Thermal inertia and energy efficiency – Parametric simulation assessment on a calibrated case study

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1. Introduction

The reduction of energy consumption and CO_2 emission for heating and cooling services in the existing building stock is an important challenge as residential and commercial buildings today account for approximately 40% of total primary energy at the European level [1] and approximately one third of the energy consumption at the global level [2]. In most of the cases, the primary energy demand for heating and cooling services constitutes the predominant part of the overall demand in buildings. Despite the ambitious goals set at the European level by the EPBD recast [3], which states that by 2020 all new buildings and existing building undergoing to major refurbishment will have to be "Nearly Zero Energy Buildings" (NZEB) [4,5], the critical challenge remains the radical efficiency upgrading (deep retrofit practices) of the existing building stock to standards compatible with a sustainable use of resources, potentially up to NZEB level of performance [6]. In fact,

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Nomenclature

Variables and parameters

C	thermal capacity of building zone
A	area
g	solar gain factor
k	internal area heat capacity
m	thermal capacity per unit of surface
q	heat transfer rate density
U	thermal transmittance
Y	periodic thermal transmittance
θ	temperature

Subscripts and superscripts

^	complex amplitude
1, 2	thermal zone, boundary condition
e	external side
f	net floor area
i	internal side
j	j-th element of building fabric in direct contact with the air of an internal zone
m	mass-related capacitance

while a newly constructed NZEB can employ the "state of the art" of efficient technologies and design practices available, the effort to be put in the design optimization for existing buildings refurbishment in view of NZEB standards is much larger [7].

The importance of optimal design, technological learning and innovation at the building system level [8–12] is often undervalued in favour of a component level view of the performance where single efficient technologies and products appear to be more important than an efficient system design according to multiple appropriate performance criteria [13].

In terms of system level properties, for example, the ability to store energy of the building fabric, related to its thermal inertia, can be effectively exploited in summer, to reduce cooling load [14,15] and overheating [16]. It can be also successfully exploited in the intermediate seasons to obtain comfortable conditions in a "passive" way (acceptable internal conditions are guaranteed without the operation of technical systems) [17–19]. Thermal inertia affects the way in which a building reacts to changes in external and internal conditions influencing therefore its thermal load patterns (sensible load for heating and cooling); the potential advantage in terms of energy consumption given by higher effective thermal capacity depends on the specific intermittent operating conditions [20,21].

Therefore, while the positive effects of thermal capacity are particularly evident for buildings that are operated continuously or with attenuation in mild climates [22], it is more difficult to evaluate them in cases in which operation is intermittent and more severe climate conditions are present [23–25].

In fact, the specific climate conditions of the building's site play an important role, if we think about the possible large variability of temperature and solar radiation patterns.

From a general standpoint, two other aspects are particularly important today for the design of high performance buildings (both new and retrofitted). The first one is related to the correct identification of the uncertainty and sensitivity of the results obtained by energy simulation with respect to input variations [26,27], considering also the economic dimension introduced by cost optimal analysis methodology [28–31]. The second one is related to the gap, often encountered [32,33], between the simulated energy performance (design phase) and the measured energy performance (operation phase). This gap can be reduced through the use of accurate simulation tools and calibration techniques [34–37] and that can to be controlled during building lifetime by means of continuous commissioning tools [38,39] and predictive models [40–42].

More in general, the comparability and reliability of simulations are particularly important today because computer models are largely used in the building design and operation phases.

In terms of comparability, an example is constituted by reference building methodology. Reference buildings are "buildings characterized by and representative of their functionality and geographic location, including indoor and outdoor climate conditions" as stated by the Annex III of EPBD recast [3]. Despite the inherent limitations of a research conducted on a single building which has not been proved to be a "real reference building" or a "theoretical reference building" [28], our goal is to explore by means of a parametric analysis the potential outcomes of different technical solutions.

These solution are related to the building fabric, external shading system and operation strategies, in particular free cooling through increased night ventilation [43–47], showing the influence of dynamic thermal properties on sensible energy demand for heating and cooling.

In fact, for the reasons introduced before, it is difficult to provide a general evaluation of the role of thermal inertia for energy saving purpose and therefore a characterization of the specific conditions considered is necessary. Nonetheless, it is important to evaluate the role of the effective thermal capacity (from single zones to the whole building) as one of the decision variables in the design process, showing the possible advantages or disadvantages in transparent way, possibly employing commonly used performance metrics and visualization tools.

The research presented involves the parametric simulation of a building energy model, considering combinations of different types of building components, each of them characterized by the same thermal transmittance but different periodic thermal transmittance and internal areal heat capacity. The last quantity expresses the thermal capacity per unit of surface of a building component in direct thermal contact with the air on the internal side of the building zone and thus indicates its ability to store thermal energy. Consequently, we can evaluate the incidence of the variations of the dynamic thermal properties on the energy performance in terms of sensible heating and cooling. Design parameters and performance metrics are used to characterize the building from the component level to single building zones (a virtual test cell used to simulate the behaviour of a portion of the building volume, e.g. a room) and to the overall building (multi-zone building energy model) [28]. The metrics used are based on international standards and current design practices.

The selected case study is an office building retrofitted and monitored in recent years, whose energy model has been calibrated according to its measured energy consumption [48,49]. The calibrated model has been used as a starting point and has been modified to enable the comparison of different possible alternative retrofit solutions (combinations of different solutions for the construction components and operation strategies). The research however employs the same methodological approach used for calibration (correction of the thermal transmittance to account for thermal bridges, minimum ventilation rates for infiltration, operating schedules, etc.) and part of the original building data to obtain "realistic" results. The building configurations simulated are characterized by low transmittance envelope components, intermittent operation and high and coincident internal thermal gains (occupancy, people and lighting), thus reproducing the typical operating conditions of a high-density office building.

2. Research scope and methodology

A primary goal when designing efficient buildings (both new and retrofitted ones) is the reduction of the sensible thermal energy demand for heating and cooling for the reasons expressed before.

The most important design parameter for heating demand reduction is the global heat exchange coefficient of the building (including transmission and ventilation losses) and the gain factor of transparent surfaces [50], while cooling demand is determined by the dynamic interaction of a much larger set of parameters [51,52]. Consequently, dynamic simulation tools are required to enable a correct design especially from the cooling point of view, in particular if we want to correctly evaluate factors such as window-to-wall ratio, fixed/movable shading systems, size and position of openings for natural ventilation, etc. All these aspect clearly constitutes an important reflection point, in particular in view of future building codes for countries where cooling demand is relevant and a transition towards dynamic simulation tools has not yet happened [53].

