MEDITERRANEAN BUILDINGS REFURBISHMENT: THERMAL MASS AND NATURAL VENTILATION SIMULATED CONTROL

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ABSTRACT

This paper aims to analyse the state of the art of energy performance simulated control in existing buildings refurbishment. It focuses on the contribution of thermal mass and natural ventilation as strategies aimed at improving passive buildings' performance in Mediterranean climates represented by three locations, Rome, Neaples and Messina.

As for single sided and cross ventilation combined with two different massive typologies, simulation results show an average discomfort hours and energy consumption reductions of respectively 82% and 68 % in Rome and Neaples, 45% and 28% in Messina, where those strategies are less effective due to lesser thermal daily range.

INTRODUCTION

The existing building stock in Europe accounts for over 40% of the global demand of primary energy: buildings in Europe consume approximately 40% of economy's incoming materials and are responsible for over 45% of total amount of greenhouse gases produced (Ardente et al., 2011). Considering that in Europe new constructions account for 1,5% of the building stock, there is a great potential for reducing global energy consumption and mitigate the environmental impact – one of the main political and economical issues of our time – through interventions on existing buildings (Economidou et al., 2011); (Baek and Park, 2012). Energy refurbishment consists in applying the best technology set to achieve improved energy performance while maintaining satisfactory levels of service and indoor thermal comfort, under a given numberof operational constraints (Ma et al., 2012). Numerous studies have been conducted on the application of the techniques of upgrading the energy efficiency of residential buildings (Cohen et al., 1991) analyse practices and intervention costs on the envelope in the nineties showing that interventions on the opaque envelope insulation are more efficient in terms of both energy and cost of replacing the glass surfaces (Hens, 2010) shows how the interventions on the central plants and optimisation of ventilation (even in terms of air tightness) are generally more impactful in terms of energy efficiency compared to the benefits of solar collectors and photovoltaic panels. As for retrofits that exploit thermal inertia and natural ventilation, it is essential to analyse the complex relationship between the two bioclimatic control strategies and environmental, technological and design-specific factor (Braun, 2003).

MEDITERREAN AREA

The Mediterranean area is defined in the present study according to the Köppen climatic classification. The definition refers to those territories directly facing the Mediterranean basin, because of their climatic specificity.

Figure 1: reference areas of the Mediterranean basin

For the purpose of this study, the Köppen-Pinna Mediterranean classification of Italian climate is compared with the national legal classification. Although the latter is valid only for the winter condition, it is largely employed as a reference in architectural practice and energy certification. This specification is intended to frame the study within a possible line of future development of legislation, whose climate classification is now deeply rooted in professional practice.

Following subtypes are defined:

- subtropical (Csa prone to Bs): humid tropical climate with very hot summer prone to arid climate with average temperature above 18°C, low and irregular rainfall
- mild temperate (Csa): humid tropical climate with very hot and dry summer with average temperature of the hottest month above 22 °C.
- sub-coastal (Csb prone to Cfb): humid temperate climate with hot summer and average temperature of the hottest month below 22 °C.

These climatic subtypes are represented in this study by respectively, Messina (M), Naples (N) and Rome(R) (Italy).

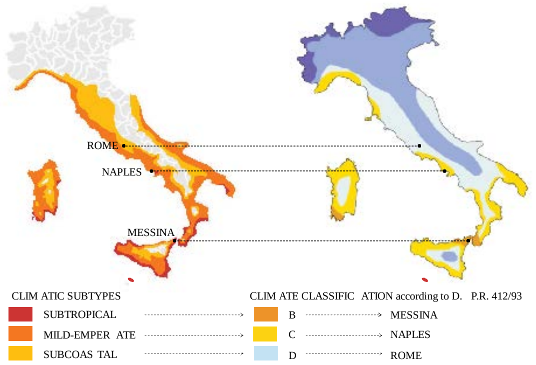

Figure 2: reference location matching to the climatic subtype compared with climatic classification according to D.P.R. 412/93

The temperature range amplitude – a key element for the future legislation for the summer conditions - is a prerequisite to optimal functioning of both the thermal mass and natural ventilation strategies, as it enhances the heat loads dispersion of the building in the warm season. Rome and Naples have an optimal value (above 14 °C between day and night), while Messina has the lowest value (9 °C), below the threshold of efficient application of the strategies examined (Givoni, 1998; Szokolay, 1985).

