BUILDING SHAPE AND HEATING REQUIREMENTS: A PARAMETRIC APPROACH IN ITALIAN CLIMATIC CONDITIONS

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Summary

Bioclimatic architecture deals with the relationship between buildings and natural environment in order to guarantee indoor comfort conditions and to minimize energy requirements. The building shape is a fundamental aspect of that relationship. Usually, in thermal behavior analysis this parameter is considered only from the point of view of compactness (defined by the so called "shape coefficient", i.e. the envelope surface / inner volume ratio). This is a reductive approach, because two buildings with the same coefficient could have different shapes and so a different thermal behavior (even considering indoor comfort conditions), where some aspects such as orientation, openings, exposition to atmospheric agents and natural elements must be strictly considered.

In scientific literature some studies about the relationship between shape coefficient and energy requirements during the heating season can be found. In particular, some simplified design rules considering shape coefficient have been developed for buildings in European northern (cold) countries. Generally, no indications are given to designers who operates in mild or southern climate conditions.

In this context, at the Laboratory of Building Design of the University of Trento (Italy) researches are carried on in order to fill in this gap. In this paper, the results of a research activity focused on heating requirements of buildings with different shapes and laid in the Italian territory is presented. Monthly calculations have been performed on three-dimensional models. The results show that shape coefficient is not the only parameter to be considered in the first stage of the design process, but that better results can be achieve considering a bioclimatic (even if simplified) approach by the very beginning.

Keywords: building shape, heating requirements, solar exposure, bioclimatic architecture

1 Introduction: shape and energy requirements

The relationship between shape and energy requirements is still an open question. Ourghi et al. (2007) asserted: "No definitive and simple correlations were established between the basic attributes associated with buildings (such as form, window size and glazing type) and their total annual energy use and/or heating/cooling loads." [1]

Depecker et al. (2001) studied relationship between shape and energy requirements during the winter season in Paris and Carpentras, a town placed in southern France with a milder climate [2].

In order to qualify the shape, a "shape coefficient" C_f is defined as follows:

$$C_f = \frac{S}{V}$$

where S is the envelope surface of the building, i.e. the external skin surfaces, and V is the inner volume of the building.

In Paris they found a strong correlation between energy consumption and shape coefficient, in Carpentras they did not. So Depecker et al. (2001) gave no specific indications for building design in a mild climate; for climatic conditions similar to those of Carpentras they asserted: "A link between the energy consumption of a building and its shape can no longer be stated. As a consequence, that leaves architects to choose any shape".

In our opinion, the conclusion that "in mild climates the architectural design can leave out of consideration the shape of buildings" is not appropriate. The goal of the research work hereafter presented is therefore to fill in that gap, i.e. to find relationships between buildings shape and heating requirements even in mild climates.

This work examines the relationship between buildings shape and energy requirements considering not only the shape coefficient, but also how external surfaces are oriented regarding the cardinal directions. This aspect is indeed very important for the exploitation of solar energy.

2 Calculation models and method

2.1 Geometry

Depecker et al. (2001) considered different models. All of them are made of 16 base modules having parallelepiped shape. The difference among the models consists in the different assembling modality of the base modules.

In the research presented in this paper, a base model very similar to the one of Depecker et al. (2001) has been considered. In **Fig. 1** its main geometrical dimensions are represented.

The north side and the roof do not have openings. On the south side there is a glazing surface of $5.25m^2$, equal to 40.6% of the total surface, net of delimitation elements. Both on the east and the west side there is a glazing surface of $1.54m^2$, equal to 11.9% of the total surface, net of delimitation elements. The frame occupies the 9% of the hole for the big window, the 16% for the little one.

