, thus requiring the construction of large buildings. The yearly statistics of the Italian Ministry of Economy considered two different activities: malls ("Grandi Magazzini", in Italian), mainly dedicated to the sale of non-food products, and supermarkets ("Supermercati", in Italian), specialized in food sales. Both of these activities require a commercial area above 400 square meters (Osservatorio Nazionale del Commercio, 2017).

Figure 3 shows the total number of shopping centers (malls and supermarkets) and the number of commercial buildings having an area that is larger than 2000 square meters since 2001 in Italy. The figure also shows the segmentation by geographic location, dividing Italy into four areas: Middle, North East, North West, South & Islands. As energy consumption indicator, the overall heated surface of malls and supermarkets respectively amounts to 3.26 and 9.76 millions of square meters (Osservatorio Nazionale del Commercio, 2017).

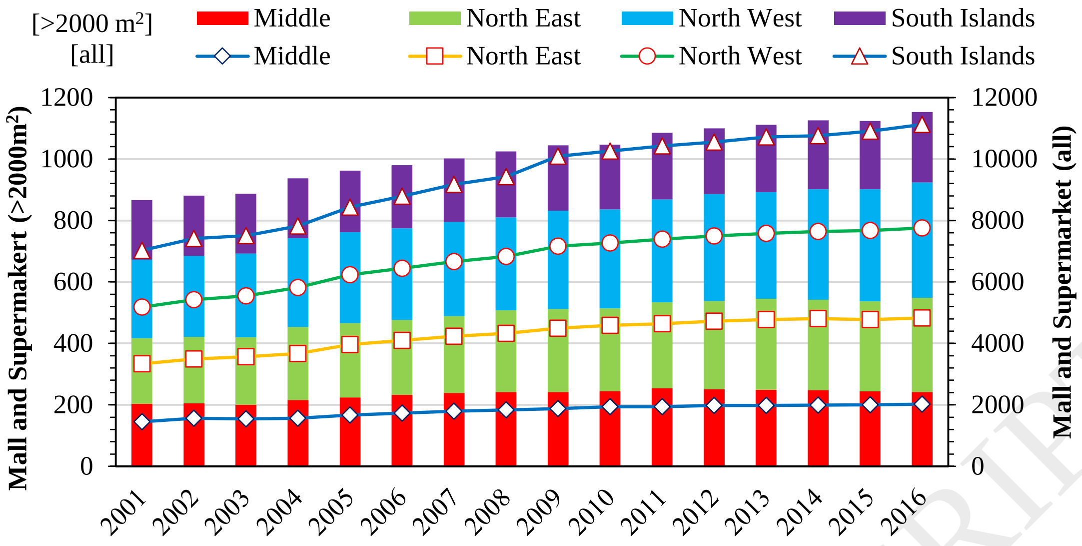

Figure 3. Number of shopping centers over sixteen years in Italy

These buildings are considered very energy-intensive (International Council of Shopping Centers (ICSC), 2016), mainly because of the high air conditioning demand. As the number of this kind of buildings is growing very rapidly, a case study on the energy saving potential in shopping centers appears to be interesting for the scientific community; besides very few studies about similar topics are reported in literature.

HVAC systems in shopping centers usually have a central air-conditioning system, providing also for indoor air exchange, representing only a fraction of the total airflow used to offset thermal losses (*ASHRAE Handbook - Fundamentals*, 2017). As in most cases HVAC systems serving shopping centers are obsolete, working with fixed airflow (Canbay, Hepbasli, & Gokcen, 2004; Homod, 2014), the installation of smarter technologies may induce interesting energy and economic savings. Some examples of technological improvements are air-to-air heat exchangers to recover energy from the air extracted or inverter-equipped fans and motorized shutters for the regulation of the airflow.

The work carried out in this paper belongs to a growing literature sector (Calay & Wang, 2013; Chenari, Dias Carrilho, & Gameiro Da Silva, 2016; Curto, Montana, & Milone, 2018; Yu et al., 2016) concerning the evaluation of potential energy and economic savings resulting from the installation of heat recovery exchangers and automation technologies in the HVAC plant of non-residential buildings. In details, the work is focused only on the savings related to the indoor air change, as the whole energy consumption for the heating and cooling of the building is more related to the thermophysical features of building envelope and to the local climate, thus making the results obtained in this analysis more general.

As the modulation of the airflow rate, according to the real-time demand of occupants for health reasons, is not considered by the technical standards below considered, the authors want to demonstrate the potential benefits that can be achieved introducing innovative techniques to control the indoor air quality.

In order to demonstrate the suitability of these solutions, big shopping center buildings have been selected as case study. In order to generalize the results presented in this paper, three shopping centers were selected in Italy, one near Milan (Northern Italy) with a gas-based heating system, and two near Bari (Southern Italy), one with an electrical-based and the other with a gas-based heating system. In this way, retrofit benefits are also compared between two shops with similar climate but different heating systems and between two shops with similar heating system but different climate conditions.

All the three case studies are investigated considering the economic benefits, using the initial investment, the breakeven time and the discounted cash flow in ten year as indicators. From the environmental point of view, the avoided CO_2 emissions and the avoided primary energy, electricity and gas consumptions were evaluated and compared.

2 BACKGROUND

2.1 Theoretical Background on air ventilation

Air is composed mainly of gases such as nitrogen (78%), oxygen (21%), argon (1%), and carbon dioxide (0.04%). Other materials, whose concentration is variable, may be contained in outdoor air depending on natural phenomena, as wind erosion or volcanic eruption, or on anthropogenic processes, as electric power generation or agriculture. These substances, known as contaminants or pollutants, can affect the human health and should be somehow limited or removed. This problem is particularly important in the indoor environment, where people spend most of their time (European Comission, 2003; Klepeis et al., 2001) and where other pollutants may also appear, because of human presence (e.g. tobacco smoke, carbon dioxide, ammonia or ethanol) or building materials (e.g. formaldehyde, paints, VOC or radon, that is also radioactive) (*ASHRAE Handbook - Fundamentals*, 2017).

The main solution to reduce the concentration of pollutants and odors in the indoor air is the dilution with external air, eventually pre-treated (filtered), if air contaminants concentration overcomes values defined by national standards ("ANSI/ASHRAE 62.1 - Ventilation for Acceptable Indoor Air Quality," 2013). As an example, Table 1 provides a list of acceptable concentration of contaminants in the external air that allows to skip the filtration process in USA. While the air change in residential buildings is generally carried out by opening the windows, in non-residential buildings the air dilution is mainly provided with mechanical ventilation systems to stay below maximum air pollutants concentration values.

Ventilation systems designers are assisted by international standards, as ASHRAE Standard 62.1 ("ANSI/ASHRAE 62.1 - Ventilation for Acceptable Indoor Air Quality," 2013) in USA and European Report CEN CR 1752 ("CEN CR 1752 - Ventilation for Buildings: Design Criteria for the Indoor Environment," 1998). These documents contain a prescriptive method, based on minimum ventilation rates values indicated for different types of buildings, and an analytical method to calculate the required ventilation rate, depending on type of pollutants, acceptable concentrations, and emission rates. The difference between these standards lays into the approach, as CEN CR 1752 method is based on people entering a space, while ASHRAE 62.1 method is aimed at satisfying adapted persons, i.e. people occupying a space that have adapted to the odor level (Olesen, 2004).

Table 1. Acceptable contaminant concentration for external air direct use in USA ("ANSI/ASHRAE 62.1 - Ventilation for Acceptable Indoor Air Quality," 2013)

Pollutant	Primary Standard	Averaging Times	Secondary Standard
Carbon monoxide	9 ppm (10 mg/m^3)	8 hours	None
	35 ppm (40 mg/m^3)	1 hour	None
Lead	0.15 μg/m^3	Rolling three-month average	Same as primary
Nitrogen dioxide	100 ppb	1 hour	-
	0.053 ppm (100 μg/m^3)	1 year (arithm. mean)	Same as primary
Particulate matter (PM$_{10}$)	150 μg/m^3	24 hours	Same as primary
Particulate matter (PM$_{2.5}$)	12 μg/m^3	1 year (arithm. mean)	15 μg/m^3
	35 μg/m^3	24 hours	Same as primary
Ozone	0.075 ppm	8 hours	Same as primary
Sulfur dioxide	75 ppb	1 hour	-
	-	3 hours	0.5 ppm

2.2 Mathematical Background on air ventilation

In order to evaluate the rated airflow necessary for the dilution of an air pollutant in a room, both analytical methods of ASHRAE 62.1 and CEN CR 1752 rely on a mass balance evaluated over the indoor space. Figure 4 shows the philosophy behind these standards. In the figure, a room with volume V is depicted. This room is characterized by a constant internal pollutant production rate $\dot{C}$, diluted by an external airflow $\dot{V}$ with pollutant concentration C_{out}.

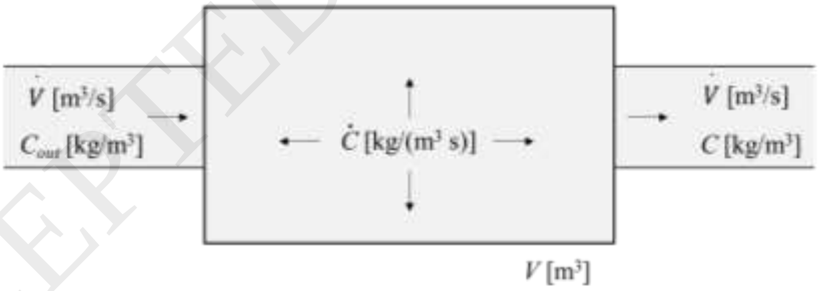

Figure 4. Schematic for rate dilution airflow calculation

Assuming a perfect air mixing in the room (lumped parameters approach), the pollutant mass balance provides:

$$\frac{d\left(C \cdot V\right)}{d\tau} = \dot{C} \cdot V + C_{out} \cdot \dot{V} - C \cdot \dot{V} \qquad 1.$$

where the unknown $C(\tau)$ is the pollutant concentration course in the room or in the extraction air varying with time τ.

Solving this equation and assuming known the pollutant concentration in the room when the dilution starts, i.e. $C(\tau=0) = C_0$, Eq. 1 can be integrated over the time τ to obtain the function $C(\tau)$ reported in Eq. 2:

$$C(\tau) = C_{out} + \frac{\dot{C}}{n} + \left(C_0 - C_{out} - \frac{\dot{C}}{n} \right) \cdot \exp(-n \cdot \tau) \qquad 2.$$

where $n = \dot{V} / V$ is the air change rate. When steady state conditions are achieved $(\tau \rightarrow \infty)$, the exponential term tends to zero and the required airflow can be calculated as:

$$\dot{V} = \frac{\dot{C} \cdot V}{C_\infty - C_{out}} \qquad 3.$$

where C_∞ is the pollutant concentration in the room in steady state condition, i.e. the required indoor value, indicated by national standards. Ventilation efficiency E_v can be introduced in Eq. 3, in order to consider non-perfect air mixing in the room, thus rising the required ventilation value:

$$\dot{V} = \frac{\dot{C} \cdot V}{(C_\infty - C_{out}) \cdot E_v} \qquad 4.$$

Prescriptive methods are instead based on a different approach. As an example, ANSI/ASHRAE 62.1 ("ANSI/ASHRAE 62.1 - Ventilation for Acceptable Indoor Air Quality," 2013) reports the following formula, that calculates the ventilation airflow rate as a function of people's emissions and of the floor area:

$$\dot{V} = R_p \cdot P + R_a \cdot A \qquad 5.$$

where $\dot{V}$ is the breathing zone outdoor airflow, R_p is the outdoor airflow rate required per person, P is the rate number of occupants in the ventilation zone, R_a is the outdoor airflow rate required per unit area and A is the occupiable floor area.