EXISTING BUILDING STOCK

The existing housing stock covers approximately 75% of the total building stock in Europe. Most of the stock was built before the '70s. In Italy the most common and energy-consuming building type refers to the period between 1961 and 1981.

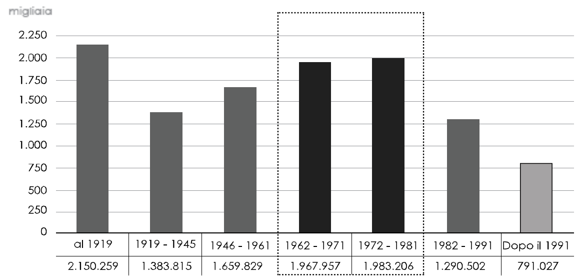

Figure 3: data relating to the 2001 ISTAT census of Italian building(Corrado et al., 2012)

Typically, these buildings have massive structures with the following main features:

- concrete structure with cladding of hollow brick or concrete/prefabricated concrete blocks or hollow masonry;
- no thermal insulation before 1976, low level (0.8 W/mqK) between 1976 and 1991;

THERMAL INERTIA

The energy storage (primarily heat but also electricity) is an optimisation and rationalisation strategy that has been widely investigated in recent years. It proved to be particularly effective where energy demand and supply diverge. It shows significant potential as for the exploitation of renewable sources and the recovery of energy that would be lost (ECES, 2012). The thermal storage is an essential requirement of buildings especially in the Mediterranean area, as it allows the exploitation (and management) of the solar radiation, which is the most influencing factor in the energy balance. To this extent, several types of energy storage can be distinguished (Karlsson, 2012):

- sensible heat storage, due to the thermal capacitance of building materials;
- latent heat storage, based on the material phase change from the solid state to the liquid and vice-versa, in relation to a thermal threshold (melting temperature);
- chemical storage, a long-term chemical process that triggers within the material itself.

Usually, buildings apply the principle of sensible heat storage, since the materials always absorb and retain heat, depending on their own thermo-physical properties and inside/outside temperature differential.
The storage principle can be passive when the thermal mass is directly exposed to the air of the interior space (indirect gain) or to the heat source (direct gain), it can be active when it is due to an indirect action within the construction element (through masonry gaps or sub-flooring, ceilings or crawl spaces) by both the thermal mass and a mechanically controlled heat transfer fluid. The passive mode is the traditional way of thermal storage as shown by the Mediterranean archetypes: in summer, the energy provided by the high solar gains in a given period of the day is absorbed in large part by a massive wall and released later on. To reduce the cooling load, the solar gain must be removed through heat dissipation strategies, such as natural ventilation and superficial convective motions (Braun, 2003).
To show sufficient values of thermal inertia, the construction materials must possess a proper thermal diffusivity, that determines the depth that the diurnal thermal wave reaches within the architectural component: materials with a high thermal diffusivity are much more effective for the accumulation of cyclic heat at great depths than those with a low value (Li and Xu, 2006)
A proper thermal mass design can theoretically keep the temperature of the environment within the comfort range (Balaras, 1996) by absorbing/releasing heat by convection between its inner surface and the internal environment and by radiation among the mass itself, the surrounding surfaces and the external environment (Lechner, 2009). It is specified that the

directly irradiated components are most effective for heat storage, while, those indirectly irradiated, and then exposed to the indoor environment, are more suitable for the management of the indoor temperature in summer conditions (International PLEA Conference et al., 1989). However, the effectiveness of the thermal mass in providing the appropriate thermal inertia of the building, depends on a number of environmental, design and technological factors, such as climate specificity, wall orientation, natural ventilation, space and activities organisation, location of insulation and thermal mass, and occupants' behavior and activities.

NATURAL VENTILATION

In the process of ventilation inside a building, air exchange occurs within the confined environment. Ventilation performs two main function: it regulates the concentration of air pollutants and affects igrothermal condition of the environment (Tucci, 2012). With the increased air tightness of buildings, Mechanical Ventilation (MV) was responsible for the largest increase in energy consumption of the building sector in recent years (Kwon et al., 2013); (Heiselberg, 2002). Ventilation that uses simple physical principles as driving force is called natural (NV) and occurs through envelope openings or spaces specifically design. The benefits of Natural Ventilation in terms of energy consumption, comfort (air velocity fluctuations arising from natural ventilation are more comfortable than uniform fields of mechanical ventilation air flow) and hygiene (connected to the phenomena of Sick Building Syndrome of mechanical ventilation systems) have attracted renewed attention on this strategy and its variations in hybridisation with the mechanical systems (Su et al., 2009); (Kleiven, 2003). Natural ventilation can be triggered by the winds (for dynamic pressure difference) or by buoyancy (for static pressure difference mainly resulting from a temperature differential between external and internal environment, and from an elevation differential between the openings on the envelope) (Linden, 1999; Allard, 1998; Chenvidyakarn, 2013).
The ventilation principle can be (Grosso, 1997):