2.1. Understanding the role of thermal inertia for energy efficiency

If we analyze the dynamic thermal behaviour of a building [14] a considerable part of the heat gains due to solar radiation and internal heat sources (appliances, lighting, people) is stored in the components constituting the building fabric (roof, walls, floors) [15,54]. This process helps stabilizing the internal conditions and attenuating the operation of technical systems [23,54,55]. Further, natural ventilation can be employed to passively cool the building [56,57], for example by increasing the air flow rate during the night when the outside air temperature is sufficiently low to dissipate the heat stored in the building fabric during the day.

The exploitation of the capabilities of the effective thermal capacity of the building fabric depends clearly on the climate data patterns and on operation strategies [21]; the diurnal temperature patterns are particularly important.

In fact, when the average daily temperature is too high or the temperature swing is too small with respect to the building "balance point" [58,59], the effect of thermal capacity for cooling purpose is rather limited.

In winter conditions also, when the outdoor daily temperatures are sensibly lower than the internal set point, thermal capacity can also play a role, if properly used. In fact, the possibility to effectively exploit the solar heat gains depends on the ability of the components to store and restitute gradually the heat, which would cause otherwise an "accumulated overtemperature" [60], in particular in lightweight highly insulated buildings with high thermal gains (large glazed surfaces, coincidence of occupancy, appliances and lighting gains, etc.).

2.2. Calibrated energy models and building thermal parameters identification

While the capabilities of effective thermal capacity for energy saving purpose can be questioned, based on the specific climate and building operation condition, it is undeniable the importance of the correct identification of the dynamic behaviour of the building for control, commissioning and energy management purposes.

On the one hand, model calibration has become an increasingly important issue [35,36], due to the large use of software, not only for building design, but also for building operation optimization. Several approaches are possible for model calibration, like using directly "white-box" models [61] or, alternatively, using "grey-box" or "black-box" models (e.g. meta-model based approach) [48].

On the other hand, building energy simulation, starting from building physics modelling methodologies [62], poses the problem of the appropriate level of detail and accuracy for the different scales of analysis. Given the increasing necessity of establishing a methodological "continuity" among design, commissioning and operation practices, it should be noticed how the identification of the global heat exchange parameter for calibration can be derived by the "energy signature" [63,64] using regression analysis [59], also for industrial buildings and facilities [65,66].

However, in order to reproduce correctly the dynamic behaviour of the building, the global heat exchange is not sufficient and "grey-box" models (a combination of physical knowledge and statistics) [67,68], using lumped thermal capacity definitions and appropriate linearizations, can also contribute to more transparent calibration procedures by means of time-series analysis [69].

Further, the correct evaluation of the effective thermal capacity can improve also the results of more simplified modelling strategies, based on daily data [70], or even "aggregated data" such as heating degree-days and cooling degree-days [71].

As a conclusion, the evolution of the existing methods for dynamic simulation, commissioning and performance monitoring can determine the conditions for a rapid development in the field of calibration of energy models [72], identifying in a correct way the role of thermal inertia.

2.3. Research methodology

As stated before, the research presented follows a simulation approach, employing a validated tool for building energy analysis, EnergyPlus [73] and different building energy models derived from an initial one, calibrated on a real building [48].

In this models two scales of analysis were considered, respectively the room one (single thermal zone), named "test cell", and the whole building one, in order to enable a comparison between local and global effects.

One important issue in the research was the selection of the combination of the components constituting the building fabric. We adopted two possible construction solutions, a "light" and a "medium-heavy" one, for every component such as external wall, rooftop and internal floor. The components considered are possible technological solutions for building refurbishment, based on the "state of the art" of construction components for the selected building typology.

Further, given the possible combinations of the construction components (different building assemblies), we determined three types of building fabric, namely a "light", a "medium" and a "medium-heavy" one [60]. The details of the combinations are illustrated in Section 3.2.

Two other fundamental aspects were considered in the parametric simulation, the presence of an adaptive shading system tested in the original building [74] and the free cooling of the building by means of increased night ventilation [45,75].

The results obtained have been analyzed to critically assess the influence of the thermal inertia properties of the building fabric on the variations of sensible thermal demand for heating and cooling, in a numerical and graphical way. All, the details regarding the input simulation data are reported in the Section 3.

The climate conditions considered in the research are typical of the Italian territory and, more in general, of Southern European and Mediterranean area. Finally, in order to enable a meaningful comparison of the different solutions across the different climatic conditions within the Italian territory, the chosen locations were Milan, Rome and Palermo, respectively at the north, center and south of Italy. A summary of the relevant climatic data is reported in Table 1 and average daily profiles are reported in Fig. 1. The weather files used for simulation are based on Test Reference Year (TRY.

3. Description of the case study

The starting point of the research is an office building built in 1998 and placed in Milan, which has been retrofitted in 2010 and which has been optimized from the point of view of energy performance, in particular with respect to envelope design. The building energy model used in the design phase has been

Table 1
Summary data of climatic conditions and operation modes for different locations.

Climatic conditions	Unit	Milan	Rome	Palermo
Heating degree-days	°C d	2265	1644	801
Heating period	–	15/10–15/4	1/11–15/4	1/12–15/3
Cooling degree-days	°C d	588	633	1002
Cooling period	–	16/4–14/10	16/4–31/10	16/3–30/11
Weather data file	–	Milano–Linate IGDG	Roma–Ciampino IGDG	Palermo–Punta Raisi IGDG