More in details, the same standard suggests evaluating the number of people, as linear function of the floor area, so:

$$P = n_s \cdot A \qquad 6.$$

Substituting this condition into Eq. 5., the following simplified equation is obtained, that determinates the rate ventilation airflow, as function of the only floor area:

$$\dot{V} = \left(R_p \cdot n_s + R_a \right) \cdot A = \dot{V}_0 \cdot A \qquad 7.$$

Another approach, based on Ole P. Fanger studies (Fanger, 1988), has been integrated in the CEN CR 1752 ("CEN CR 1752 - Ventilation for Buildings: Design Criteria for the Indoor Environment," 1998), where the ventilation rate is determined according to the *sensory load* related to pollutant emission and on statistical Percentage of Dissatisfied (*PD*) occupants, expressed by Eq. 8:

$$PD = 395 \cdot \exp\left(-3.66 \cdot R_{p,s}^{0.36} \right) \qquad 8.$$

where $R_{p,s}$ is the ventilation rate per person and per unit sensory load. Moreover, the report suggests evaluating three different values of *PD*, equal to 15%, 20%, 30%, depending on the application, in order to find the required specific ventilation rate.

2.3 Mathematical Background on air conditioning

The heating or cooling requirement of a building over the whole conditioning season ΔQ can be evaluated as the product between the air mass to be conditioned *m* and the specific heat (i.e. heat per unit mass) Δq, as in Eq. 9:

$$\Delta Q = m \cdot \Delta q \tag{9.}$$

In constant pressure conditions, the heat rise is equal to the enthalpy rise of the air mass:

$$\Delta Q = \Delta H \Rightarrow \Delta q = \Delta h \Rightarrow \Delta Q = m \cdot \Delta h \tag{10.}$$

In this case study, the heat is provided to the building through an airflow replacing the indoor air, thus the air mass can be replaced with an airflow:

$$m = \int_{\tau_0}^{\tau_{end}} \dot{m} \cdot d\tau = \int_{\tau_0}^{\tau_{end}} \rho \cdot \dot{V} \cdot d\tau \tag{11.}$$

where $\dot{m}$ is the mass airflow, ρ is the air density, $\dot{V}$ is the volume airflow, τ_0 is the time when the conditioning season starts and τ_{end} the duration of the conditioning season. Assuming the air as the homogeneous mix of two perfect gases (dry air and water vapor), a common hypothesis in psychrometry (Çengel & Boles, 2006) can be adopted: the enthalpy of the air can be evaluated as the sum of the enthalpies of the two gases. In details, dry air enthalpy is represented by a sensible heat term (i.e. heat transfer related to a temperature variation) while the water enthalpy is composed by a sensible heat term and a latent heat term (i.e. heat transfer related to a phase transition):

$$\begin{gathered} h = h_a + h_w = c_{p,a} \cdot t + x \cdot \left(r + c_{p,w} \cdot t \right) \\ dh = dh_a + dh_w = c_{p,a} \cdot dt + dx \cdot \left(r + c_{p,w} \cdot dt \right) \end{gathered} \tag{12.}$$

where c_p is the specific heat capacity, *t* is the air temperature, *x* is the specific humidity and *r* is the latent heat of vaporization of the water. Replacing Eqs. 11 and 12 in Eq. 10:

$$\Delta Q = m \cdot \Delta h = m \cdot \int_1^2 dh = \int_{\tau_0}^{\tau_{end}} \rho \cdot \dot{V} \cdot d\tau \cdot \int_1^2 dh$$

$$\Delta Q = \int_{\tau_0}^{\tau_{end}} \int_1^2 \rho \cdot \dot{V} \cdot d\tau \cdot dh \tag{13.}$$

where enthalpy integration is evaluated between outdoor condition *1* and indoor condition *2*. As outdoor conditions are time dependent, while indoor climate is typically kept constant, Eq. 13 can be simplified in a single integral term, where the integration variable is time.

$$\Delta Q = \int_{\tau_0}^{\tau_{end}} \int_{1}^{2} \rho \cdot \dot{V} \cdot d\tau \cdot dh = \int_{\tau_0}^{\tau_{end}} \rho \cdot \dot{V} \cdot \left[h_2 - h_1(\tau) \right] \cdot d\tau \qquad 14.$$

Depending on the plant and the demand (heating is a sensible requirement while cooling may be also a latent requirement), the air conditioning may provide sensible only or both sensible and latent contributions, thus these two cases are analyzed separately.

2.3.1 Sensible requirement only

If no latent heat is exchanged, the air can be assumed as a unique gas with equivalent properties evaluated at average temperature, thus the enthalpy difference can be evaluated as:

$$\Delta x = 0 \;\Rightarrow\; \Delta h = \bar{c}_p \cdot \Delta t \qquad 15.$$

$$\Delta Q = \int_{\tau_0}^{\tau_{end}} \rho \cdot \dot{V} \cdot \bar{c}_p \cdot \left[t_2 - t_1(\tau) \right] \cdot d\tau$$

$$\Delta Q = \overline{\rho \cdot \dot{V} \cdot \bar{c}_p} \cdot \int_{\tau_0}^{\tau_{end}} \left[t_2 - t_1(\tau) \right] \cdot d\tau \qquad 16.$$

In Eq. 16, the product of air density, airflow and specific heat capacity can be considered as a constant, where thermodynamic properties are equal to the average values between external (variable) temperature and indoor required temperature, while the airflow is known and equal to the rated airflow of the fan, if no regulation is adopted. The integral term in Eq. 16 represents the cumulated requirement of air conditioning during the whole conditioning period and is commonly known as *degree days*. Thus, Eq. 16 can be simplified as in Eq. 17 adopting degree days in heating and cooling period:

$$\Delta Q_{heat,sens} = \overline{\rho \cdot \dot{V} \cdot \bar{c}_p} \cdot DD_{heat}$$

$$\Delta Q_{cool,sens} = \overline{\rho \cdot \dot{V} \cdot \bar{c}_p} \cdot DD_{cool} \qquad 17.$$

2.3.2 Sensible and latent requirement

The cooling requirement of a building may include the latent energy as an additional contribution to the sensible requirement. Assuming the air as the mixture of two perfect gases, the sensible and latent enthalpy difference can be evaluated as:

$$dh = c_{p,a} \cdot dt + dx \cdot \left(r + c_{p,w} \cdot dt \right)$$

$$\Delta h = c_{p,a} \cdot \left[t_2 - t_1(\tau) \right] + \left[x_2 - x_1(\tau) \right] \cdot \left\{ r + c_{p,w} \cdot \left[t_2 - t_1(\tau) \right] \right\} \qquad 18.$$

$$\Delta Q = \int_{\tau_0}^{\tau_{end}} \rho \cdot \dot{V} \cdot \Delta h(\tau) \cdot d\tau$$

$$\begin{aligned} \Delta Q = \overline{\rho \cdot \dot{V}} \cdot \Bigg\{ \int_{\tau_0}^{\tau_{end}} c_{p,a} \cdot \left[t_2 - t_1(\tau)\right] \cdot d\tau + \int_{\tau_0}^{\tau_{end}} r \cdot \left[x_2 - x_1(\tau)\right] \cdot d\tau + \\ + \int_{\tau_0}^{\tau_{end}} c_{p,w} \cdot \left[x_2 - x_1(\tau)\right] \cdot \left[t_2 - t_1(\tau)\right] \cdot d\tau \Bigg\} \end{aligned} \quad 19.$$

The last integral in Eq. 19, composed by the integral of a higher order differential term, can be neglected with respect to the other two terms. Thus, adopting the degree days for the first integral, and the accumulated difference of specific humidity, the equivalent of degree days for specific humidity (UNI - Ente Italiano di Normazione, 2016), for the second integral, the combined sensible and latent requirement can be expressed as:

$$\begin{aligned} \Delta Q_{heat,sens+lat} \cong \overline{\rho \cdot \dot{V}} \cdot \left(\bar{c}_{p,a} \cdot DD_{heat} + \bar{r} \cdot ADSH_{heat} \right) \\ \Delta Q_{cool,sens+lat} \cong \overline{\rho \cdot \dot{V}} \cdot \left(\bar{c}_{p,a} \cdot DD_{cool} + \bar{r} \cdot ADSH_{cool} \right) \end{aligned} \quad 20.$$

2.4 Retrofit techniques on non-residential buildings

Non-residential buildings are known to be very energy-intensive. Neglecting industrial processes, the main energy uses in this kind of buildings are air conditioning and lighting. Energy saving techniques in non-residential buildings have been rarely considered in existing literature. Very few examples are available, and also International Energy Agency programs on this topic are scarce, with IEA SHC Task 47 being the most known example (International Energy Agency, 2011).

Indeed, many works are focused on residential buildings, covering the larger portion of buildings (Wu & Skye, 2018). In order to achieve a primary energy saving, different techniques can be used:

- Increasing the energy performance of buildings' envelope (Ferrari & Zanotto, 2012);
- Supplying plants by renewable energy sources (Lucentini, Naso, & Borreca, 2014);
- Installing more modern and efficient technologies (Vakiloroaya, Samali, Fakhar, & Pishghadam, 2014);
- Optimizing the energy demand for final uses (Capozzoli, Piscitelli, Gorrino, Ballarini, & Corrado, 2017).

The first solution can potentially generate the highest energy saving, especially if applied in the design phase. In the existing literature, examples of heritage buildings in arid regions are based on free-cooling solutions, avoiding significant primary energy consumption for the indoor comfort (Khalili & Amindeldar, 2014). A common retrofit solution is the improvement of the energy performance of the envelope (Ferrari & Zagarella, 2015), replacing the external doors and windows with more performing ones, as double and triple glazed windows, and the realization of thermal insulation of the walls and roofs (Huang, Qi, & Mi, 2017).

The installation of building integrated Renewable Energy Sources (RES) is a common solution to reduce the primary energy demand from the electrical grid (Chel & Kaushik, 2018).

Although the environmental benefits related to the installation of RES systems is well demonstrated (Gerbinet, Belboom, & Léonard, 2014), in the authors' opinion it is a priority to increase the energy efficiency in final uses, in order to reduce the total energy demand of buildings regardless of which source is used.

Concerning retrofit actions, many examples are related to air-conditioning systems, and more specifically to ventilation systems (Jouhara & Yang, 2018).