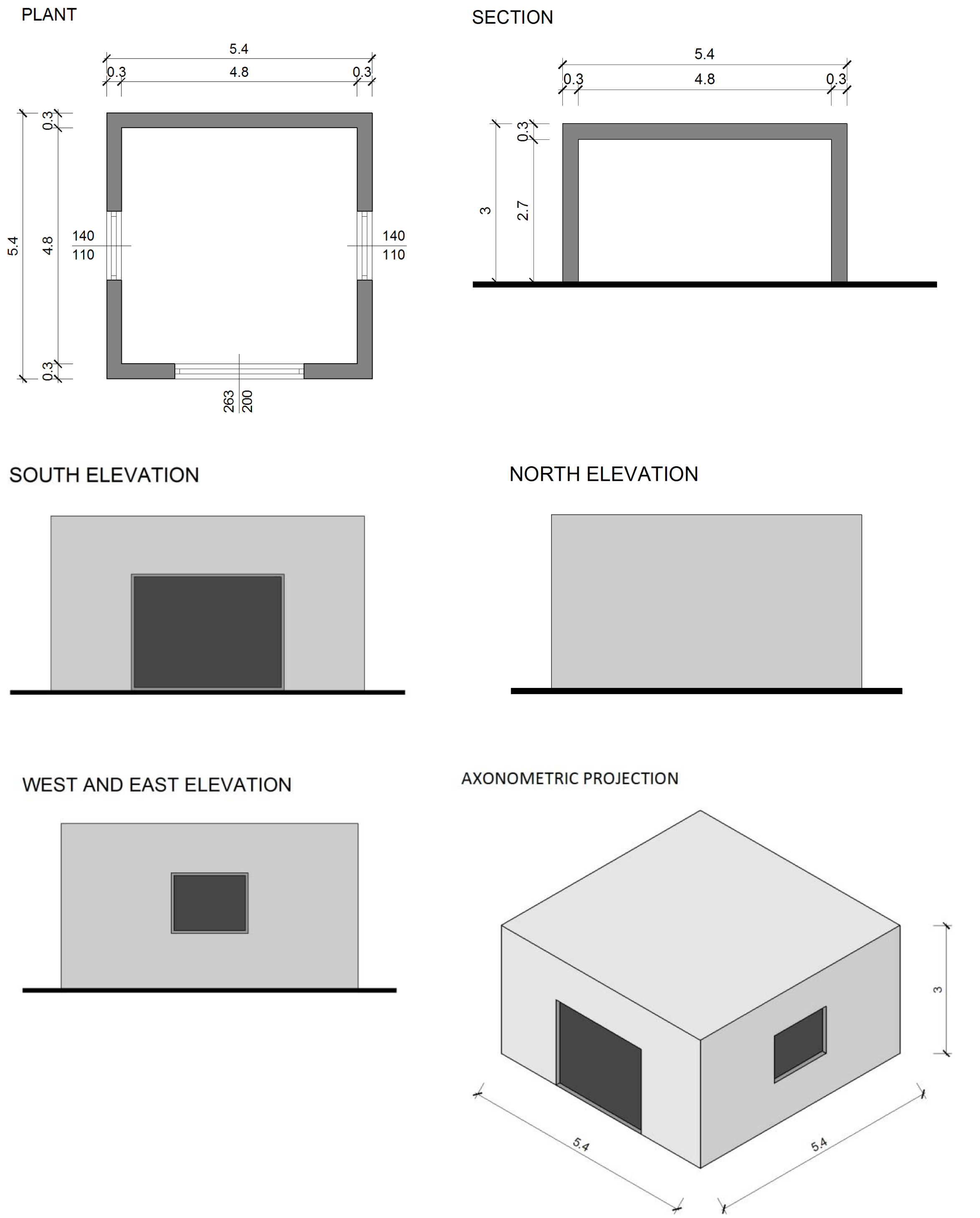


Fig. 1 Geometrical dimensions of the base model

In the first part of the work 4 models composed by the base module were considered. They are presented in **Fig. 2**.

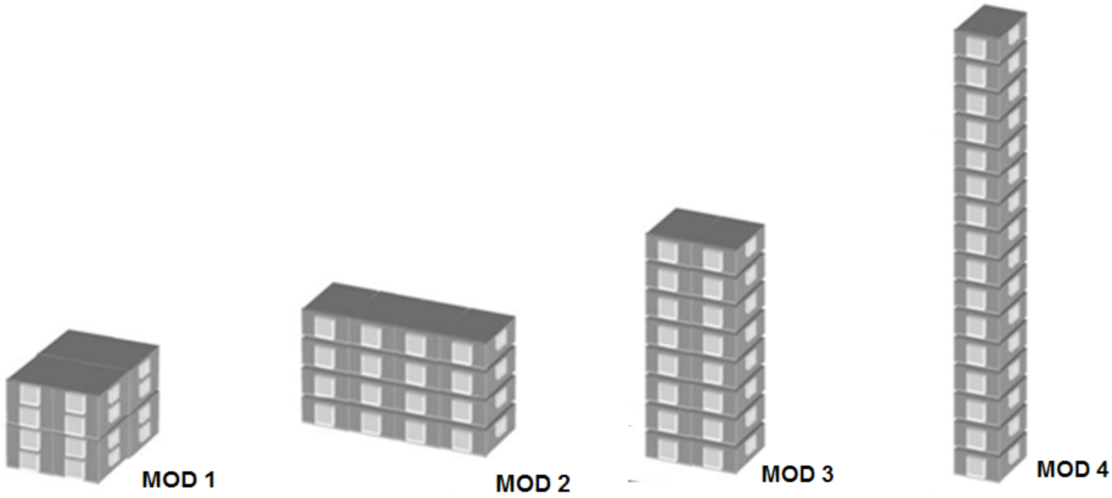


Fig. 2 Models composed by the base module

As regards compactness the best solution is MOD 1, as regards solar exposition the best solution is MOD 4 (see **Tab. 1** and **Fig. 3**).