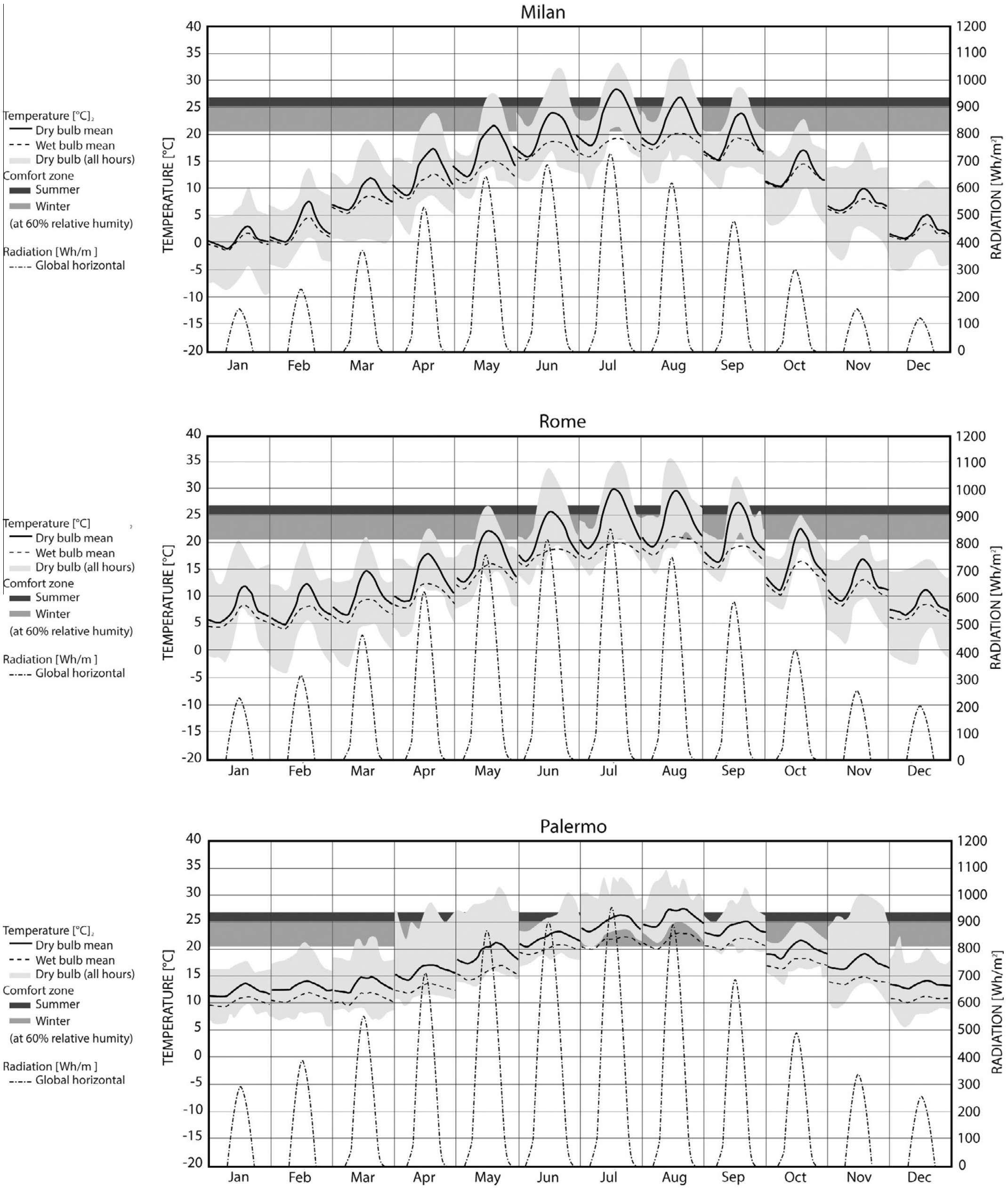

Fig. 1. Average daily profiles of climatic data for the different locations.

calibrated on the real energy consumption data collected in the monitoring phase, considering different possible approaches to calibration [48].

The choice of an existing office building characterized by high performance envelope and high density (with coincident internal thermal gains for occupancy, lighting and people) is related on the one hand to the evaluation of deep retrofit strategies potential for office buildings, on the other hand to the will to investigate the role of thermal inertia in realistic operating conditions, by means of simple performance indicators.

As we introduced before, giving a generalized evaluation of the role of thermal inertia for energy efficiency is rather difficult, due to the variability of possible climate and operating conditions; it seems more appropriate to investigate the outcomes of the simulation process in a simple and transparent graphical way. In other words, the effective thermal capacity should be more clearly identified as one of the design parameters and its effect on energy performance more clearly unveiled for the specific realistic operating conditions.

The research focuses on the identification of the potential advantages or disadvantages of building fabric types characterized by higher effective thermal capacity, across the different climate conditions considered. In Fig. 2 the building prior and after the refurbishment is depicted, respectively in the images at the top left and at the top right, while the image at the bottom shows the building simulation model.

3.1. Building components

As introduced in the previous section, two types of construction components were considered, as shown in Fig. 3:

(1) “light” components;
(2) “medium-heavy” components.

These components present the same thermal transmittances but differentiate with respect to the dynamic thermal properties (periodic thermal transmittance, internal and external thermal admittances, decrement factor and time shift) [76].

In the research we will concentrate on periodic thermal transmittance, to verify the fulfillment of the normative requirements, and on internal areal heat capacity, to use it in the calculation of an indicator of the effective thermal capacity for the building [60].

Given the multi-scale nature of the design optimization problem, it is necessary to establish a link between the component level view of performance and the zone and the building level. As will be illustrated in the next section, we will use the internal heat capacity of the building zones, based on the sum of the internal areal capacity of the single components. On the one hand, the importance of the internal heat capacity for cooling behaviour has been already identified [77]; on the other hand, the sinusoidal boundary conditions used in the calculation according to UNI EN ISO 13786:2008 norm are different from the more general boundary conditions that can be present in a realistic transient behaviour. However, a research study [78] suggest that the approach of UNI EN ISO 13786:2008 can be improved by applying Fourier analysis and recombining the effects of the harmonics of the external forcing conditions. Therefore, the selection of a “lumped” thermal capacity as a synthetic indicator, although determined from simplified dynamic calculations, seems to be reasonable for a comparative analysis such as the one presented.

The periodic thermal transmittance and the internal areal heat capacities are calculated as follows, using the global heat transfer matrix of each component (multiplication of the heat transfer

Fig. 2. Real building prior and after refurbishment and building energy model.