In details, as the air change requirement for health reasons also requires the air thermal treatment, a possible measure is the installation of heat recovery exchangers, in order to minimize the energy expenditure for ventilation (Rose & Thomsen, 2015). New techniques try to recover the latent thermal energy related to the air humidity, introducing a thermal storage (Chen, Zhang, & Zhai, 2016; Cui, Xiao, & Wang, 2016) or a desiccant wheel, a rotating heat recovery exchanger equipped with adsorption materials (Antonellis, Intini, Joppolo, Molinaroli, & Romano, 2015).

Thanks to the improvement of control techniques, the energy efficiency of ventilation systems can be also increased through the installation of modulating control systems, as inverters to change the rotary speed of fans and compressors (Ahmed, Gao, & Kareem, 2017; Delwati, Merema, Breesch, Helsen, & Sourbron, 2018). The energy saving is achieved thanks to the smooth operative conditions of systems in comparison with the old regulation techniques (on-off control and step capacity control) (Qureshi & Tassou, 1996).

Finally, an even more sophisticated control is the innovative approach of modulating plants according to the real-time demand. As an example, the indoor artificial lighting can be modulated measuring the natural contribution from windows and skylights (Curto & Milone, 2018). In the case of HVAC system, a profitable solution is the installation of temperature sensors to control the airflow (Zhou & Huang, 2015). More specifically, in the case of ventilation systems, the air exchange rate could be managed considering the actual number of occupants or pollutants inside the indoor space.

Focusing on the thermal energy production system, two main technologies are available nowadays for the centralized indoor ventilation and climatization: air handling units (AHU) and rooftop units (RTU). The main difference between these latter technologies, in terms of heat treatment, is that AHUs only include heating or cooling heat exchangers, allowing the thermal production from any source, while RTUs enclose a heat pump/air conditioner, enabling local thermal generation and reducing piping and distribution losses. The reason to prefer one system to the other mainly resides in space or noise constraints, as both systems are very efficient, allowing temperature and airflow regulation through different systems (e.g. fan speed regulation, heat pump compressor speed regulation).

3 METHODOLOGY

Given the context depicted above, the authors are interested in evaluating the potential energy savings related to the ventilation system of large commercial buildings. Among the above reported techniques, the paper investigates the effects produced by the installation of heat recovery exchangers and control systems to modulate in real-time the air exchange flow as a function of the actual number of occupants. As demonstrated in the following sections, these techniques are characterized by limited investments and do not require significant changes on the existing buildings, as compared to the improvement in energy efficiency of the envelope or the installation of plants supplied by renewable energy sources. These peculiarities are fundamental in a retrofit scenario of existing buildings. Case studies are related to three DIY centers located in different climatic zones of Italy. For each center, the AS-IS scenario has been analyzed, considering electricity and natural gas consumption data from monthly bills and extrapolating consumptions related to air conditioning. In order to consider only ventilation-related consumptions, Italian Standard UNI 10339 (UNI - Italian Organization for Standardization, 1995) methodology has been adopted, as this method was followed for the design of these plants. In order to identify potential energy and economic saving options, the following options have been investigated:

- heat recovery from air extraction through installation of sensible heat exchangers;
- regulation of air fans according to internal pollutant concentration through installation of inverter-equipped air fans and pollution concentration sensors;
- combination of both interventions.

These improvements have been compared according to following criteria:

- primary energy savings related to airflow thermal treatments, assessed by an approach based on heating and cooling degree-days, as no latent cooling is operated in these buildings;
- primary energy savings related to fans electricity consumption;
- discounted cash flow for the period of ten years;
- breakeven time of the investment;
- avoided operating CO_2 emissions;
- avoided primary energy consumption.

In details, discounted cash flow has been evaluated through the following Eq. 21:

$$DCF = -I_0 + \sum_{i=1}^{N} \Delta E \cdot c \cdot \left[\frac{1+f}{1+\alpha} \right]^i \qquad 21.$$

where I_0 is the initial investment, N is the useful life of the investment, ΔE is the avoided yearly energy consumption, c is the energy cost, f is the inflation rate for energy sector and α is the monetary interest rate. In order to estimate operating savings deriving from the fan regulation, a standard trend for occupancy was considered, derived from a similar store, as more detailed data were not available.

Furthermore, results for each store were compared, considering two criteria:

- same location but different conditioning plant;
- different location but same conditioning plant.

4 CASE STUDIES

4.1 AS-IS scenarios analysis

As case study, the authors selected three stores belonging to a worldwide chain of DIY shopping centers. As shown in Figure 5, two stores are located in Bari (Casamassima and Santa Caterina) and one in Milan (Caponago).

Figure 5. Location of the three case studies. Maps from Google Earth Pro

The selected stores are characterized by large sales areas (over 5,000 m^2), covering a large area of the store and consequently being the most energy-consuming part. In details, the sales area is equal to 5,346 m^2 for Casamassima store, 7,745 m^2 for Santa Caterina and 6,686 m^2 for Caponago.

From the analysis of the energy bills related to last four years (2015-2018), the following graphs (see Figures 6-8) have been elaborated, showing the average annual trends of electricity and natural gas consumptions for each store.

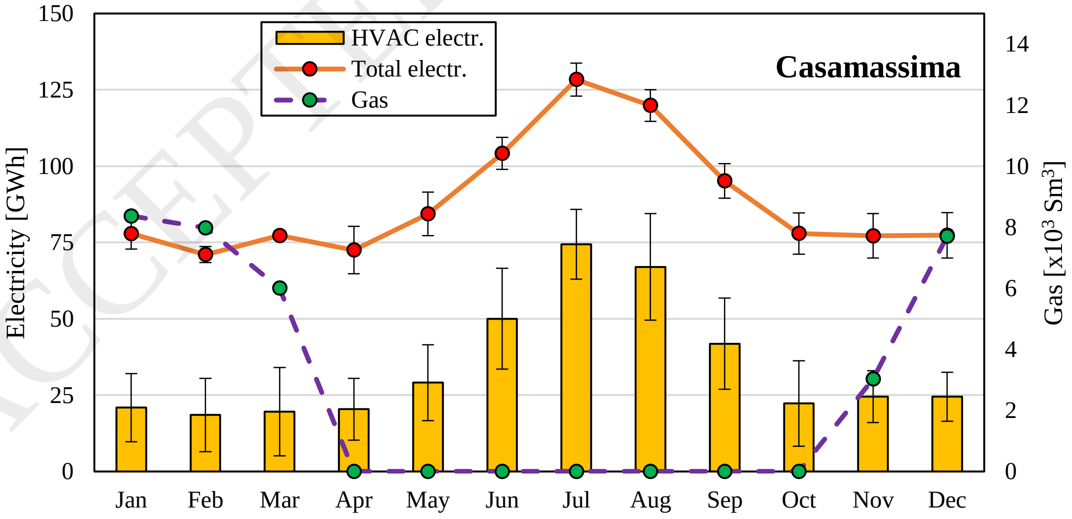

Figure 6. Average annual energy consumption of Casamassima store

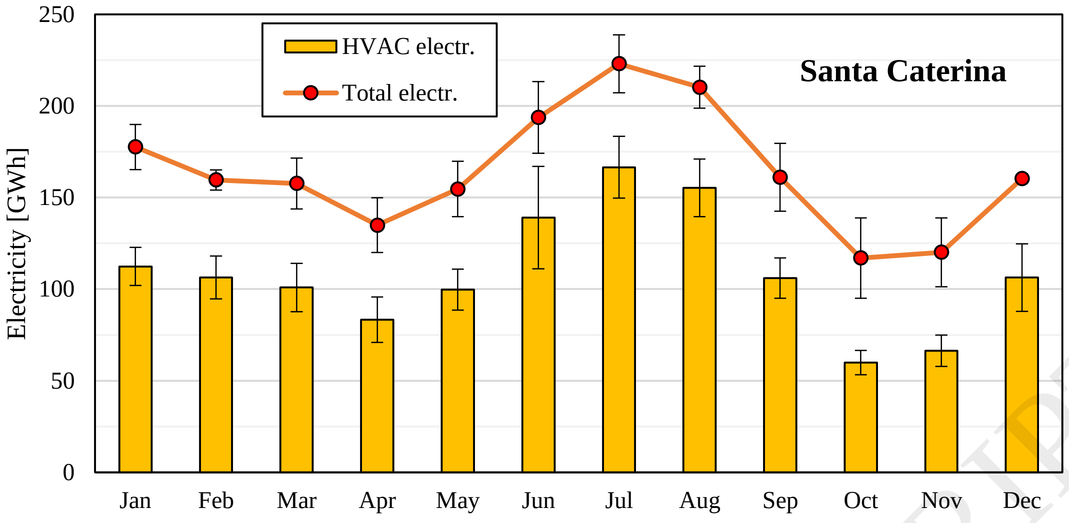

Figure 7. Average annual energy consumption of Santa Caterina store

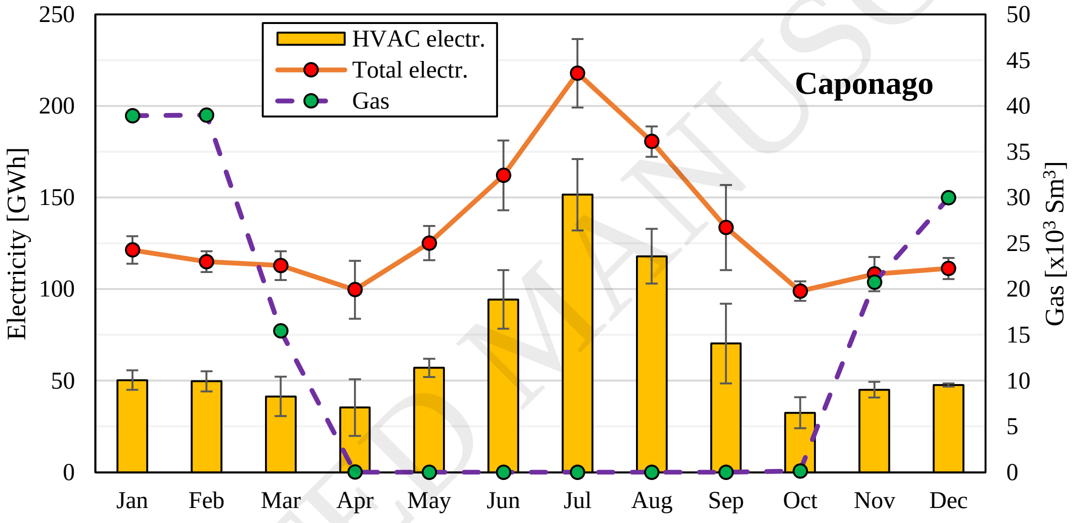

Figure 8. Average annual energy consumption of Caponago store

In the above graphs, the energy consumption for HVAC was extrapolated considering the total electricity and natural gas consumption reported in bills and removing the energy consumption related to lighting and other services, that were estimated taking into account the average daily working hours. Furthermore, data are presented with an uncertainty interval, as in the last four years several changes have happened in each store, as replacement of lighting system with LED technology, change of the daily working hours, failure of some HVAC unit, extraordinary weather conditions, change of HVAC units set-points, etc. Furthermore, data reported on bills (especially gas bills) were sometimes based on consumption estimations, verifying the actual consumption only few times per years.