Tab. 1 Dimensions concerning the models composed by the base module

	MOD 1	**MOD 2**	**MOD 3**	**MOD 4**
V [m^3]	1399.68	1399.68	1399.68	1399.68
S_i [m^2]	751.68	881.28	894.24	1095.12
S_e [m^2]	635.04	764.64	835.92	1065.96
S_i / V [m^2/m^3]	0.54	0.63	0.64	0.78
S_e / V [m^2/m^3]	0.45	0.55	0.60	0.76
S_{South} / V [m^2/m^3]	0.09	0.19	0.19	0.19
S_{E+W} / V [m^2/m^3]	0.19	0.09	0.09	0.37
$A_{win,south}$ [m^2]	42.08	84.16	84.16	84.16
$A_{win, E+W}$ [m^2]	24.64	12.32	24.64	49.28

DEFINITIONS:
S_i: surface of the envelope, ground floor slab included
S_e: surface of the envelope, except ground floor slab
S_{South}: surface of the envelope on south side
S_{E+W}: surface of the envelope on east side + on west side
$A_{win,south}$: glazing surface of on south side
$A_{win, E+W}$: glazing surface of on east side + on west side

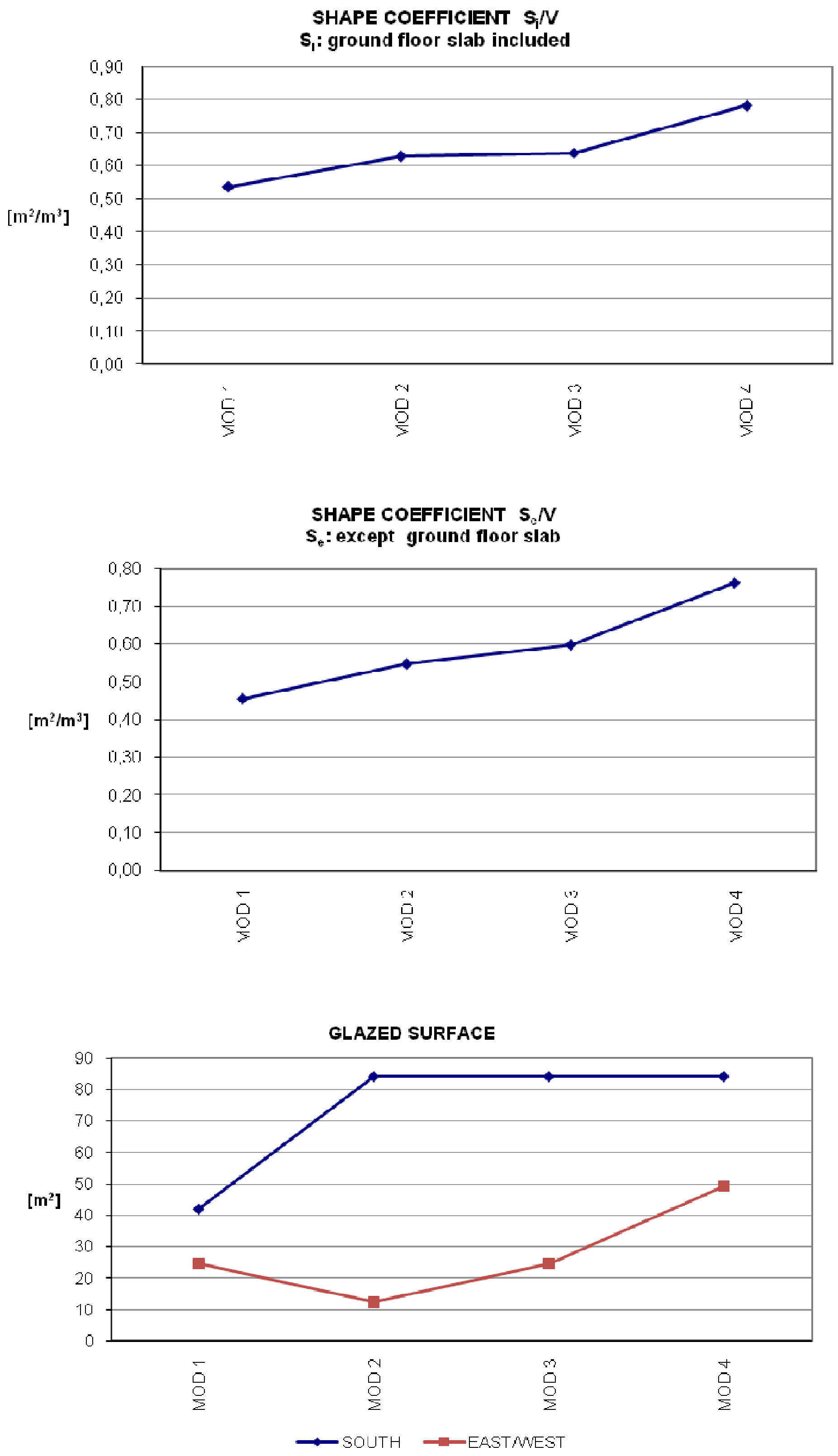


Fig. 3 Physical quantities concerning the compactness and the exposition to solar radiation of the four models considered in the first part of the research work

In the second part of the work, buildings with a parallelepiped shape have been considered as well, having the same glazing surface percentage for every orientation as the models considered in the first part, but with free plant dimension. In this way we have more freedom in the dimensional parameters looking for buildings with certain fixed heating requirements.

2.2 Thermal properties

2.2.1 Thermal transmittance

The values considered are the limit values for Trento according to Italian legislation [3].

external walls $U = 0.34$ W/(m^{2}K) roof $U = 0.30$ W/(m^{2}K)

ground slab $U = 0.30$ W/(m^{2}K) window $U = 2.2$ W/(m^{2}K)

2.2.2 Thermal bridges

The values correspond to standard EN ISO 14683:2007 for external insulating layer and refer to internal dimensions of walls and roof [4].
connection external wall – internal partition $\psi_i = 0.1$ W/(mK)
corner between two external walls $\psi_i = 0.15$ W/(mK)
connection external wall – roof $\psi_i = 0.15$ W/(mK)
connection external wall – ground slab $\psi_i = 0.75$ W/(mK)
connection external wall – internal slab $\psi_i = 0.1$ W/(mK)

2.2.3 Optical properties of the glass