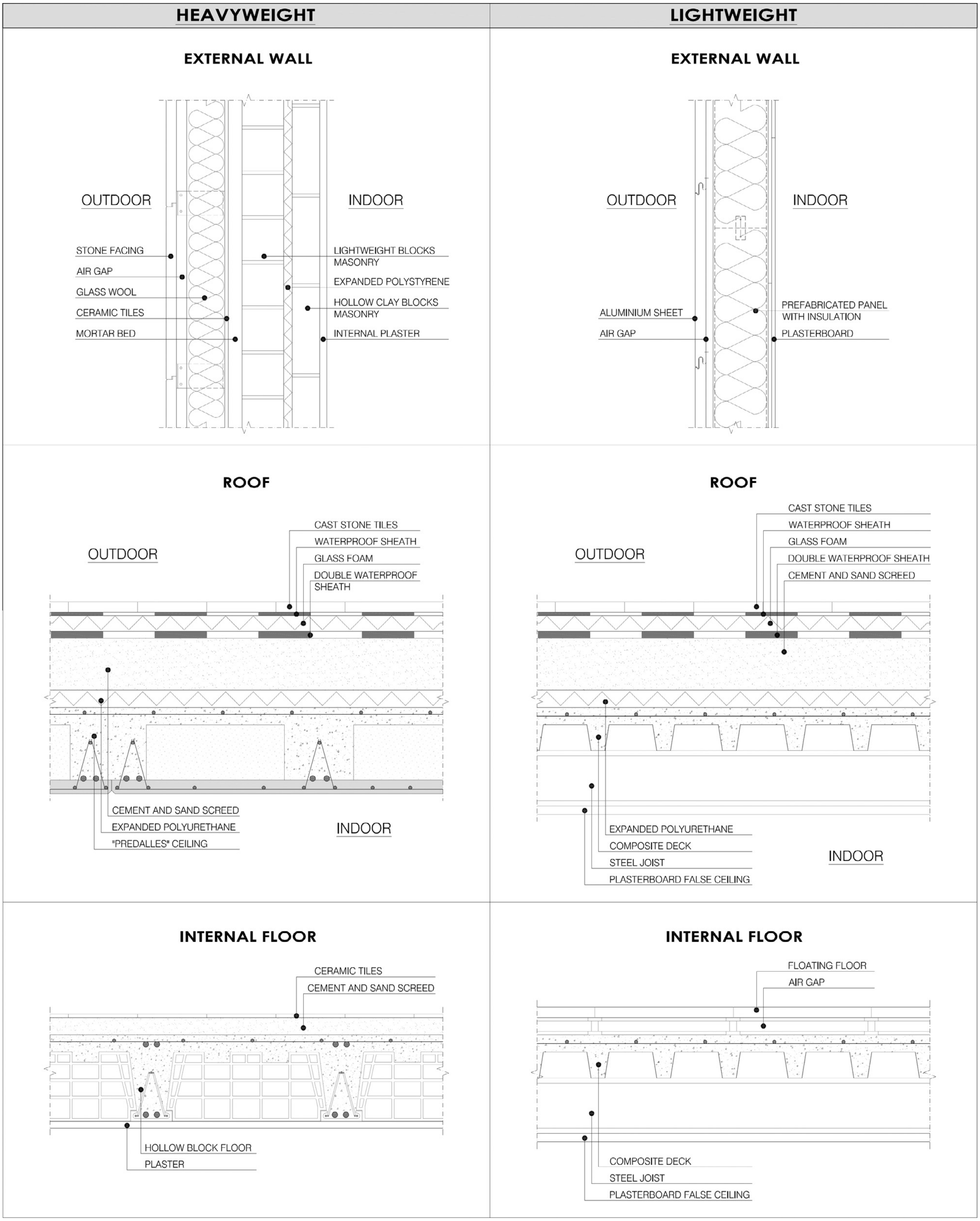

Fig. 3. Details of construction components.

matrices of each layer), assuming a periodic oscillation of the thermal conditions. The elements of each matrix are functions with complex variables of the ratio between the thickness of the construction layer and periodic penetration depth. The periodic penetration depth is the amplitude at which the temperature variations are reduced by the factor "e" in a homogeneous material of infinite thickness subjected to sinusoidal temperature variations on its surface.

The heat transfer matrix relates the complex amplitudes of the temperature and the heat flow rate on one side of a construction

Table 2
Opaque building components data.

Components	Envelope type	Milan			Rome			Palermo		
		U (W/m ^{2}K)	$\|Y_{ie}\|$ (W/m ^{2}K)	k_i (kJ/m^2 K)	U (W/m ^{2}K)	$\|Y_{ie}\|$ (W/m ^{2}K)	k_i (kJ/m^2 K)	U (W/m ^{2}K)	$\|Y_{ie}\|$ (W/m ^{2}K)	k_i (kJ/m^2 K)
External wall	Light	0.22	0.102	25	0.28	0.119	26	0.33	0.123	31
	Medium-heavy	0.22	0.015	58	0.28	0.017	58	0.33	0.031	58
Rooftop	Light	0.22	0.002	42	0.28	0.004	42	0.33	0.005	42
	Medium-heavy	0.22	0.001	70	0.28	0.002	70	0.33	0.002	70
Internal floor	Light	–	–	45	–	–	45	–	–	45
	Medium-heavy	–	–	66	–	–	66	–	–	66

Table 3
Transparent building components data.

Components	Milan		Rome		Palermo	
	U (W/m^2 K)	g (–)	U (W/m^2 K)	g (–)	U (W/m^2 K)	g
Windows	1.36	0.55	1.60	0.55	1.76	0.55

layer to the ones on the other side [76], as expressed by the following formula.

$$\begin{pmatrix} \hat{\theta}_2 \\ \hat{q}_2 \end{pmatrix} = \begin{pmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{pmatrix} \cdot \begin{pmatrix} \hat{\theta}_1 \\ \hat{q}_1 \end{pmatrix} \tag{1}$$

$$Y_{12} = -\frac{1}{Z_{12}} \tag{2}$$

$$\kappa_i = \frac{T}{2\pi}\left|\frac{Z_{11} - 1}{Z_{12}}\right| \tag{3}$$

In the case of periodic thermal transmittance and internal heat capacity for the complete component, the subscripts "1" and "2" become respectively "i" and "e" (internal and external side). The calculation performed according to the normative standard assumes a daily oscillation of temperature and heat flux on the two sides of the construction component.

The chosen construction components satisfy for each location (Milan, Rome, Palermo) all the requirements of the Italian National Standards implemented within the EPBD framework [79,80]. The thermal transmittances chosen for the different sites consider both the normative requirements and the specific climate conditions, to obtain an appropriate scaling of the results. The limit values of the periodic thermal transmittance have also been respected. The limits are currently 0.12 W/m^2 K for opaque external walls and 0.20 W/m^2 K for rooftop components [79] and are not differentiated with respect to the different climatic zones.

Components' data are summarized in Tables 2 and 3, showing the difference among "light" and "medium-heavy" ones. It has to be highlighted that only the "light" external walls arrive to the performance limit in terms of periodic thermal transmittance; all the other components are order of magnitudes lower.

Finally, the combination of the different components determines the types of building fabric ("light", "medium" and "medium-heavy") used in the parametric simulation and illustrated in the next section.

3.2. Test cell and building

The analysis of results focuses on two scales, the room one and the whole building one. The room, named "test cell", is a single thermal zone with its exterior components (façade wall and window) oriented to south. The internal walls adjacent to similar rooms are modelled as adiabatic construction elements. The fundamental data for simulation regarding both the "test cell" and the "building" are reported respectively in Tables 4 and 5, highlighting the data that are common to all the different simulations and the variations in night ventilation. The algorithm of the adaptive shading system used in both cases is described in detail in literature [74].