As shown in Figure 6 and Figure 8, Casamassima and Caponago stores consume natural gas for heating during winter, while Santa Caterina store consumes only electricity (see Figure 7). In the first two cases, gas is consumed only for heating.

In any case, graphs demonstrate the strong relevance of the electricity consumption for HVAC, representing about 38.8% (Casamassima) and 50% (Caponago) in the cases of gas supplied for heating, while this item rises up to 66.8% (Santa Caterina) in the case of absence of gas supply.

Table 2. Yearly electrical and gas consumptions by utilities in 2017

Utility	**Casamassima electricity cons. [kWh/year]**	**Casamassima yearly cost [Sm^3/year]**	**Santa Caterina electricity cons. [kWh/year]**	**Caponago electricity cons. [kWh/year]**	**Caponago gas consumption [Sm^3/year]**
HVAC	535,230	33,069	1,476,101	757,127	144,202
Lighting	394,184	0	382,605	726,050	0
IT services	40,042	0	44,938	47,549	0
Other uses	50,057	0	60,069	57,971	0
Total	1,019,513	33,069	1,963,712	1,578,698	144,202

Focusing on year 2017, Table 2 reports the annual distribution of the electricity and gas consumptions for each building, considering four main items: HVAC, lighting, IT services and Other uses. As explained above, these values are based on mathematical models. In order to monitor the actual consumptions for the main items, these buildings will be equipped with a Building Automation System (BAS) within a few months, in order to control and measure all main loads, with attention on HVAC units.

Data reported in Table 2 were used as a starting point for the proposal of retrofit interventions and for the economic saving calculations. As large companies usually stipulate a unique supply contract for many stores, these centers' energy costs are the same, equal to 140 €/MWh for electricity purchase and to 0.35 €/Sm^3 for the gas purchase.

In order to estimate the potential energy saving related to the ventilation system, the design external airflow value has been compared to the value indicated by the technical standards. Italian standard UNI 10339 (UNI - Italian Organization for Standardization, 1995) suggests to evaluate the ventilation rate through Eq. 22:

$$\dot{V} = R_p \cdot n_a \cdot A \qquad 22.$$

This relation has the same form of Eq. 7, as the ventilation airflow is evaluated as a function of occupants only, but the occupants' number is assumed to be proportional to the net occupiable floor area.

In detail, this term is evaluated considering the number of occupants per unit surface n_a, that is tabulated for different kinds of buildings. Values obtained by Eq. 22 are in accordance with the design flowrate of ventilation systems fans, thus these values were used for the energy saving calculations. However, as UNI 10339 is quite obsolete and the external airflow values indicated in this standard are often generic, they tend to overestimate the actual number of occupants. For this reason, results of calculation evaluated with UNI 10339 have been compared with the methodology reported in the European EN 15251 standard (European Committee for Standardization, 2007), which is more recent than the Italian standard. This standard categorizes air ventilation systems for non-residential buildings according to three categories of PD value (15%, 20% and 30%), as in CEN CR 1752, while buildings are also distinguished in three further categories, according to the pollutants emissions (non-low polluted, low polluted, and very low polluted). The comparison between design external flow rate values is reported in Table 3, where the evaluation was carried out considering a building with a unitary surface, using Eq. 7 for EN 15251 and Eq. 22. for UNI 10339.

It turns out that using the norm UNI 10339 provides results that are very similar to the values obtained by applying EN 15251 in the case of low polluted building with category III ventilation system (*PD = 30%*). Thus, it is possible to state that the approach followed in UNI 10339, although resulting more energy saving-oriented, in this case, may lead to a low-quality internal comfort.

Table 3. External flow rate according to standards UNI 10339 and EN 15251 considering a store with a unitary surface

	Unit	**EN 15251**						**UNI 10339**
		Category I		**Category II**		**Category III**		
		Non-low polluted	**Low polluted**	**Non-low polluted**	**Low polluted**	**Non-low polluted**	**Low polluted**	
External air flow rate per surface	l/s m^2	3.0	2.0	2.1	1.4	1.2	0.8	0.0
Occupants per unit surface	people/m^2	0.143	0.143	0.143	0.143	0.143	0.143	0.25
External air flow rate per person	l/s people	14.7	14.7	10.5	10.5	6.3	6.3	6.5
Total design external flow rate per surface	l/s m^2	5.10	4.10	3.60	2.90	2.10	1.70	1.63

Currently, the air exchange in each store is realized using Roof Top Units (RTUs), that are installed on the roof of the sales area. These air exchange systems work with a fixed flow rate value, without the use of a heat recovery exchanger. Excluding HVAC components used for the offices, warehouse and the cooling system for the server room, the case studies buildings are equipped with the following systems:

- Casamassima's plant is composed by 4 RTUs (rated electrical power 81 kW each one) and a boiler (rated thermal power 420 kW);
- Santa Caterina's plant is equipped with 8 RTUs (51 kW);
- Caponago's plant consists in 5 RTUs (95 kW) and two boilers (735 kW each one).

In these conditions, meeting the air exchange requirement produces a significant waste of energy, for this reason, in this phase the Authors considered the hypothesis of installing a heat recovery exchanger for each HVAC unit.

The primary energy consumption for ventilation *E* has been calculated through Eq. 23:

$$E = \int_{\tau_1}^{\tau_2} \frac{\rho \cdot c_p \cdot \dot{V} \cdot |t_{out} - t_{in}|}{\eta_{vent}} d\tau \qquad 23.$$

where ρ is the air density, c_p is the air specific heat capacity at constant pressure, $\dot{V}$ is the external air flow rate, t_{out} is the external air temperature, t_{in} is the required indoor air temperature, $d\tau$ is the time interval, and η_{vent} is the energy conversion efficiency, that is equal, depending on the equipment and on the season, to:

- $\eta_{vent} = \eta_{boil}$ if a gas boiler is used during winter,
- $\eta_{vent} = COP \cdot \eta_{plant}$ if a reverse cycle machine is used during winter
- $\eta_{vent} = EER \cdot \eta_{plant}$ if a reverse cycle machine is used during summer

where η_{boil} is the gas boiler efficiency, *COP* is the reverse cycle machine Coefficient Of Performance, *EER* is the reverse cycle machine Energy Efficiency Ratio and η_{plant} is the average efficiency of the national power plant system.

As most of the variables in Eq. 23 are time dependent, a simplified approach, based on degree-days, has been adopted. The degree-day is a parameter representing the specific energy demand for heating and cooling of indoor spaces. Values of degree-days for all the main Italian cities are provided by technical standard UNI 10349-3 (UNI - Ente Italiano di Normazione, 2016) for multiple indoor air temperatures. Thus, Eq. 23 can be simplified in Eq. 24, considering the definition of degree-day (DD_{cool} during the cooling season, DD_{heat} in the heating season):

$$E_{cool} = \frac{\rho \cdot c_p \cdot \dot{V}}{COP \cdot \eta_{plant}} DD_{cool}$$

$$E_{heat} = \frac{\rho \cdot c_p \cdot \dot{V}}{EER \cdot \eta_{plant}} DD_{heat} \qquad 24.$$

where E_{cool} is the primary energy consumption for ventilation during the cooling cool season and E_{heat} is the primary energy consumption for ventilation during the hot season. It is trivial that $E_{cool} + E_{heat} = E$. The values of parameters in Eqs. 24 adopted in this study are reported in Table 4. In detail, different values of air density and specific heat capacity are reported, considering air as a perfect gas. It is important to specify that the heating season is established by the Presidential Decree 26 August 1993, n. 412 (Presidente della Repubblica Italiana, 1993). Regarding the cooling season, as the duration is not fixed by regulation, data are based on the technical standards UNI 10349-3 (UNI - Ente Italiano di Normazione, 2016).

Table 4. Values of main parameters adopted in the case studies

Parameter	Unit	Values for Casamassima	Values for Santa Caterina	Values for Caponago
Heating season	days	166 (from 1 Nov. to 15 Apr.)	166 (from 1 Nov. to 15 Apr.)	183 (from 15 Oct. to 15 Apr.)
Cooling season	days	124 (from 15 May to 15 Sep.)	124 (from 15 May to 15 Sep.)	107 (from 1 Jun. to 15 Sep.)
External air flow rate	m^3/s	8.69	12.59	10.86
Air density during winter	kg/m^3	1.292	1.292	1.316
Air density during summer	kg/m^3	1.156	1.156	1.157
Air specific heat capacity at constant pressure during winter	J/(kg K)	1.004	1.004	1.003
Air specific heat capacity at constant pressure during summer	J/(kg K)	1.005	1.005	1.005
Indoor air temperature during winter	°C	20		
Indoor air temperature during summer	°C	24		
Heating degree-days	°C day	1654	1654	2454
Cooling degree-days	°C day	314	314	212
Operating hours during winter	hours/year	2,263	2,263	2,392
Operating hours during summer	hours/year	1,687	1,687	1,393
Gas boiler efficiency	-	85%	-	85%
Coefficient Of Performance	-	-	3.24[2]	-
Energy Efficiency Ratio	-	2.99[2]		
Primary energy conversion factor for electricity from Italian grid	TOE/MWh	0.184[3]		
Primary energy conversion factor for natural gas	TOE/MWh	0.086		
CO_2 emission factor for electricity from Italian grid	ton CO_2/MWh	0.303 (ISPRA, 2018)		
CO_2 emission factor for natural gas	ton CO_2/MWh	0.201 (Italian Ministry of the Environment and for Protection of the Land and Sea, 2017)		

Using Eqs. 24 with the parameters reported in Table 4, the yearly electricity and gas consumptions for the air ventilation have been evaluated.

Table 5. Evaluation of the energy demand for ventilation in the case studies

Parameter	Unit	Casamassima	Santa Caterina	Caponago
Electricity demand during summer	MWh/year	28.0	41.3	24.3
Electricity demand during winter	MWh/year	21.5	141.5	26.3
Electricity demand during neutral period	MWh/year	7.6	11.4	8.2
Gas demand during winter	Sm^3	31,358	-	56,742
Annual electricity expenditure	€/year	7,993.73	27,175.06	8,229.85
Annual gas expenditure	€/year	10,975.33	-	19,859.64
Total annual expenditure for ventilation	€/year	18,969.06	27,175.06	28,089.49

---

[2] Values based on datasheet of similar machines, having same sizes and produced in the same period.

[3] Author's elaboration from data contained in (Terna, 2016)

It is interesting to compare the results reported in Table 5 with the data reported in Table 2. Considering that the energy demand for ventilation is only a part of the total energy consumptions for HVAC systems, it is expected that the estimations of energy consumptions for ventilations (reported in Table 5) are a small fraction of values reported in Table 2.

This statement is confirmed in all cases about electricity consumptions, as the ratio between ventilation to the total HVAC consumption assumes the values equal to 0.107, 0.132, 0.078, for Casamassima, Santa Caterina and Caponago, respectively. On the opposite, analyzing the gas consumption, the ratio between ventilation to total HVAC consumption takes values equal to 0.948 and 0.393. These high values may be explained considering that, in the common operation of the store, the ventilation air exchange is reduced as much as possible, in order to limit the energy consumption, especially during winter.