- Cross Ventilation (CV): wind driven, efficient in terms of flow rate and dependent on the wind incidence angle, on the ratio between the height and depth of the room, and the presence of obstacles to the flow;
- Single-Sided Ventilation (SSV): mainly wind-driven, less efficient in terms of flow rate and more influenced by the temperature difference between outside and inside, and the height difference between the openings;
- Downward Ventilation (DV): wind-driven, it has the advantage of capturing the winds at a greater heights than the environment to be ventilated, so that it is able to achieve higher flow rates. This category may also include Earth Pipes (EP) that use the downward ventilation principle as a driver;
- Upward Ventilation (UV): buoyancy-driven, it depend on the temperature differential between outside and inside, from the height differences between the openings, and from the section of the duct.

The ventilation strategy must ensure adequate levels of Indoor Air Quality (IAQ) via air changes throughout the whole year. However, whilst natural ventilation can be sufficient for achieving adequate igrothermal comfort and IAQ in the middle season, in the cold season this supply air will constitute an heat loss to be limited by a passive means (pre-treatment), and in the hot season the dispersions should be maximised in order to reduce energy consumption. Ventilation heat exchanges occur through the air (used as heat transfer fluid) by convection between air and building surfaces using other natural or artificial elements (like the same air, the ground, the water, the sky or the building mass) as thermal flywheel. Ventilation techniques are:

- Body Ventilation (BV): cooling purpose, based on convective exchanges between the body of the occupants and the external air. It depends on the speed of the air and the temperature difference between air and skin) (Grosso, 1997);
- Structural Ventilation (SV): cooling purposes based on convective exchanges between external air and the mass of the building, depending on daily thermal range, the thermal inertia of the structures, flow speed and direction (Siew et al., 2011). The absence of occupants allows for greater air flow and lower temperature during the night;
- Room Ventilation (RV): both cooling and heating purpose in case of air pre-treatement, based on convective exchanges between air and the environment and charaterised by igrothermal comfort limits for the occupants.

Table 1:
Natural Ventilation summary

HEAT EXCHANGE TYPE (HET)	VENTILATION TECHNIQUE	VENTILATION PRINCIPLE
Microclimatic, air (M)	BV,SV,RV	CV,SSV,DV,UV
Geothermal, ground (G)	RV	EP
Evaporative, Water (W)	RV	DV
Radiative, night Sky (S)	SV,RV	through collectors

The technological systems currently available for the use of natural ventilation in an energy retrofit project can be classified in Physical (PE) and Non-Physical (NPE) elements (Siew et al., 2011).

Physical Elements

- Openings on the building envelope - Working Range (WR): hot and middle seasons. Heat Exchange Type (HET): microclimatic. The openings act as the basis of almost all the natural ventilation systems and always constitute a context-based necessary feature for the optimisation of natural ventilation systems. Openings positioning triggers and defines the path of the wind flow, reducing at the same time the energy consumption that results from the use of artificial light. Artificial obstacles wing walls may be used in combination with the openings to increase the pressure differential between two windows, and then the induced natural ventilation (Mak et al., 2007).
- Ventilated façade and roof - working range: all year. Heat exchange type: microclimatic, radiative night sky. Ventilated facades and roofs are constitutive elements of the envelope. They consist of two layers separated by an air gap with openings to the outside and / or inside, which allow the air passage to and from the interspace. In the summer, buoyancy forces create a circulation of air that subtracts heat from the building by convection. During the winter the gap may be closed to exploit the effect of static air gap, or opened to disperse the vapor avoiding condensation, particular outside-inside circulation can be allowed by passive systems like the Trombe-Michel wall;
- Couryards, bioclimatic atria, sunspaces and buffer spaces - working range: all year. Heat exchange type: microclimatic. All these systems act as thermal mediators (with courtyards being more efficient on low rise buildings and bioclimatic atria being more efficient over a certain height) (Aldawoud and Clark, 2008). The buffer space and sunspaces are both thermal and ventilative intermediate environments between the inside and the outside. During the winter, they can be used as a store of pre-heated supply air if the exposure allows, whilst in the summer they can be used as extractors (Tucci, 2012).
- Wind towers, earth pipes - working range: all year. Heat exchange type: microclimatic, evaporative water, geothermal ground. The wind towers are morphological-constructive elements with a vertical development that allows both upward and downward air flow. They are usually associated with other ventilation systems, and generally used at the beginning of the process (such as underground earth pipes or openings on the building), or at the top of the tower (windcatchers), or in synergy with the tower as the evaporative system or the presence of vegetation.