The research presents the values of sensible thermal energy demand (obtained by means of simulations) as a function of building fabric characteristics and operation strategies. The combination of building components determines the type of construction:

1. "light" (light walls, roof and internal floors);
2. "medium" (light walls, medium-heavy roof and internal floors);
3. "medium-heavy" (medium-heavy walls, roof and internal floors).

Table 4
Test cell simulation data.

Group	Type	Unit	Value
Envelope	Length × Width × Height	m × m × m	8 × 4 × 3
	Net floor area	m^2	32
	Net volume	m^3	96
	Orientation	–	South
Activities and lighting	Total internal gains	W/m^2	18
	Operation schedule heating/cooling system	–	00:08–20:00
	Operation schedule internal gains	–	00:09–19:00
	Weekly operating days	–	5/7
Control and operation	Heating set-point (temperature)	°C	20
	Cooling set-point (temperature)	°C	26
	Minimum ventilation rate (fresh air) in operating hours	vol/h	1,35
	Night ventilation baseline	vol/h	0,1
	Night ventilation enhanced (cooling mode)	vol/h	4

Table 5
Building simulation data.

Group	Type	Unit	Value
Envelope	Number of building blocks	–	3
	Net floor area	m^2	5236
	Net volume	m^3	18,355
Activities and lighting	Total internal loads	W/m^2	18
	Operation schedule heating/cooling system	–	00:08–20:00
	Operation schedule internal gains	–	00:09–19:00
	Weekly operating days	–	5/7
Control and operation	Heating set-point (temperature)	°C	20
	Cooling set-point (temperature)	°C	26
	Minimum ventilation rate (fresh air) in operating hours	vol/h	1,35
	Night ventilation baseline	vol/h	0,1
	Night ventilation enhanced (cooling mode)	vol/h	4

Table 6
Effective thermal capacity of the test cell.

Building fabric type	Milan m_f (kJ/m^2 K)	Rome m_f (kJ/m^2 K)	Palermo m_f (kJ/m^2 K)
Light	102.7	103.3	106.5
Medium	155.7	156.3	159.5
Medium-heavy	176.2	176.2	176.3

The internal heat capacity of the building zones (calculated for the test cell and the whole building) is obtained by summing all the internal heat capacities (defined in the previous section) of construction components multiplied by their surface.

$$C_m = \sum_j \kappa_{ij} \cdot A_j \tag{4}$$

We selected the internal heat capacity per unit of net floor area as a synthetic indicator of the effective thermal capacity both for the test cell and the whole building.

$$m_f = \frac{C_m}{A_f} \tag{5}$$

The data related to the effective thermal capacity given the different construction types, are reported in Tables 6 and 7.

The other possible variations in simulation data are related to:

(1) presence or absence of the adaptive shading system;
(2) normal or increased night ventilation rate in cooling mode.

Finally, we considered three possible simulation alternatives and applied them to all the construction types and locations:

(1) “baseline” (absence of adaptive shading system and normal night ventilation rate);
(2) “adaptive shading” (presence of shading system and normal night ventilation rate).
(3) “optimized” (presence of shading system and night cooling ventilation).

Table 7
Effective thermal capacity of the building.

Building fabric type	Milan m_f (kJ/m^2 K)	Rome m_f (kJ/m^2 K)	Palermo m_f (kJ/m^2 K)
Light	117.6	118.5	122.5
Medium	159.7	160.6	164.6
Medium-heavy	185.4	185.4	185.5

Table 8
Configurations considered in the simulation for the different building fabric types and locations.

Configuration	Operation mode	Adaptive shading	Enhanced night ventilation
Baseline	Heating	No	No
	Cooling	No	No
Adaptive shading	Heating	Yes	No
	Cooling	Yes	No
Optimized	Heating	Yes	No
	Cooling	Yes	Yes

Table 9
Specific thermal energy demand of the test cell for the different configurations.

Configuration	Building fabric type	Energy demand	Milan (kW h/m^3)	Rome (kW h/m^3)	Palermo (kW h/m^3)
Baseline	Light	Heating	4.87	1.09	0.02
		Cooling	7.94	10.01	11.13
	Medium	Heating	4.85	0.93	0.00
		Cooling	7.70	9.73	10.94
	Medium-heavy	Heating	4.85	0.89	0.00
		Cooling	7.60	9.63	10.88
Adaptive shading	Light	Heating	5.17	1.42	0.04
		Cooling	6.55	8.41	9.62
	Medium	Heating	5.17	1.29	0.01
		Cooling	6.36	8.12	9.43
	Medium-heavy	Heating	5.18	1.25	0.00
		Cooling	6.29	8.08	9.38
Optimized	Light	Heating	5.17	1.42	0.05
		Cooling	3.05	4.66	6.89
	Medium	Heating	5.17	1.29	0.01
		Cooling	2.40	3.97	6.17
	Medium-heavy	Heating	5.18	1.25	0.00
		Cooling	2.11	3.69	5.90

The configurations are summarized in Table 8 and the results obtained through simulation are illustrated and discussed in the next section.

4. Discussion of results

Observing the data obtained in the parametric simulation, presented in Tables 9 and 10 respectively for the test cell and the whole building, we can immediately identify how the conditions chosen affect particularly the sensible cooling energy demand,

Table 10
Specific thermal energy demand of the building for the different configurations.

Configuration	Building fabric type	Energy demand	Milan (kW h/m^3)	Rome (kW h/m^3)	Palermo (kW h/m^3)
Baseline	Light	Heating	10.72	4.24	0.87
		Cooling	9.03	11.82	14.03
	Medium	Heating	10.79	4.18	0.74
		Cooling	8.81	11.47	13.74
	Medium-heavy	Heating	10.86	4.19	0.70
		Cooling	8.71	11.31	13.61
Adaptive shading	Light	Heating	11.00	4.62	0.96
		Cooling	7.14	9.36	11.15
	Medium	Heating	11.07	4.56	0.83
		Cooling	6.94	9.05	10.87
	Medium-heavy	Heating	11.12	4.56	0.79
		Cooling	6.84	8.92	10.75
Optimized	Light	Heating	11.00	4.62	0.96
		Cooling	4.05	6.29	8.72
	Medium	Heating	11.07	4.56	0.83
		Cooling	3.35	5.50	7.96
	Medium-heavy	Heating	11.12	4.56	0.79
		Cooling	2.96	5.10	7.61

because the thermal transmittance remains unchanged for the single location (it changes only for the different climate zones), while the effective thermal capacity changes with respect to the different building fabric types.