As the authors' goal is to assure that the air exchange satisfies technical standards, data reported in Table 5 are used as terms of comparison in the following sections.

4.2 TO-BE scenarios 1: Heat Recovery Exchanger

As energy consumption for air ventilation conditioning accounts for more than 19,000 €/year per building (in the best case), the first retrofit option considered aims to achieve a reduction in this energy demand. For this reason, the installation of heat recovery exchangers was analyzed. In order to identify the correct size of the heat exchanger and the related energy saving and investment cost, a simulation was performed with a sizing tool provided by a manufacturer (Sabiana S.p.a., 2018). For this reason, different values of recovery energy efficiency are reported, evaluated as a function of the outdoor and indoor temperatures. In Table 6, the technical data of the heat exchangers considered are reported:

Table 6. Technical data of the heat recovery exchangers

Parameter	**Unit**	**Values for Casamassima**	**Values for Santa Caterina**	**Values for Caponago**
Design air flow rate	m^3/h	7,818	5,663	6,519
Number of units	-	4	8	6
Recoverable thermal power during winter	kW	41.77	30.25	45.9
Recovery efficiency during winter	-	74.36 %	74.33 %	76.82 %
Recoverable thermal power during summer	kW	14.85	10.75	12.39
Recovery efficiency during summer	-	75.24 %	75.21 %	75.31 %
Installation cost	€	5,363	4,300	4,811

The authors evaluated the energy saving potential deriving from the installation of heat recovery exchangers. The results of this analysis are reported in Table 7. In details, as direct effects of the first retrofit solution, the reduction of electricity and gas consumptions have been evaluated. From the economic point of view, Table 7 reports the initial investment, the annual avoided expenditure for purchase of electricity and gas, the expected cash flow for a period of ten years and the breakeven time of the investments. Regarding the environmental benefits, the annual avoided primary energy consumption and the avoided CO_2 emission are evaluated.

Table 7. Results of first retrofit solution in the three case studies

Parameter	Unit	Values for Casamassima	Values for Santa Caterina	Values for Caponago
Annual electricity demand	MWh/year	46.4	93.9	50.1
Annual gas demand	Sm^3/year	8,153	0	14,753
Annual electricity saving	MWh/year	10.8	100.2	8.7
Annual gas saving	Sm^3/year	23,205.0	0.0	41,989.0
Initial investment	€	21,452.00	34,400.00	28,866.00
Annual avoided expenditure	€/year	9,627.65	14,022.84	15,915.78
Discounted cash flow (ten years)	€	78,871.59	113,777.04	136,761.65
Breakeven time	year	2.20	2.41	1.80
Annual avoided primary energy consumption	TOE/year	21.1	18.4	36.2
Annual avoided CO$_2$ emissions	t CO$_2$/year	48.0	30.3	83.6

To perform the DCF evaluation, the authors assumed the following parameters:

- Electricity inflation rate equal to 1.0%;
- Natural gas inflation rate equal to 0.7%;
- Interest rate equal to 5.0 %.

About the economic aspects, Figure 9 shows the comparison of the discounted cash flow performed in the case of installing a heat recovery exchanger in each HVAC unit. Three different case studies are shown: the heating demand in Casamassima and Caponago is fulfilled by gas boiler during winter, while heat pumps are used in Santa Caterina. As introduced before, Casamassima and Santa Caterina are located in the same climatic region.

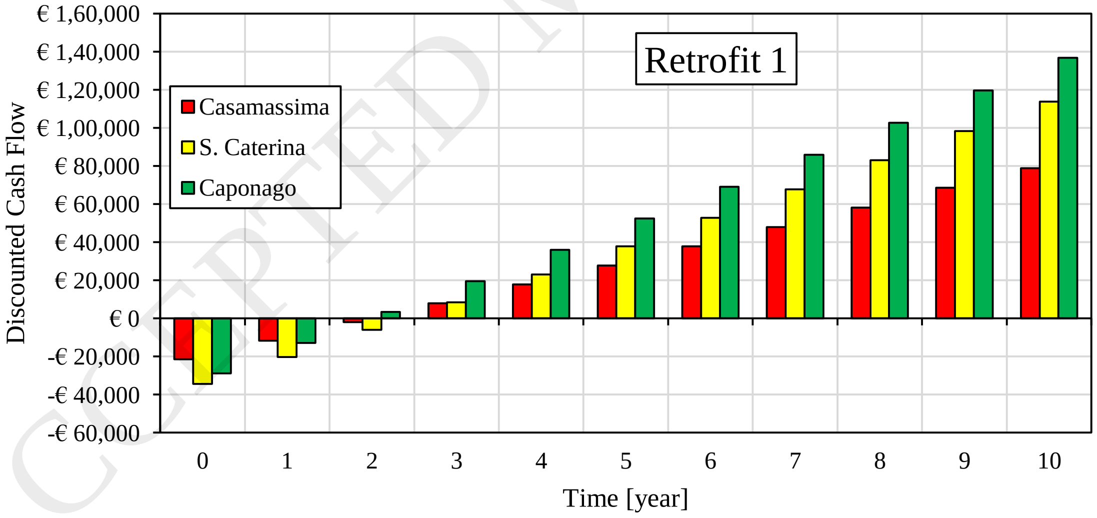

Figure 9. Discounted cash flow, applying the Retrofit 1

The suitability of the first retrofit solution (installation of heat recovery exchangers) is clearly shown in Figure 9. The comparison between breakeven times shows that this solution is more suitable in case of heating by gas boilers, especially in harsher climates, as the breakeven time of Caponago store (North Italy) is lower than Casamassima store (South Italy), both supplied by gas during winter. Santa Caterina store, using heating pump, shows a higher breakeven time, also in comparison with Casamassima store, that is located in the same climatic region. In any case, the breakeven time assumes very low values (about 2 years). The analysis of the discounted cash flow demonstrated the relevance of climatic conditions, as the retrofit solution is able to produce the highest revenues for Caponago store. Regarding the two stores with the same climate, revenues are higher for Santa Caterina store than for Casamassima store.

4.3 TO-BE scenarios 2: Air quality control system

In this section, the authors suggest an interesting solution to optimize the energy expenditure for ventilation: install an air quality control system in order to modulate the ventilation rate according to the actual need. The approach can be easily applied also in old HVAC units realizing very limited upgrades: it is enough the installation of a CO_2 and VOC sensor in each extraction air duct, in order to manage automatically the opening of the ejection dampers. Alternatively, the air quality control system could activate the extraction fans.

The authors consider two tracer gases for the evaluation of indoor air quality, since CO_2 is emitted only by occupants, not being other activities producing CO_2 inside shopping centers, while VOC is emitted essentially by materials and objects exposed in the sales area. As these tracers have different origins, the emission rate of VOC is stable during the 24 hours of the day, while the CO_2 emission is directly linked to the number of occupants, of which three different trends are reported in Figure 10. Since data are not available per each single store, a normalized profile has been modeled, dividing the number of people for the extension of the sales area. The values include also workers in the count.

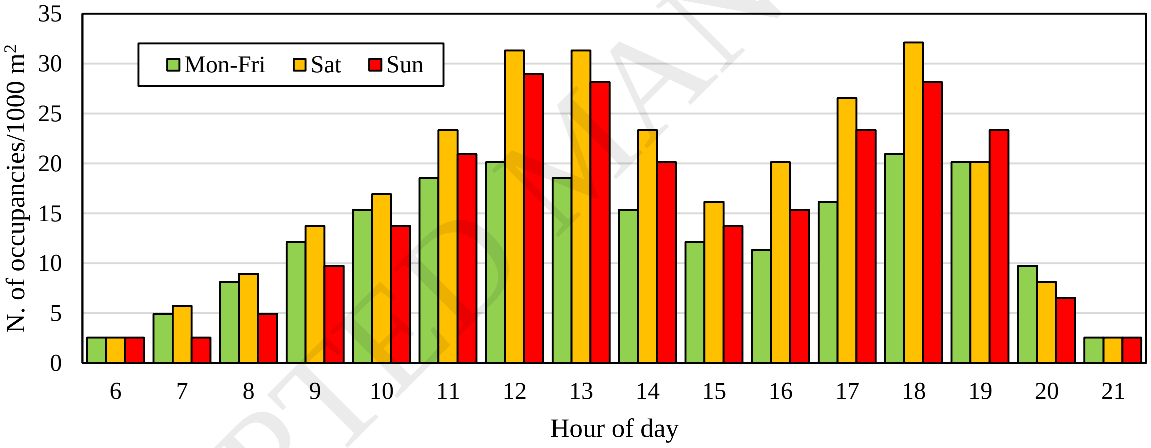

Figure 10. Trends of number of occupants in three typical days

A quick analysis reveals that the values of occupants according to technical standards UNI 10339 and EN 15251 are overestimated as compared to the statistical number of occupants in the case studies. As reported in Table 3, UNI 10339 suggests a people density equal to 0.25, EN 15251 indicates 0.143, while the graph reported above provides a value that, in the worst case, is equal to 0.0321.

As consequence, the non-modulation of air flow rate produces a large waste of energy, due to the thermal treatment, not justified by the actual requirements for the indoor health.

In order to maximize the energy saving for the ventilation, a simplified mathematical model is introduced by Eqs. 25, reported below.

$$\frac{d}{dt}\left[C_{CO2}(t)\cdot A\cdot l\right]=n(t)\cdot\varepsilon_{CO2}-\left[C_{CO2}(t)-C_{CO2,out}\right]\cdot\dot{V}(t) \qquad 25.$$

$$\frac{d}{dt}\left[C_{VOC}(t)\cdot A\cdot l\right]=A\cdot\varepsilon_{VOC}-C_{VOC}(t)\cdot\dot{V}(t)$$

$$\dot{V}(t)=\begin{cases}\dot{V} & C_{CO2}>C_{CO2,rif}\vee C_{VOC}>C_{VOC,rif}\\ 0 & C_{CO2}\le C_{CO2,rif}\wedge C_{VOC}\le C_{VOC,rif}\end{cases}$$

The first two equations represent a mass balancing of pollutants, considering the time variation of the concentration of CO_2 and VOC, the indoor generation of pollutants and the removal of pollutants, thanks to the ventilation. In detail, the indoor volume is expressed by the product of the occupiable surface area A and the average height l, the indoor generation of CO_2 is linearly related to the number of occupants (time dependent function) while the generation of VOC is considered stable during the day and is related to the extension of the sale area. Finally, the removal of pollutants is based on the model reported in Figure 4, assuming the absence of VOC in the external airflow.

The first two equations are interrelated, as the definition of ventilation air flow, expressed in the third equation. In detail, the ventilation system is started when the CO_2 or VOC sensor measures a concentration of pollutants greater than the respective set points. This check is realized with a time step equal to 5 minutes, avoiding a frequent switching on of the ventilation systems.