Non-Physical Elements

Manual or automatic control – working range: all year. The automatic control requires the installation of special sensors capable of measuring the necessary parameters required for the application of control strategies (Mahdavi and Pröglhöf, 2005). Although a user is often willing to accept a wider range of comfort when in control of the openings, automatic control is usually more effective than manual control (Baker and Standeven 1995; Allard, 1998).

THE SIMULATION CONTRIBUTION

The impact of strategic decisions on energy and environmental characteristics of bioclimatic design is higher when these decisions are close to the early stages of the process (Lechner, 2009). In order to maximize comfort and reduce energy consumption the design of a naturally ventilated massive building has to adapt to site-specific microclimatic conditions on a daily basis. A proper simulation analysis can be a useful starting point for solving the problem (Stephan et al., 2007). The Numerical Simulation (NS) is the creation of a "behavioral" model of a building at a given stage of its development. The numerical simulation also implies that this model is run through a computer, calculated and analysed in its performance post-processing the results. The models are elaborated by reducing to a certain level of abstraction the physical entities of the real world and the phenomena related to them (Augenbroe, 2002). Numerical simulation is therefore a key tool in the energetic retrofit of the building stock, because it treats the building as a system of interrelated elements that can be optimised, rather than a sum of a number of elements designed and optimised separately for subsystems (Hensen, 2004). The use of a correct simulative methodology does also imply the use of an appropriate scale of resolution on the model. For example, a numerical simulation is much more effective for comparing different design alternatives in terms of energy performance rather than accurately predicting the energy performance of a design solution in absolute terms (Hensen, 2004). The numerical simulation then looks for the sensitive variables, those energetic trends, that are more influent on the final result of the simulations and then on the objectives to be achieved through them (Attia et al., 2013). This paper addresses one specific question: as in the Mediterranean climate thermal mass and natural ventilation have a dominant role in the energy behavior of a building, what is the impact in terms of comfort and energy savings of their interaction? The following table summarizes four different simulation sub-categories, including dynamic multi-zonal numerical simulation. This was chosen to address our question due to the fact that it represents a good compromise between computation time and the degree of knowledge acquired on the simulated building, thus allowing to get immediate results on the igrothermic state of the simulated environments, air flow, comfort, and energy consumption. (Chen, 2009; Clarke, 2001; Foucquier et al., 2013; Hensen, 2003; Morbitzer, 2003; Ramponi and Blocken, 2012).

Table 2:

Simulation sub-categories summary

SUB-CATEGORIES	MAIN USE	STRENGTHS AND WEAKNESSES
Semi-empirical model	Broad quantitative indication	inaccurate results, low level of knowledge obtainable on the building
Multi-zonal model	Application to the whole building, able to deal with the time evolution of the physical parameters.	Short computation time, high interoperability with other models
Zonal model	Suited to the study of indoor comfort and air flow analysis of air	High Computation time, high degree of expertise required.
Computing fluyd dynamics	Suitable for the distribution of contaminants in the air and air flow analysis	Highest level of accuracy and computing time, very high degree of expertise required.

PERFORMANCE INDICATORS

During the last two decades, the time spent by people in confined environments (currently around 90% of their own life) has increased. European and national legislation has gradually tightened quality standards on living spaces (Lopardo, 2011), placing indoor environmental comfort (including igrothermal comfort and indoor air quality, IAQ) as the ultimate goal, and as main condition for the success of adopted refurbishment strategies.

As such, it is necessary to translate the building's behavior through a series of synthetic indicators measuring the building's trend in various fields of investigation: indicators are generally a combination of several quantifiable and verifiable factors, which should preferably be of widespread use to easily understand how to promote communication between different stakeholders of the refurbishment process (Milardi, 2012). The comfort index is the most important factor, since it represents the main prerequisite to the refurbishment success; in parallel, the energy consumption index is used not only as a key to understand the building's behavior, but also as a useful tool to verify, even if in a theoretical way, the improvements of the building's energy performance through the selected strategies of natural ventilation in combination with Thermal Mass (TM).