The results are also plotted in Fig. 4 to enable a general analysis of heating and cooling energy demand as a two objective optimization problem. In other words, our goal is to identify for each location the optimal trade-offs (non-dominated solutions, Pareto frontier) [8] of the building configurations. In Fig. 4 the lines of “light” and “medium-heavy” configurations are plotted to highlight the different performance among the two extreme cases; the performance of the “medium” configuration lays clearly between the other two.

The identification of the influence of effective thermal capacity on cooling demand in highly insulated refurbished buildings is clearly an important topic for Southern Europe and the Mediterranean area, where this demand is particularly significant and standard insulation levels have been rapidly increasing in recent years, due to normative requirements.

It can be noticed that, when the adaptive shading system is present, there is a moderate reduction of the useful solar gains in winter, because it controls the possible glare and therefore it reduces partially the useful gains also in the heating season, if we compare it with a configuration where there is not any shading device.

However, the increase of winter energy demand is practically negligible while the advantages in terms of cooling energy demand reduction are particularly evident if we compare the baseline with the adaptive shading configuration.

An important evidence that appears from data is that the performance advantage of the “medium-heavy” building fabric configurations over the “light” ones becomes relevant only in the optimized cases (i.e. where increased night ventilation is present), although the very modest advantage recognizable in the other cases increases moderately going from Milan (where there is practically no difference) to Palermo. These results clearly relates to the arguments illustrated in Section 2.1, because if we consider an air-tight and highly insulated building envelope where all the windows are closed during the night, the air-change rate is very limited and, therefore, cannot enable a passive cooling process by itself. During the day, on the other hand, there is a coincidence between internal gains (occupancy, appliances and lighting) and external gains (solar radiation and transmission through the envelope) and so the advantage, if we do not cool down the building passively with increased night ventilation, is much less evident. The very modest night cooling effect is related to the higher thermal transmittance in Rome and Palermo.

It has to be highlighted that the dynamic simulation and optimization process, in general, has to consider not only the standard operating conditions but also intermittent and optimized conditions and, possibly, evaluate the behaviour with respect to different comfort models to account for end user perception more

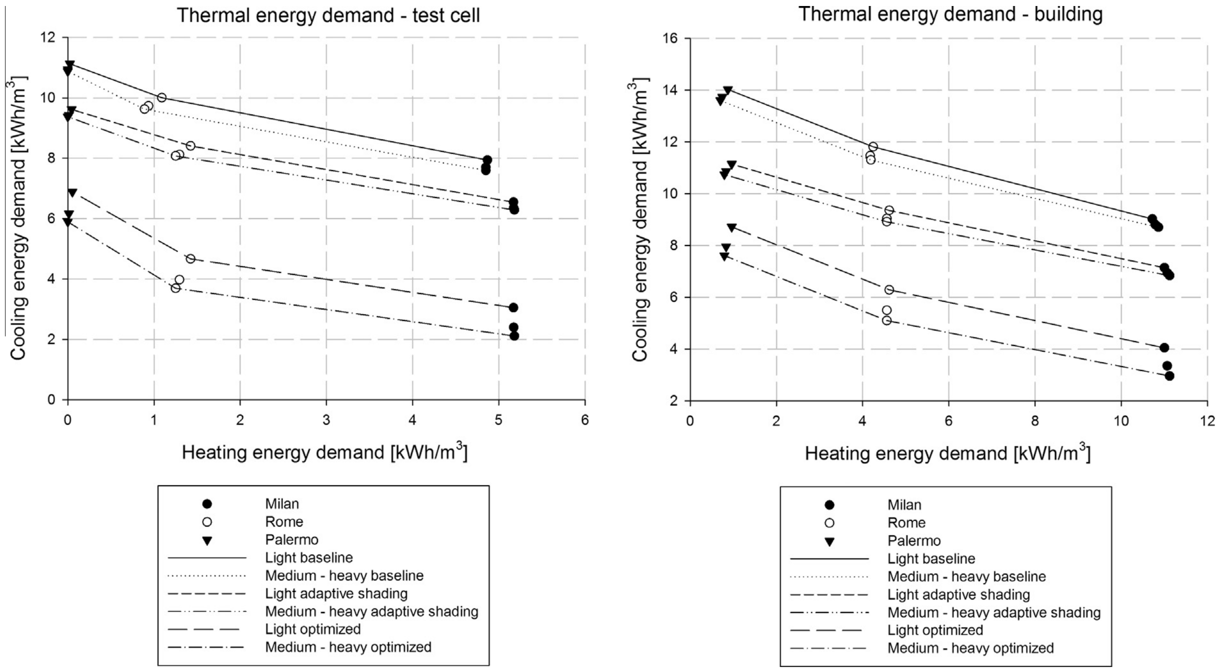

Fig. 4. Sensible thermal energy demand for heating and cooling of the test cell and the building.

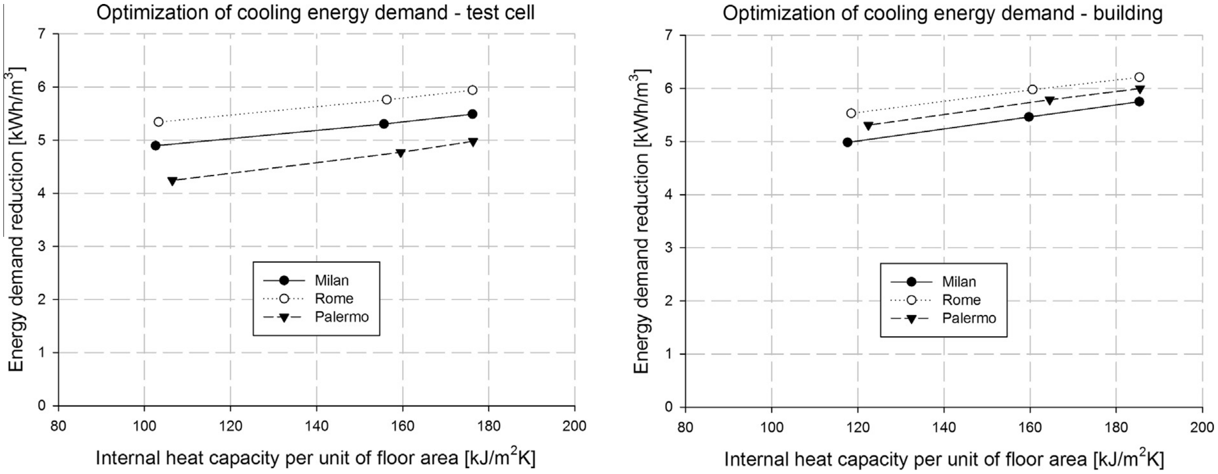

Fig. 5. Cooling sensible energy demand reduction of optimized configuration with respect to baseline for the test cell and the building as a function of effective thermal capacity.