The following according to the indications of the technical standard UNI/TS 11300-1:2008 for Low E double glazing [5] has been choosen:
total solar energy transmittance of the windows $g = 0.67$

2.2.4 Ventilation

The following value according to the technical standard UNI/TS 11300-1:2008 has been chosen:
0,3 AC/H (air change / hour)

2.2.5 Internal gains

The following value according to the technical standard UNI/TS 11300-1:2008:
3,9 W/m^2

2.3 Calculation of heating requirements

The calculation of heating requirements is made with the monthly methods presented in the standard EN ISO 13790:2008 [6]. It is a stationary calculation in which a coefficient, the “gain utilization factor”, is present to consider the non-stationary effects.

$$Q_{h,nd} = Q_{h,ht} - \eta_{h,gn} Q_{h,gn}$$

where
$Q_{h,nd}$ is the heating need
$Q_{h,ht}$ is the total heat transfer from inside to outside

$Q_{h,gn}$ is the total heat gain
$\eta_{h,gn}$ is the gain utilization factor

$$Q_{h,ht} = Q_{h,tr} + Q_{h,ve}$$

where
$Q_{h,tr}$ is the total heat transfer by transmission
$Q_{h,ve}$ is the total heat transfer by ventilation

$$Q_{h,ht} = H_{tr} \cdot (\theta_{int} - \theta_e) \cdot t$$

where
H_{tr} is the overall heat transfer coefficient by transmission
θ_{int} is the set-point temperature of the building for heating, equal to 20°C
θ_e is the temperature of the external environment
t is the duration of the month considered (the calculation is repeated for every month)

$$H_{tr} = \sum_i (S_i U_i) + \sum_k \psi_k l_k$$

where
S_i is the area of element i of the building envelope (ground floor slab included)
U_i is the thermal transmittance of element i of the building envelope
ψ_k is the linear thermal transmittance of thermal bridge k
l_k is the length of linear thermal bridge

$$Q_{h,ve} = H_{ve} \cdot (\theta_{int} - \theta_e) \cdot t$$

where
H_{ve} is the overall ventilation heat transfer coefficient

$$H_{ve} = \varrho_a c_a q_{ve}$$

where
$\varrho_a c_a$ is the heat capacity of air per volume
q_{ve} is the airflow rate

$$Q_{h,gn} = Q_{int} + Q_{sol}$$

where
Q_{int} is the sum of internal gains over the given period
Q_{sol} is the sum of solar heat gains over the given period