According to an approach that places the comfort as an “objective” and the energy consumption as a "cost" aimed to achieving comfort, the passive behavior of the building will be assessed through a comparison of the energy performance index and the environmental comfort achieved (both in the hot season).

Since this study focuses on the passive thermal mass and natural ventilation simulated control in Mediterranean area, it will be possible to proceed according to the adaptive comfort model defined by EN 15251:2008 which identifies three categories in relation to the ideal operating temperature trend T_o, among which the paper chooses the second with $T_o = 0.33T_e$ (external temperature) $+18.8 \pm 3$ (with an 80% of acceptability).

The above-mentioned indicator is associated with the ideal energy consumption value for cooling purpose (shown in kWh/m^2y), in order to transfer the reasoning to professional practice.

To this purpose, the considered range for the ideal plant's setting refers to the adaptive comfort temperature range, larger that the Fanger's one - in order to better evaluate the contribution of a passive strategy to the reduction of energy consumption.

SIMULATION

Using *openings on the building envelope* and *automatic control* in their interactions with two different thermal masses, 18 cm thick concrete wall (A), 30 cm thick concrete wall (B), referring to the hot season (from the 1st June to the 30th September) for three different cities (Rome, Naples and Messina), a set of numerical simulations of single-sided and cross room ventilation is then run.

The simplified model adopted is an isolated residential house, south facing, representative of the existing Italian building stock, with a floor area of 56 square meters (7 m width x 8 m depth), and a height of 3 meters. Internal gains (lights, people and electric equipment) are set from a hypothetical residential occupancy pattern.

The single-sided ventilation is triggered by a window, the cross-ventilation by two windows on opposite sides, both with low-emissivity glass (to represent the most disadvantaged condition in terms of ventilation and ach point of view), whose areas are (individually or in pairs) one-eighth of the floor area of the apartment according to the hygiene regulations in force in Italy.

Table 3:

Model envelope thermo physical properties

CONSTR. TYPE	U [W/(m²K)]	Y_{IE} [W/(m²K)]	Φ [h]	F_D -
Roof	0.88	0.20	10.45	0.23
Ground floor	0.43	0.11	10.31	0.26
18 CLS wall	2.41	1.13	6.00	0,47
30 CLS wall	2.01	0.48	9.14	0,24
Window	1.00	/	/	

The software adopted for the simulations is Energy+ (Henninger and Witte 2011). For each interpolation between locations, envelope type and natural ventilation principle (es. R, _A_SSV), two Benchmark Simulations (BS), set with a minimum of 0,5 ach from infiltration, paired with two natural ventilation simulation, are run. The first benchmark simulation, called Discomfort Benchmark Simulation (DBS), calculates the model as it is and shows the total hours of discomfort during the simulation running period (expressed in hours/yearly in reference to the heat excess discomfort in the summer period). Associating to this simulation its Naturally Ventilated Relative Simulation (DNV) allows to obtain an estimate of the Discomfort hours Reduction Potential (DRP), expressed as a percentage, of the passive systems in examination. The other benchmark simulation, called Energy Benchmark simulation (EBS), has a thermostat that activates (on adaptive comfort range) a theoretical plant whenever the igrothermal condition of the building goes beyond the limits of comfort, taking into account the subsequent primary energy consumption (expressed in kWh/m²y for cooling purpose). Energy Naturally Ventilated simulation (ENV) along with thermostat and theoretical plants shows the Energy Consumption reduction Potential (ECP). The relationship between these two reductions and the effectiveness of natural ventilation and thermal mass are then investigated. In order to simulate this combination, the Airflow Network model of Energy+ that allows for calculation of multizone airflows due to wind and surface leakage, is adopted (NREL, 2013). A ventilation control mode based on the temperature differential between inside and outside temperature is set: if the room temperature (T_{room}) > outdoor temperature (T_{out}) and T_{room} > summer threshold temperature (T_{st} = 21°C), windows are opened with an opening factor set to 0,5, and T_{room} and T_{out} difference lower and upper limit set to 5°C and 10°C.

ANALYSIS OF THE RESULTS

In terms of absolute values of discomfort hours and energy consumption, the benchmark simulations confirm the results of previous research (Cesaratto and De Carli, 2010; Sibilio et al., 2009) revealing comparable Rome and Naples values (around 24 kWh/m²y and 1600 discomfort hours per year) and a sharp rise in the city of Messina (on average 1.7 times the hours of discomfort, 2.5 times the energy consumption).