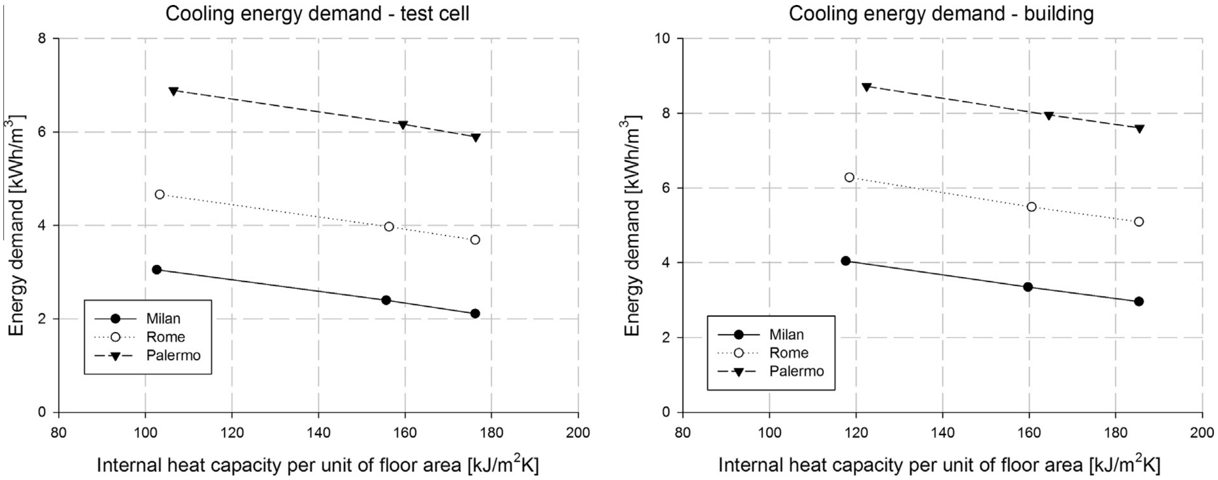

Fig. 6. Sensible cooling energy demand of the test cell and the building as a function of effective thermal heat capacity.

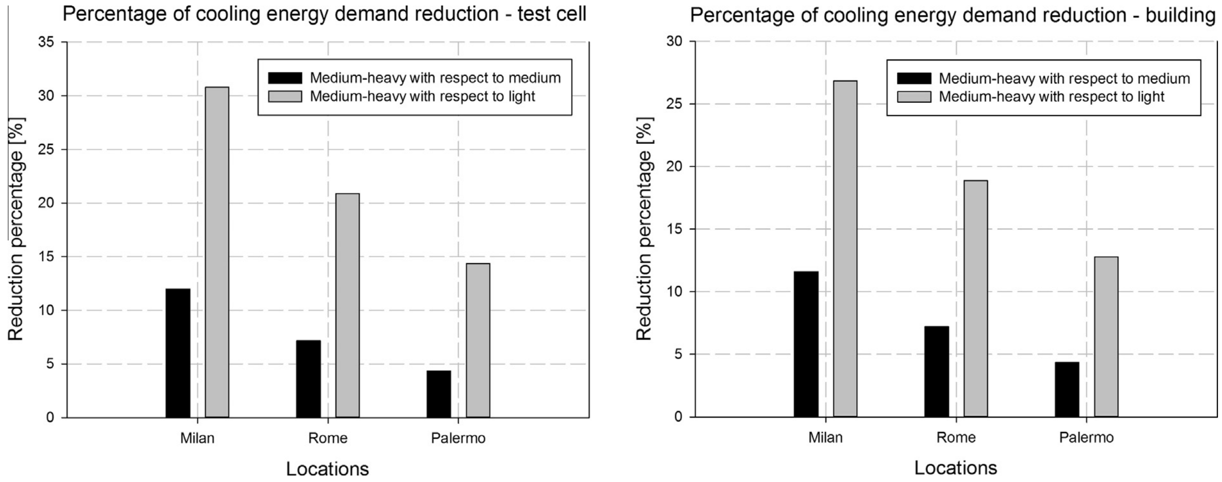

Fig. 7. Percentage of reduction of sensible cooling energy demand for the test cell and the building for medium-heavy over medium and light configurations.

realistically. Comfort models can enable a larger degree of flexibility in the operation of the technical systems for heating and cooling and therefore enhance the results achievable in terms of energy saving.

If we concentrate our analysis in the optimized cases for the different locations, where the role of the thermal inertia (higher effective thermal capacity) becomes relevant, and we plot the sensible cooling energy demand reduction (due to the optimization pro-