As furthermore simplification, the external air flow rate is assumed to be selected according the UNI 10339, commonly used in existing plants. At the same time, since specific data about the occupants' time profile are not available, the number occupant in each store is assumed to be equal to the trends reported in Figure 10, multiplied by the sales area surfaces. As consequences, Eq. 25 can be simplified into Eq. 26:

$$\frac{d}{dt}\left[C_{CO2}(t)\cdot l\right]=n_0(t)\cdot\varepsilon_{CO2}-\left[C_{CO2}(t)-C_{CO2,out}\right]\cdot\dot{V}_0(t)$$

$$\frac{d}{dt}\left[C_{VOC}(t)\cdot l\right]=\varepsilon_{VOC}-C_{VOC}(t)\cdot\dot{V}_0(t) \qquad 26.$$

$$\dot{V}_0(t)=\begin{cases}\dot{V}_0 & C_{CO2}>C_{CO2,rif}\vee C_{VOC}>C_{VOC,rif}\\ 0 & C_{CO2}\le C_{CO2,rif}\wedge C_{VOC}\le C_{VOC,rif}\end{cases}$$

Where $\dot{V}_0$ represents the air flow rate per unit surface, equal to 1.625 lt/(s-m^2) and $n_0(t)$ is the normalized number occupants, reported in Figure 10.

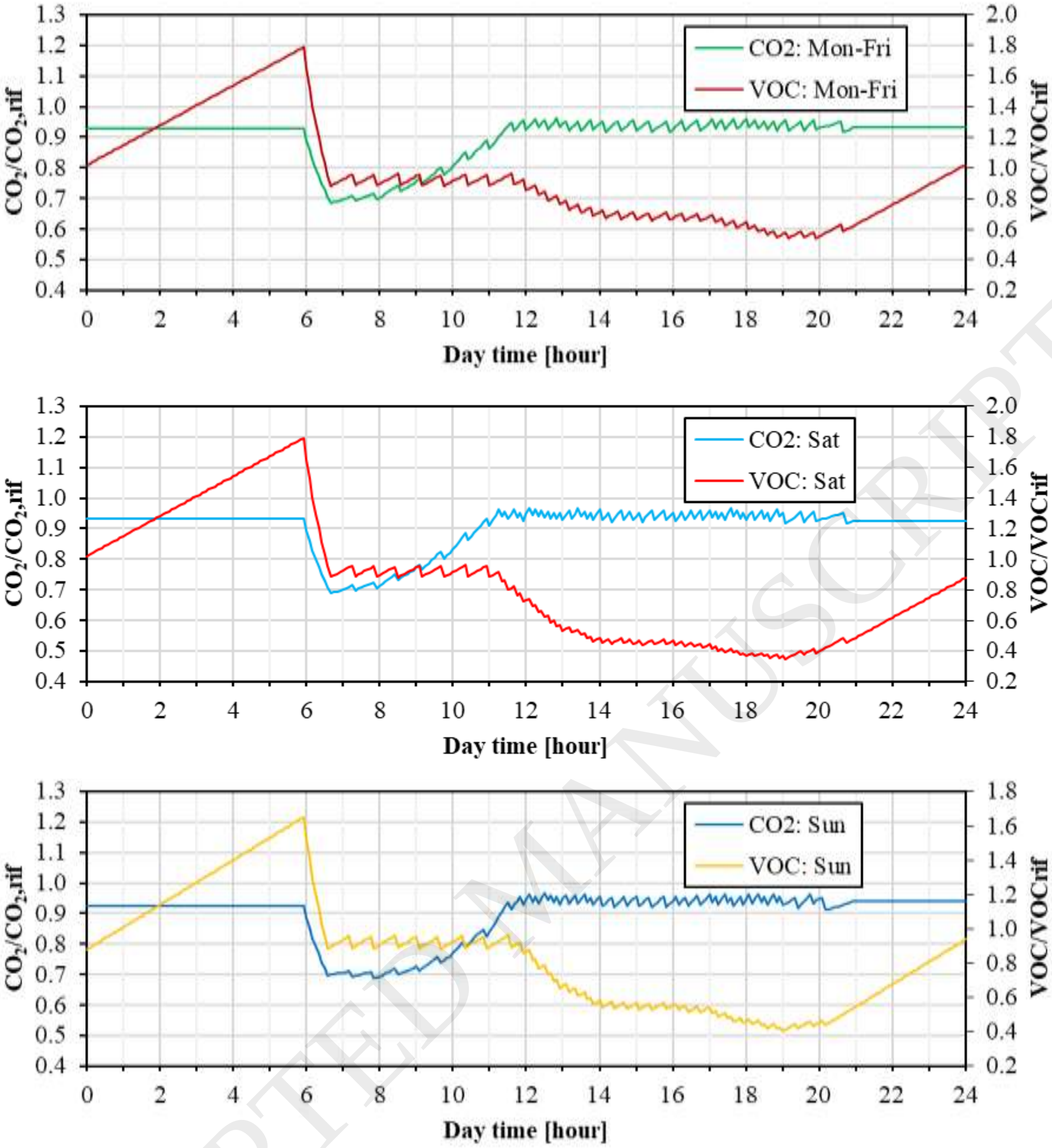

Figure 11. CO_2 and VOC concentrations trends in sales area for weekdays, Saturdays and Sundays in Retrofit scenario 2

As the daily working hours are practically the same in the three stores, a single numerical simulation has been performed. The numerical results are reported in Figure 11, considering three different trends, according to the data of number of occupants introduced in Figure 10.

In the first hours of the day, the ventilation is required to remove the excess of VOC concentration, accumulated during the night. For this reason, the switching on of the ventilation system is set at 6 a.m., one hour before the arrival of workers. The control of CO_2 is dominant after the 12:00 p.m. since the number of occupants increases significantly.

The model is used also to evaluate the equivalent operating time of ventilation plants ensuring the indoor health. In detail, from Monday to Friday (having the same time trend of occupants) 3.5 operating hours are required for the air exchange, 4.6 on Saturday and 3.7 on Sunday.

Known the potential operative profile of ventilation plants, the authors evaluate the effects on the HVAC units, using the same parameters introduced in Table 7. The results of the second retrofit solutions are reported in Table 8.

Table 8. Results of second retrofit solution in the three case studies

Parameter	Unit	Values for Casamassima	Values for Santa Caterina	Values for Caponago
Annual electricity demand	MWh/year	15.5	52.7	16.7
Annual gas demand	Sm^3/year	8,520	0	16,087
Annual electricity saving	MWh/year	41.6	141.4	42.1
Annual gas saving	Sm^3/year	22,838.1	0.0	40,654.7
Initial investment	€	8,000.00	11,000.00	9,500.00
Annual avoided expenditure	€/year	13,817.24	19,791.56	20,128.35
Discounted cash flow (ten years)	€	92,323.59	137,177.04	156,127.65
Breakeven time	year	0.83	0.78	0.59
Annual avoided primary energy consumption	TOE/year	26.5	26.0	41.3
Annual avoided CO_2 emissions	t CO_2/year	56.6	42.8	91.1

Figure 12 shows the comparison of the discounted cash flow calculated in the case of installing a BAS, able to modulate the external airflow, according to the indoor levels of CO_2 and VOC. All three different case studies show a very low breakeven time (lower than one year), due to the limited budget for the initial investment and the great energy potential savings.

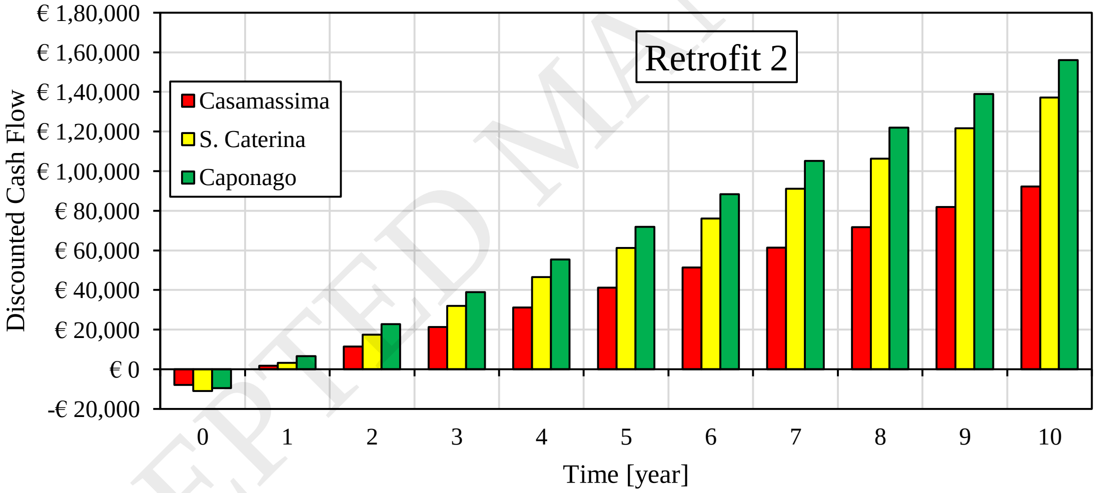

Figure 12. Discounted cash flow, applying the Retrofit 2

4.4 TO-BE scenarios 3: Combined Heat Recovery Exchanger and Air Quality System

In last scenario, the effects of heat recovery exchanger and air quality control system are simultaneously analyzed. In this case, the working hours are the same of the case of installing the air quality system, but the operating energy cost is reduced thanks to the effects of heat recovery exchangers.

The same parameters, used in the previous retrofit solutions, have been evaluated also in this scenario. The results are reported in Table 9. Regarding the economic aspect, Figure 13 shows the comparison of the discounted cash flow in the three case studies. As regard to the breakeven time in this case it is estimated to be ranging between 1.5 to 1.9 years, confirming the great economic convenience of this hypothesis.

Table 9. Results of third retrofit solution in the three case studies

Parameter	**Unit**	**Values for Casamassima**	**Values for Santa Caterina**	**Values for Caponago**
Annual electricity demand	MWh/year	12.6	25.5	14.2
Annual gas demand	Sm^3/year	2,215	0	4,183
Annual electricity saving	MWh/year	44.5	168.6	44.6
Annual gas saving	Sm^3/year	29,142.9	0.0	52,559.2
Initial investment	€	29,452.00	45,400.00	38,366.00
Annual avoided expenditure	€/year	16,433.09	23,601.59	24,640.70
Discounted cash flow (ten years)	€	142,422.61	203,994.07	218,814.10
Breakeven time	year	1.77	1.90	1.54
Annual avoided primary energy consumption	TOE/year	32.2	31.0	51.5
Annual avoided CO_2 emissions	t CO_2/year	69.7	51.1	114.8

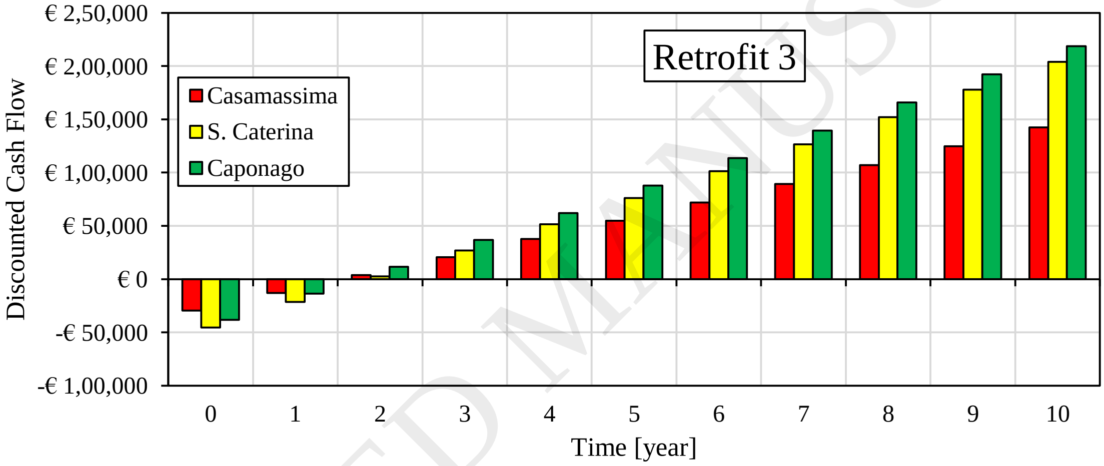

Figure 13. Discounted cash flow, applying the Retrofit 3

Table 10 shows a comparison of the three different retrofit scenarios of energy savings for the ventilation of the sales area: the installation of heat recovery exchangers, the installation of an air quality control system and the realization of both solutions. Data in table were colored to show the most (in green), the intermediate (in yellow) and the least (in red) profitable alternative.