Table 4:

Simulation results

Model Type	DBS	DNV	DRP	EBS	ENV	ECP
/	[h/y]	[h/y]	%	[kWh/m² y]	[kWh/ m²y]	%
R_A_SSV	1.688	286	-83	23	9	-61
R_A_CV	1.657	235	-86	22	6	-71
R_B_SSV	1.776	50	-97	21	6	-72
R_B_CV	1.621	82	-95	20	4	-80
N_A_SSV	1.464	497	-66	28	11	-60
N_A_CV	1.431	484	-66	27	10	-63
N_B_SSV	1.494	260	-83	25	8	-69
N_B_CV	1.724	270	-84	24	7	-71
M_A_SSV	2.761	1.694	-39	64	51	-21
M_A_CV	2.607	1.366	-48	63	43	-31
M_B_SSV	2.665	1.578	-41	58	44	-24

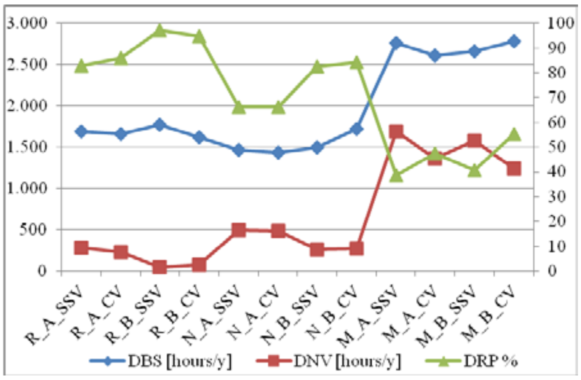

Figure 4: Discomfort hour analysis

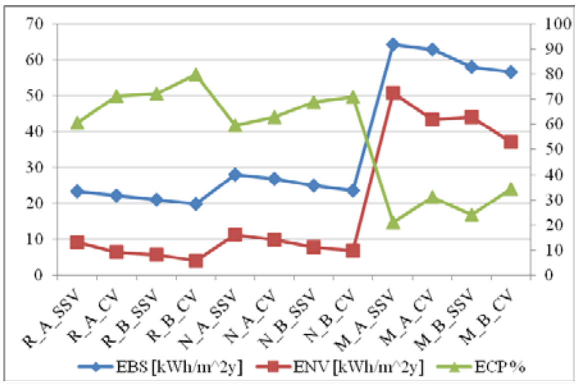

Figure 5: Energy consumption analysis

Similarly, the natural ventilation simulations show an average discomfort hours reduction in Rome and Naples of 82%, and of 45% in Messina. The same goes for average energy consumption, with a decrease of 68% in Rome and Naples and 28% in Messina. In absolute terms the energy saved and the largest decrease of discomfort hours take place in Messina, where those strategies are less effective due to lesser thermal daily range compared to the ideal location of Rome and Naples.

It should be noted that the effectiveness of the mechanisms of natural ventilation in terms of reduction of discomfort hours, (if compared with the mass usage), grows with increasing mass in Rome and Naples, which register an average increase of 14%, and in Messina (5%). Similarly, it is possible to analyse the energy consumption by noting that in the benchmark simulation the heaviest typology consumes in all three locations approximately 10% less than the lightest, whilst results of energy naturally ventilated simulation show that the heaviest typology consumes 9% less in Rome and Naples and 3% less in Messina compared to the lighter one.

SUMMARY

Reported results on the efficiency of the combined effect of natural ventilation (both single sided and cross ventilation) on buildings of medium (18 cm thick concrete wall) and heavy (30 cm thick concrete wall 18) mass in Mediterrean area, highlight:

- the effectiveness, in terms of energy savings and comfort improvement, of minimally invasive (and therefore suitable) refurbishment actions for energy retrofits of existing buildings, such as the windows opening replacement along with the installation of automatic control systems;
- an effectiveness reduction - in relative terms - of the strategies adopted in relation to the reduction of the thermal range of the reference site (Messina), nevertheless corresponding to greater reductions in absolute terms of energy consumption and discomfort hours compared to other locations analysed (Rome and Naples);
- cross-ventilation is not always related to a decrease in discomfort hours compared to the single-sided ventilation because of the discomfort generated by extreme air changes per hour (and therefore by an excessive air velocity). Energy consumption with cross-ventilation instead decreases on average by 7% in the three locations compared to single-sided ventilation.

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