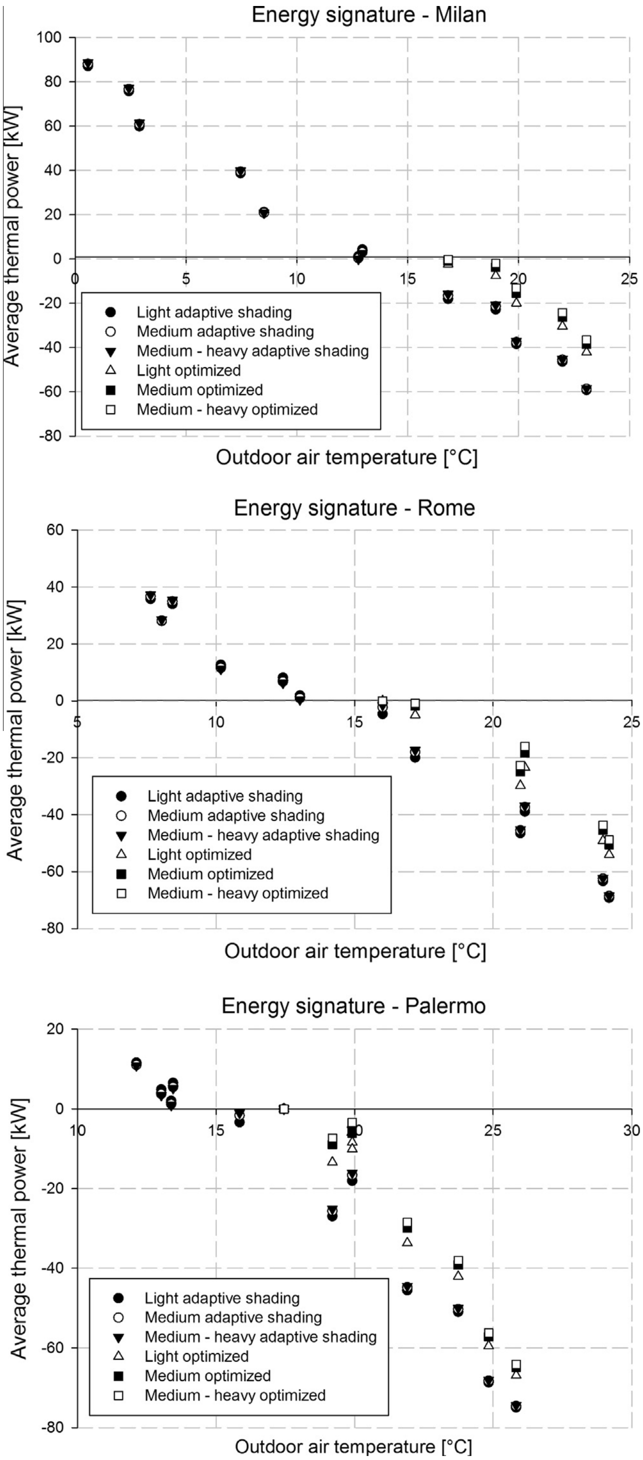

Fig. 8. Energy signature of the building for Milan, Rome and Palermo.

cess) with respect to the indicator of thermal capacity (the effective thermal capacity per unit of net floor area), we obtain the results presented in Fig. 5, respectively for “test cell” and “building”. The reduction potential (referring to the baseline configuration) appears to be quite similar in the different locations and increases linearly with the thermal capacity.

On the other hand, if we look at the final results in terms of sensible cooling energy demand reported in Fig. 6 we can identify how this demand is very different in the locations chosen, but that it decreases linearly, with similar trends, as the thermal capacity increases. This simple graphical representation can be useful in the design process to highlight whether or not building fabric inertial properties are effectively exploited for energy saving; for the “baseline” and “adaptive shading” cases the results would have been practically on a horizontal line, thus confirming the fact the inertial properties do not influence the energy demand.

The effective thermal capacity gives a positive contribution in the optimization process (increase in cooling energy saving potential) and also in the optimized energy demand (decrease in cooling energy demand). With respect to heating demand savings, the variations are negligible, as shown before.

Finally, we can identify the relative advantage (in terms of percentage of energy demand reduction) of “medium-heavy” building fabric over “medium” and “light” ones for “test cell” and “building” in Fig. 7. The relative advantage becomes proportionally more relevant where the cooling demand is lower, in this case the location of Milan (nearly 30% for the whole building), but the effect can be relevant also in the other locations (between 15% and 20% for the whole building respectively in Palermo and Rome). We have to recall the fact that these effects in terms of energy demand are evident only for the “optimized” cases if we consider a building operated intermittently and characterized by high and coincident internal gains. It is important however to recognize that the analogies in the data between “test cell” and “building” confirm the scalability of the positive effects related to a higher thermal capacity of the building fabric.

Finally, we present in Fig. 8 the energy signature of the building in the different locations, highlighting the variations of the “optimized” configurations (cooling optimization with enhanced night ventilation) with respect to the “adaptive shading” ones; in these cases we can see how the use of enhanced night ventilation affects monthly average power (heating is plotted with positive value, cooling with negative) and therefore monthly sensible energy demand patterns, changing the building “equilibrium temperature”.

It is worth noticing that, while the present work focuses on energy demand reduction, other topics such as the stability of internal thermal conditions with intermittent and attenuated operation of HVAC, the reduction of peak loads and the possibility to differ thermal loads can be relevant decision criteria for building optimization, in particular if we consider the interaction among the building, the electric grid (when thermal loads are satisfied by technologies fed by electricity) and the end user. However, the evaluation of these specific aspects goes beyond the scope of the research presented.

5. Conclusions

The correct design of building components represents an essential element for the refurbishment of the existing building stock. Existing buildings constitute a challenge today, because of the necessity to achieve high performance levels in a short time frame.

The increase of the insulation levels, the increase of the airtightness and the enhancement of solar control capabilities are useful aspects in the design of components, but the role of dynamic thermal properties on the energy performance cannot be underestimated, in particular if we are trying to optimize the overall building performance.

The positive effect of thermal capacity appears to be relevant for moderate climates (e.g. Southern Europe and the Mediterranean area) and intermediate seasons, where it can work as a stabilizing factor of the thermal dynamics of the whole building system.

The comparison between the results obtained by the “test cell” and the “building” highlights the scalability of the positive contribution of building fabrics characterized by higher effective thermal capacities when coupled with other energy savings strategies and, in particular, with correct operation strategies such as the enhanced night ventilation.

The data visualization strategies employed in the research can help in the design optimization process (two objective visualization, energy demand plotted as a function of the effective thermal capacity indicator, etc.) giving a direct feed-back to the energy modeller regarding the contribution of the thermal capacity to the energy performance for heating and cooling (i.e. highlighting whether the thermal capacity is effectively exploited or not). As a matter of fact, the energy modeller can directly identify the contribution of thermal inertia to energy saving, in this case relevant only in the optimized cases.

Finally, today normative requirements and energy labeling of buildings are verified mostly with design phase data, but the empirical evidence shows that the measured performance may deviate significantly from this theoretical design performance. For these reason the development of full scale testing methodologies, synthesizing the findings of recent research in the field of commissioning and performance monitoring, can positively contribute in this sense, especially if a methodological continuity with design practices will be established. For example "energy signature" models, used for the inverse estimation of the heat transfer coefficients of buildings, can be complemented by "grey-box" models (a combination of physical knowledge and statistics) to identify the unknown parameters of the system (lumped thermal capacitance in particular) by means of time-series analysis.

As a conclusion, the potential role of thermal inertia for energy saving purpose can be thoroughly investigated only if we consider the possibility of using thermal system identification techniques to derive "reduced order" models, suitable for predictive control. The optimization of the interaction with the energy infrastructures ("smart" electric grid in particular) and the possibility of using different comfort models (enabling a greater flexibility in the fulfillment of building services or even the "passive" behaviour of the building) clearly extend the variability of the conditions to be considered, incorporating further dimensions in this research topic.

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