Data reported in Table 10 demonstrate that each retrofit solution is able to produce better results where the climate is harsher. The comparison of different technologies for the winter indoor heating shows better results in the case of gas supply (see Casamassima and Santa Caterina). From an economic and environmental point of view, this aspect can be related to the progressive introduction of Renewable Energy Sources (RES) in the Italian power grid, that reduces the impacts related to electricity consumption. Conversely, the case of gas supply is independent by the progressive diffusion of RES. Nevertheless, the three case studies reported in this paper demonstrate a great feasibility for all three retrofit scenarios.

Table 10. A comparison of three retrofit scenarios of energy savings for the ventilation of sales area

	Parameter	**Unit**	**Retrofit 1: HX**	**Retrofit 2: BAS**	**Retrofit 3: HX+BAS**
Casamassima	Annual electricity saving	MWh/year	10.8	41.6	44.5
	Annual gas saving	Sm^3/year	23,205.0	22,838.1	29,142.9
	Initial investment	€	21,452.00	8,000.00	29,452.00
	Discounted cash flow (ten years)	€	78,871.59	92,323.59	142,422.61
	Breakeven time	year	2.20	0.83	1.77
	Annual avoided primary energy consumption	TOE/year	21.1	26.5	32.2
	Annual avoided CO_2 emissions	t CO_2/year	48.0	56.6	69.7
Santa Caterina	Annual electricity saving	MWh/year	100.2	141.4	168.6
	Annual gas saving	Sm^3/year	0	0	0
	Initial investment	€	34,400.00	11,000.00	45,400.00
	Discounted cash flow (ten years)	€	113,777.04	137,177.04	203,994.07
	Breakeven time	year	2.41	0.78	1.90
	Annual avoided primary energy consumption	TOE/year	18.4	26.0	31.0
	Annual avoided CO_2 emissions	t CO_2/year	30.3	42.8	51.1
Caponago	Annual electricity saving	MWh/year	8.7	42.1	44.6
	Annual gas saving	Sm^3/year	41989.0	40654.7	52559.2
	Initial investment	€	28,866.00	9,500.00	38,366.00
	Discounted cash flow (ten years)	€	136,761.65	156,127.65	218,814.10
	Breakeven time	year	1.80	0.59	1.54
	Annual avoided primary energy consumption	TOE/year	36.2	41.3	51.5
	Annual avoided CO_2 emissions	t CO_2/year	83.6	91.1	114.8

In order to provide a comparison between proposed interventions and one of the most typical retrofit interventions currently adopted, the installation of PV plant for the reduction of electricity bill has been proposed. In details, the comparison was evaluated against the first retrofit intervention, as it is the less profitable (check Table 10), and employing average data from Italian photovoltaic market (Enel X Italia S.p.A., n.d.), as reported in Table 11.

If the installation cost is kept constant between HX and PV installation, the second scenario provides almost the half annual saving and the double payback time for each shopping center. Similarly, if the yearly economic saving is kept constant between HX and PV installation, the initial investment in the second scenario ranges between 1.6 times (for Santa Caterina) and 2.6 times (for Caponago) the investment related to HX adoption. Regarding the avoided energy consumption and emissions, in both comparisons the quantities related to PV adoption range between 13% (for Caponago) and 51% (for Santa Caterina) of the HX installation scenario.

Table 11. Average market data for Italian photovoltaic sector

Parameter	Unit	Casamassima	Santa Caterina	Caponago
Specific PV cost	€/kW	1,300	1,300	1,300
Yearly equivalent operating hours	h	1,930	1,930	1,630
Average electricity selling price	€/kWh	0.17	0.17	0.17
Surface occupancy	m^2/kW	6.00	6.00	6.00

5 CONCLUSIONS AND FUTURE DEVELOPMENTS

This paper demonstrated the great energy savings potential that can be achieved in big shopping centers thanks to the employment of new technologies. Unlike most of existing literature, that is focused on energy savings of residential buildings, this paper shows the great relevance of primary energy consumption in non-residential buildings. Furthermore, studies on HVAC are typically related to the energy performance of the building envelope, representing the highest share, while the ventilation contribution is rarely analyzed. However, the case studies reported above demonstrated that the thermal treatment of external air flow produces also a not negligible contribution to the total energy demand. For this reason, the authors suggested innovative approaches, comparing the economic and thermal benefits.

A brief review of international technical standards on ventilation systems has been provided, showing that the suggested values for air exchange are to be used only in general case, when a specific value is not available. Moreover, Italian UNI 10339 standard requires an update, to take into account the new available technologies.

In order to reduce the energy demand for ventilation, different solutions have been considered, such as the installation of heat recovery exchangers, especially in existing buildings, and air quality control systems. The comparison has been provided considering both natural gas and electrical supply to the indoor heating, showing that the case of natural gas supply has greater environmental and economic benefits, compared to the electrical heating case. The comparison of the same technologies in different climatic context demonstrated the relevance of climatic conditions, from an economic and environmental point of view.

Regarding the considered retrofit cases, although every considered option was shown to be very profitable, air quality control system (Retrofit 2) appears to be the most appealing choice, thanks to the limited initial investment and the high annual energy saving potential.

On the opposite, the third scenario, where the initial investment is equal to the sum of the two separate solutions, shows a significantly lower achievable energy saving than the combined potentials of the single investment solutions. This is caused by the lower amount of heat recovered by the exchanger because of the airflow reduction. Nevertheless, the last solution is also actionable, as the breakeven time is quite low. The Authors wish to underline that the adoption of airflow regulation systems may conflict with the prescriptions provided in the technical standards.

As future developments, in order to make results more reliable, shopping centers consumptions will be modeled through a thermophysical dynamic simulator. Moreover, a monitoring system, to account for the number of customers entering the shops, will be installed. This number will be considered as an input for the air fan speed control system.

AKNOWLEDGEMENTS

The authors wish to thank *Leroy Merlin Italia* S.r.l. and *Helexia Energy Services* S.r.l. companies for the provision of confidential data useful to the present research activity and *Consulting and Engineering Service Società di Ingegneria* S.r.l. for the technical support.

SYMBOLS AND ABBREVIATIONS

A	plan area
ADSH	Accumulated Difference of Specific Humidity
AHU	Air Handling Units
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BAS	Building Automation System
C	pollutant concentration in indoor and extraction air
C_{out}	pollutant concentration in outdoor air
C_0	pollutant concentration in indoor air when air change is off
C_∞	steady state pollutant concentration in indoor air when air change is on
c	cost for electricity supply
c_p	air specific heat capacity
COP	Coefficient Of Performance
$\dot{C}$	pollutant indoor production rate
DCF	Discounted Cash Flow
DD	Degree-Days
DIY	Do It Yourself
E	primary energy consumption for ventilation
E_{cool}	primary energy consumption for ventilation during cooling season
E_{heat}	primary energy consumption for ventilation during heating season
E_v	ventilation efficiency
EU	European Union
f	inflation rate
EER	Energy Efficiency Ratio
h	enthalpy
HVAC	Heating, Ventilation and Air Conditioning
HX	Heat exchanger
I_0	initial investment
l	height of the room
m	air mass to be conditioned
$\dot{m}$	mass airflow
N	useful life of the investment
n	air change rate
n_a	occupants per unit floor area
$n_0(\tau)$	occupants per unit floor area as time function
P	number of occupants
PD	Percentage of Dissatisfied
r	latent heat of vaporization of the water
R_a	outdoor airflow required per unit floor area
RES	Renewable Energy Sources
R_p	outdoor airflow required per occupant person
$R_{p,s}$	outdoor airflow required per occupant person and per unit sensory load
RTU	Rooftop Unit
t	air temperature
t_{in}	indoor air temperature

t_{out}	outdoor air temperature
V	room volume
$\dot{V}$	outdoor ventilation airflow rate
$\dot{V}_0$	normalized outdoor ventilation airflow rate by surface
VOC	Volatile Organic Compounds
x	specific humidity
α	interest rate
ΔH	enthalpy rise
Δh	specific enthalpy rise
ΔQ	energy requirement for air conditioning
Δq	specific energy requirement for air conditioning
ε	pollutant emission factor
η_{boil}	gas boiler efficiency
η_{plant}	average efficiency of the national power plant system
η_{vent}	primary energy to thermal energy conversion efficiency
ρ	air density
τ	time
τ_0	time when the conditioning season starts
τ_{end}	duration of the conditioning season

REFERENCES

Ahmed, A. Q., Gao, S., & Kareem, A. K. (2017). Energy saving and indoor thermal comfort evaluation using a novel local exhaust ventilation system for office rooms. *Applied Thermal Engineering*, *110*, 821–834. https://doi.org/10.1016/j.applthermaleng.2016.08.217

ANSI/ASHRAE 62.1 - Ventilation for Acceptable Indoor Air Quality. (2013).

Antonellis, S. De, Intini, M., Joppolo, C. M., Molinaroli, L., & Romano, F. (2015). c. *Energy Conversion and Management*, *106*, 355–364. https://doi.org/https://doi.org/10.1016/j.enconman.2015.09.034

ASHRAE Handbook - Fundamentals. (2017).

Beccali, M., Cellura, M., & Mistretta, M. (2007). Environmental effects of energy policy in Sicily: The role of renewable energy. *Renewable and Sustainable Energy Reviews*, *11*(2), 282–298. https://doi.org/10.1016/j.rser.2005.02.001

Calay, R. K., & Wang, W. C. (2013). A hybrid energy efficient building ventilation system. *Applied Thermal Engineering*, *57*(1–2), 7–13. https://doi.org/10.1016/j.applthermaleng.2013.03.042

Canbay, C. S., Hepbasli, A., & Gokcen, G. (2004). Evaluating performance indices of a shopping centre and implementing HVAC control principles to minimize energy usage. *Energy and Buildings*, *36*(6), 587–598. https://doi.org/10.1016/j.enbuild.2004.01.031

Capozzoli, A., Piscitelli, M. S., Gorrino, A., Ballarini, I., & Corrado, V. (2017). Data analytics for occupancy pattern learning to reduce the energy consumption of HVAC systems in office buildings. *Sustainable Cities and Society*, *35*(February), 191–208. https://doi.org/10.1016/j.scs.2017.07.016

CEN CR 1752 - Ventilation for Buildings: Design Criteria for the Indoor Environment. (1998).