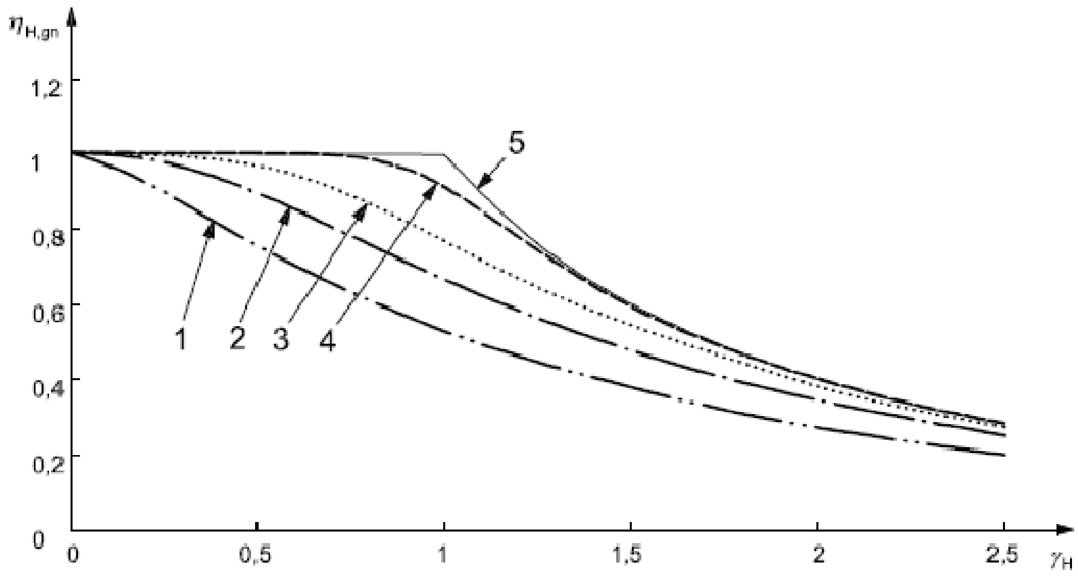
The gain utilization factor depends on the total heat gain/heating need ratio and on the thermal inertia of the building.

$$\text{if } \gamma_H > 0 \text{ and } \gamma_H \neq 1 \quad \eta_{H,gn} = (1 - \gamma_H^{a_H}) / (1 - \gamma_H^{a_H+1})$$

$$\text{if } \gamma_H = 1 \quad \eta_{H,gn} = a_H / (a_H + 1)$$

where
$\gamma_H = \dfrac{Q_{h,gn}}{Q_{h,ht}}$
$a_H = 1 + \dfrac{\tau}{15}$ with time constant of the building expressed in hours $\tau = \dfrac{C_m/3600}{H_{tr} + H_{ve}}$

C_m is the internal heat capacity of the building
The trend of the gain utilization factor is depicted in **Fig. 4**.



Key

1 time constant of 8 h (low inertia)
2 time constant of 1 d
3 time constant of 2 d
4 time constant of 7 d
5 time constant infinite (high inertia)

Fig. 4 Gain utilization factor

2.4 Climatic data

Depecker et al. (2001) considered French localities whereas the present research considers Italian localities, in order to give useful indications to local designers that work in climatic conditions milder than France.

Four different localities have been selected, presenting four different climatic conditions. Canazei and Trento are neighboring localities in Northern Italy, in an Alpine territory, but Canazei is on a higher altitude and is one of the coldest Italian localities. Florence is in north-central Italy, south of Apennines. Rome is in central Italy. The calculated energy requirements in Rome are very low and therefore no localities southern to Rome have been considered.

The climatic data are taken from the Italian standard UNI 10349:1994 [7] and are reported in **Tab. 2**. “DD” are the degree day, “mean H_{dh}” is a mean of the daily diffuse solar radiation for the heating season, “mean H_{bh}” is a mean of the daily direct solar radiation on a horizontal plane for the heating season.

Tab. 2 Climatic data concerning the selected localities

	3 altitude [m AMSL]	latitude	longitude	7 DD	'ab. 8) mean H_{dh} [MJ/m^2]	'ab. 10 1 mean H_{bh} [MJ/m^2]
Canazei	1.465	46°29'N	11°46'E	4918	3,0	4,3
Trento	194	46°04'N	11°07'E	2569	3,0	4,3
Florence	50	43°46'N	11°15'E	1821	3,3	3,9
Rome	20	41°53'N	12°29°E	1415	3,6	4,8

3 Results

The first part of the work considered the 4 models whose characteristics are presented in **Fig. 2**, **Fig. 3** and **Tab. 1** and the 4 Italian localities presented in **Tab. 2**. The calculated annual requirements for heating are presented in **Tab. 3** and **Fig. 5**.

MOD 2 e MOD 3 are less compacted and more exposed than MOD 1. In Rome they require less energy than MOD 1, in Canazei they do not. However for all the considered localities very similar energy requirements correspond to the models MOD 1, MOD 2 and MOD 3, whereas a higher requirement corresponds to MOD 4, which is less compact than all other models and do not have a greater surface facing south.

Tab. 3 **Annual requirements for heating as regards 4 models and 4 localities [kWh/m^2]**

	MOD 1	**MOD 2**	**MOD 3**	**MOD 4**
S_i/V [m^2/m^3]	**0.54**	**0.63**	**0.64**	**0.78**
Canazei	44.0	44.0	45.0	59.0
Trento	20.4	19.5	20.0	28.2
Florence	12.2	11.5	11.6	17.1
Rome	5.1	4.6	4.5	7.3

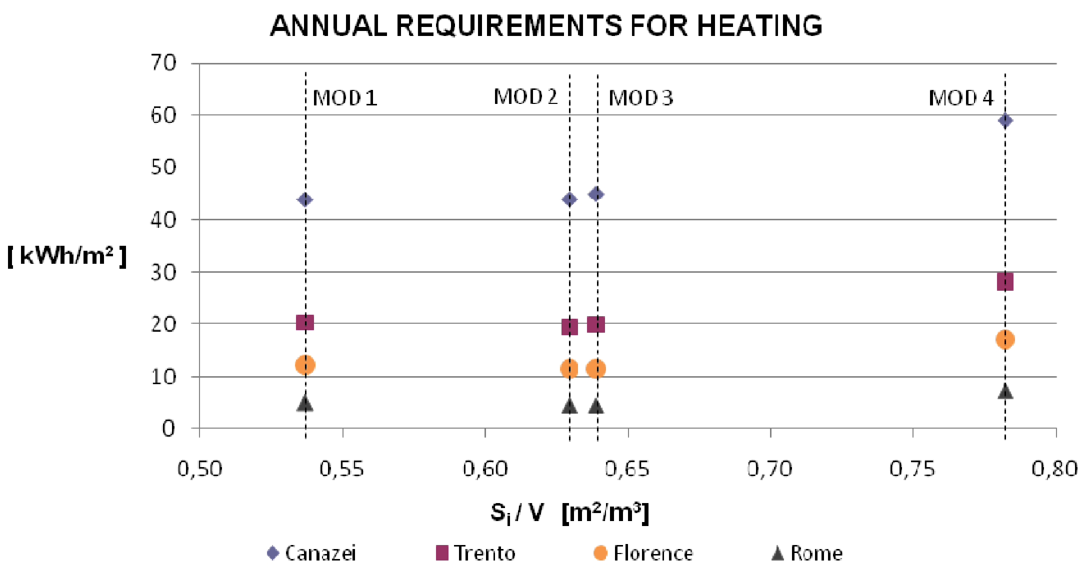


Fig. 5 Annual requirements for heating as regards 4 models and 4 localities

In the second part of the work the same localities have been considered and, together with the models MOD 1, MOD 2, MOD 3, MOD 4, other models having different dimensions (anyway parallelepipeds) have been introduced. In order to take into account the importance of the building shape with reference to the solar irradiation, a new index has been considered, S_{south}/V = south façade area/ volume. This index, all other geometrical factors being equal (specified in the following), gives an idea of how the shape changes so to allow the better surface exposure to solar irradiation. In particular, to determine the dimensions of a parallelepiped, and therefore a point on the graph (S_i/V ; S_{south}/V), three parameters are needed. In a spreadsheet the equations concerning the relationships between shape parameters and heating requirement Q_h have been set, considering the other parameters constant (climate data, which are characteristic of the location, ventilation, thermal transmittances, total solar energy transmittance of glazing surfaces, glazing surface / opaque surface ratio relative to every orientation). Then three parameters have been fixed: volume V of the building, energy demand Q_h and building height (heights have been considered with step interval of 3m: 3m, 6m, 9m... 48m). So the geometrical dimensions of a building having a determined energy requirement have been determined and the corresponding point on the graph (S_i/V ; S_{south}/V) has been fixed. Therefore each point printed in **Fig. 6** and **Fig. 7** (using different symbols) corresponds to a determined level of energy demand in a certain place and for a defined height of the model. In **Fig. 6** the points have been connected to obtain curves characterized by an equal level of heating demand.