Çengel, Y. A., & Boles, M. A. (2006). *Thermodynamics: An Engineering Approach*. McGraw Hill.

Chel, A., & Kaushik, G. (2018). Renewable energy technologies for sustainable development of energy efficient building. *Alexandria Engineering Journal*, *57*(2), 655–669. https://doi.org/10.1016/j.aej.2017.02.027

Chen, X., Zhang, Q., & Zhai, Z. (John). (2016). Energy saving potential of a ventilation system with a latent heat thermal energy storage unit under different climatic conditions. *Energy and Buildings*, *118*, 339–349. https://doi.org/10.1016/J.ENBUILD.2016.02.049

Chenari, B., Dias Carrilho, J., & Gameiro Da Silva, M. (2016). Towards sustainable, energy-efficient and healthy ventilation strategies in buildings: A review. *Renewable and Sustainable Energy Reviews*, *59*, 1426–1447. https://doi.org/10.1016/j.rser.2016.01.074

Cotana, F., Messineo, A., Petrozzi, A., Coccia, V., Cavalaglio, G., & Aquino, A. (2014). Comparison of ORC Turbine and Stirling Engine to Produce Electricity from Gasified Poultry Waste. *Sustainability*, *6*(9), 5714–5729. https://doi.org/10.3390/su6095714

Cui, B., Xiao, F., & Wang, S. (2016). Optimal Design of Active Cool Thermal Energy Storage Concerning Life-cycle Cost Saving for Demand Management in Non-residential Building. *Energy Procedia*, *103*(April), 64–69. https://doi.org/10.1016/j.egypro.2016.11.250

Curto, D., & Milone, D. (2018). Improvement of Energy Efficiency for Indoor Lighting in a Big Shopping Center. *Proceedings - 2018 IEEE International Conference on Environment and Electrical Engineering and 2018 IEEE Industrial and Commercial Power Systems Europe, EEEIC/I and CPS Europe 2018*, 1–6. https://doi.org/10.1109/EEEIC.2018.8494486

Curto, D., Montana, F., & Milone, D. (2018). Energy Saving Optimizing the Ventilation Control in a big shopping center. *2018 IEEE International Conference on Environment and Electrical Engineering and 2018 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe)*, 1–6. https://doi.org/10.1109/EEEIC.2018.8494013

Delwati, M., Merema, B., Breesch, H., Helsen, L., & Sourbron, M. (2018). Impact of demand controlled ventilation on system performance and energy use. *Energy and Buildings*, *174*, 111–123. https://doi.org/10.1016/j.enbuild.2018.06.015

Enel X Italia S.p.A. (n.d.). Enel X. Retrieved March 15, 2019, from https://www.enelx.com/it/it

European Comission. (2003). Indoor air pollution: new EU research reveals higher risks than previously thought. *European Comission*, (September), IP/03/1278.

European Commision. (2010). Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast). *Official Journal of the European Union*, 13–35.

European Committee for Standardization. (2007). EN 15251 - Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics.

Eurostat. (2019). Complete energy balances - annual data. Retrieved March 14, 2019, from http://ec.europa.eu/eurostat/estat-navtree-portlet-prod/AppLinkServices?lang=en&appId=nui&appUrl=http%3A%2F%2Fappsso.eurostat.ec.europa.eu%2Fnui%2Fshow.do%3Fdataset%3Dnrg_110a%26lang%3Den

Fanger, P. O. (1988). Introduction of the olf and the decipol units to quantify air pollution perceived by humans indoors and outdoors. *Energy and Buildings*, *12*(1), 1–6. https://doi.org/10.1016/0378-7788(88)90051-5

Ferrari, S., & Zagarella, F. (2015). Costs assessment for building renovation cost-optimal analysis. *Energy Procedia*, *78*, 2378–2384. https://doi.org/10.1016/j.egypro.2015.11.193

Ferrari, S., & Zanotto, V. (2012). Office buildings cooling need in the Italian climatic context: Assessing the performances of typical envelopes. *Energy Procedia*, *30*, 1099–1109. https://doi.org/10.1016/j.egypro.2012.11.123

Ferrari, S., & Zanotto, V. (2016). Defining Representative Building Energy Models (pp. 61–77). https://doi.org/10.1007/978-3-319-24136-4_5

Gerbinet, S., Belboom, S., & Léonard, A. (2014). Life Cycle Analysis (LCA) of photovoltaic panels: A review. *Renewable and Sustainable Energy Reviews*, *38*, 747–753. https://doi.org/10.1016/j.rser.2014.07.043

Homod, R. Z. (2014). Assessment regarding energy saving and decoupling for different AHU (air handling unit) and control strategies in the hot-humid climatic region of Iraq. *Energy*, *74*(C), 762–774. https://doi.org/10.1016/j.energy.2014.07.047

Huang, Y., Qi, R., & Mi, L. (2017). Investigation on energy-efficient retrofitting measures on commercial building external walls in cooling-dominate cities. *Procedia Engineering*, *205*, 2973–2979. https://doi.org/10.1016/j.proeng.2017.10.115

ICF Consulting Ltd. (2015). Study on Energy Efficiency and Energy Saving Potential in Industry and on Possible Policy Mechanisms, (December), 1–461.

Ingrao, C., Messineo, A., Beltramo, R., Yigitcanlar, T., & Ioppolo, G. (2018). How can life cycle thinking support sustainability of buildings? Investigating life cycle assessment applications for energy efficiency and environmental performance. *Journal of Cleaner Production*, *201*, 556–569. https://doi.org/10.1016/j.jclepro.2018.08.080

International Council of Shopping Centers (ICSC). (2016). *Shopping Center Energy Intensity Benchmarking Study*.

International Energy Agency. (2011). IEA SHC Task 47. Retrieved March 15, 2019, from http://task47.iea-shc.org/

ISPRA. (2018). *Atmospheric emission factors of greenhouse gases and other gases in the electricity sector - in Italian*.

Italian Ministry of the Environment and for Protection of the Land and Sea. (2017). National standard parameters table - in Italian (Tabella parametri standard nazionali).

Jouhara, H., & Yang, J. (2018). Energy efficient HVAC systems. *Energy and Buildings*, *179*, 83–85. https://doi.org/10.1016/j.enbuild.2018.09.001

Khalili, M., & Amindeldar, S. (2014). Traditional solutions in low energy buildings of hot-arid regions of Iran. *Sustainable Cities and Society*, *13*, 171–181. https://doi.org/10.1016/j.scs.2014.05.008

Klepeis, N. E., Nelson, W. C., Ott, W. R., Robinson, J. P., Tsang, A. M., Switzer, P., … Engelmann, W. H. (2001). The National Human Activity Pattern Survey (NHAPS): a resource for assessing exposure to environmental pollutants. *Journal of Exposure Analysis & Environmental Epidemiology*, *11*(3), 231.

Lucentini, M., Naso, V., & Borreca, M. (2014). Parametric performance analysis of Renewable Energy Sources HVAC systems for buildings. *Energy Procedia*, *45*, 415–423. https://doi.org/10.1016/j.egypro.2014.01.045

Naik, N., Dhamankar, N., & Karve, S. (2015). Assessing the Indoor Environmental Quality in Shopping Areas with a Focus on Shopping Arcades Case of Pune, India. *Indian Journal of Science and Technology*, *8*(28), 326–332. https://doi.org/10.17485/ijst/2015/v8i28/85364

Olesen, B. W. (2004). International standards for the indoor environment. *Indoor Air*, *14*(Suppl 7), 18–26.

Osservatorio Nazionale del Commercio. (2017). Tavole esercizi della Grande Distribuzione. Retrieved March 13, 2019, from http://osservatoriocommercio.sviluppoeconomico.gov.it/Indice_GDO.html

Pan, Y., Xu, Z., & Li, Y. (2012). Evaluating Commercial Building Retrofit Energy Saving by Using a Building Retrofit Tool – Case Studies in Shanghai. *ASim 2012*, (Holness 2008).

Presidente della Repubblica Italiana. (1993). *D.P.R. 26 agosto 1993, n. 412. Regolamento recante norme per la progettazione, l'installazione, l'esercizio e la manutenzione degli impianti termici degli edifici ai fini del contenimento dei consumi di energia, in attuazione dell'art. 4, comma 4, della L*.

Qureshi, T. Q., & Tassou, S. A. (1996). Variable-speed capacity control in refrigeration systems. *Applied Thermal Engineering*, *16*(2), 103–113. https://doi.org/10.1016/1359-4311(95)00051-E

Retail Forum for sustainability. (2011). *Measurement and reduction of carbon footprint of stores*.

Rose, J., & Thomsen, K. E. (2015). Energy Saving Potential in Retrofitting of Non-residential Buildings in Denmark. *Energy Procedia*, *78*, 1009–1014. https://doi.org/10.1016/j.egypro.2015.11.047

Sabiana S.p.a. (2018). Energy Smart - Sabiana RV Configurator.

Terna. (2016). *Statistical data on electricity in Italy - in Italian*.

UNI - Ente Italiano di Normazione. UNI 10349-3 Riscaldamento e raffrescamento degli edifici - Parte 3. Differenze di temperature cumulate (gradi giorno) ed altri dati sintetici (2016).

UNI - Italian Organization for Standardization. (1995). UNI 10339 - Impianti aeraulici a fini di benessere. Generalità, classificazione e requisiti. Regole per la richiesta d'offerta, l'offerta, l'ordine e la fornitura.

Vakiloroaya, V., Samali, B., Fakhar, A., & Pishghadam, K. (2014). A review of different strategies for HVAC energy saving. *Energy Conversion and Management*, *77*, 738–754. https://doi.org/10.1016/j.enconman.2013.10.023

Volpe, R., Bermudez Menendez, J. M., Ramirez Reina, T., Messineo, A., & Millan, M. (2017). Evolution of chars during slow pyrolysis of citrus waste. *Fuel Processing Technology*, *158*, 255–263. https://doi.org/10.1016/j.fuproc.2017.01.015

Wu, W., & Skye, H. M. (2018). Net-zero nation: HVAC and PV systems for residential net-zero energy buildings across the United States. *Energy Conversion and Management*, *177*(September), 605–628. https://doi.org/10.1016/j.enconman.2018.09.084

Yu, T., Heiselberg, P., Lei, B., Zhang, C., Pomianowski, M., & Jensen, R. (2016). Experimental study on the dynamic performance of a novel system combining natural ventilation with diffuse ceiling inlet and TABS. *Applied Energy*, *169*, 218–229. https://doi.org/10.1016/j.apenergy.2016.01.116

Zhou, P., & Huang, G. (2015). Experimental Study of Energy Saving Potential in Mixing and Displacement Ventilation with Wireless Sensor Networks. *Procedia Engineering*, *121*, 1497–1504. https://doi.org/10.1016/j.proeng.2015.09.076