The initial stretch of the line is curved, generally with growing derivative: for low values of S_i/V the exposition is less important than for high values of S_i/V. After that, the curves are almost linear. There are however some irregularities (see curve Q_h = 55 kWh/m^2 concerning Canazei or curve Q_h = 25 kWh/m^2 concerning Trento or the first point of curve Q_h = 15.5 kWh/m^2 concerning Florence). These irregularities are caused by models which have very different surfaces exposed to east and west compared to other models. Indeed the exposition to east and to west influences the heating requirements but in a much smaller extent than the exposition to south.

In the graphs, the points corresponding to the models MOD 1, MOD 2, MOD 3 and MOD 4 are presented as well. Points corresponding to MOD 2 and to MOD 3 are very close (mostly overlapping). This is due to the fact that they have similar south exposure and shape coefficient, and so they have even very similar heating requirements (see even Fig. 5).

With equal values of the shape coefficient S_i/V heating requirements are lower if south façade has a wider area. Points linked to lower energy requirements correspond to lower average values of the “shape coefficient”.

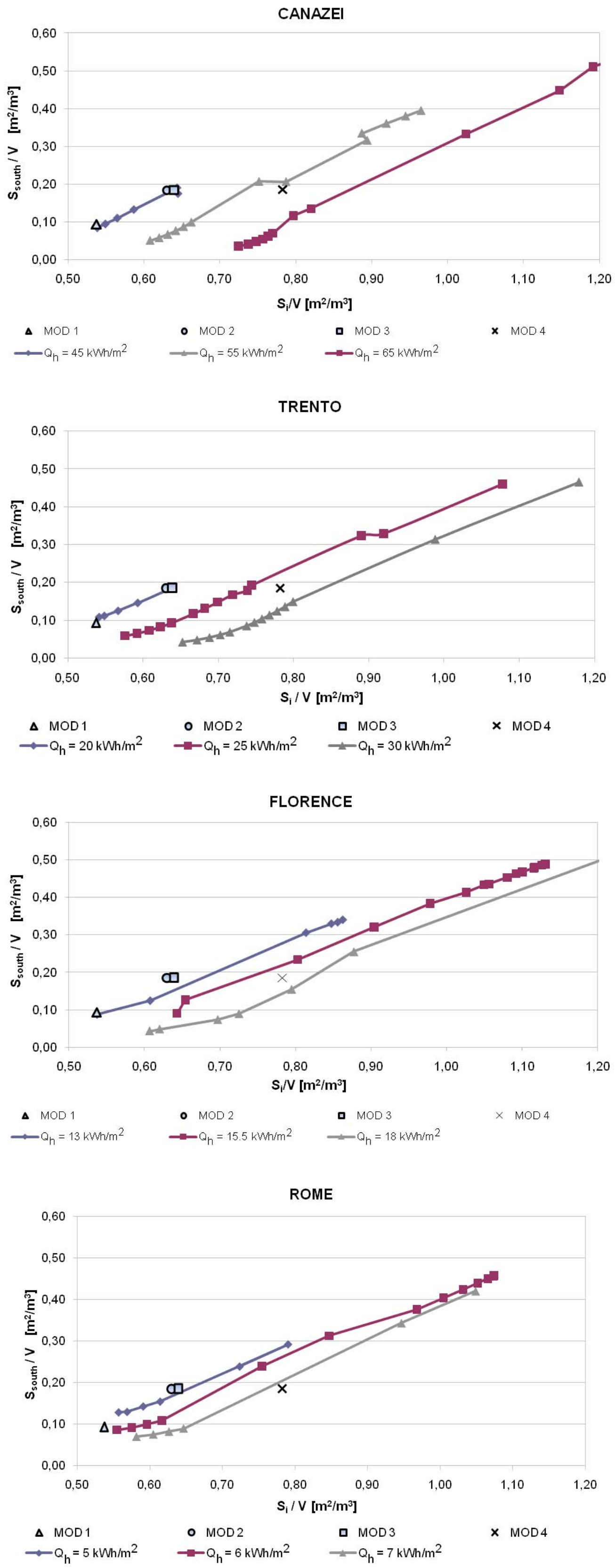


Fig. 6 Graphs (S_i/V ; S_{south}/V) with representation of points having the same heating requirement and of points relative to MOD 1, MOD 2, MOD 3, MOD 4

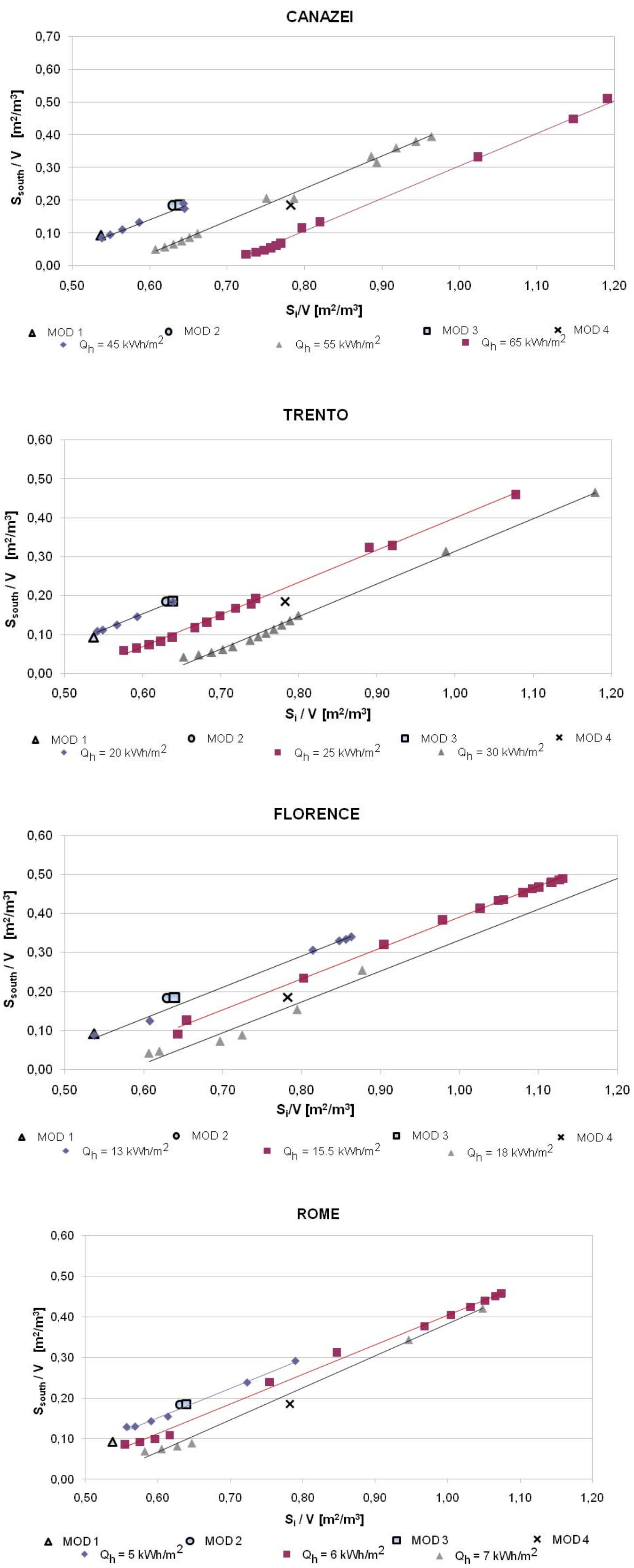


Fig. 7 Graphs (S_i/V ; S_{south}/V) with representation of points having the same heating requirement and of their straight lines of linear regression

The linear regression of each curve has been made. The deviations between the calculated points (S_i/V ; S_{south}/V) printed in **Fig. 7** and the relative straight lines of linear regression for every determined heating requirements are little. The slopes of the straight lines of linear regression for the 4 localities considered are reported in **Tab. 4**.

Tab. 4 Slopes of the straight lines of linear regression of the points (S_i/V ; S_{south}/V) depicted in **Fig. 6**

	CANAZEI	TRENTO	FLORENCE	ROME
	0.92 (Q_h=45kWh/m^2)	0.80 (Q_h=20kWh/m^2)	0.80 (Q_h=13kWh/m^2)	0.72 (Q_h=5kWh/m^2)
	0.99 (Q_h=55kWh/m^2)	0.83 (Q_h=25kWh/m^2)	0.74 (Q_h=15.5kWh/m^2)	0.73 (Q_h=6kWh/m^2)
	0.99 (Q_h=55kWh/m^2)	0.84 (Q_h=30kWh/m^2)	0.78 (Q_h=18kWh/m^2)	0.79 (Q_h=7kWh/m^2)
mean	0.97	0.82	0.77	0.75

We can observe that slopes value are higher in colder localities. This means that a greater increase in southerly exposure is needed to compensate for a given increase in the shape coefficient. The compactness is therefore more important in cold localities than in warm ones.

4 Conclusions

The present work focuses on energy requirements during winter season by means of a monthly calculation in according to standard EN ISO 13790:2008, a stationary calculation in which a gain utilization factor is introduced in order to consider the non-stationary effects of inertia. The results give indications about the importance of compactness and exposition to the sun in different Italian localities.

Compared to Depecker et al. (2001) it confirms than the compactness is more important in cold localities than in warm ones but, in addition, it formalizes the question concerning the solar exposition by means of the introduction of a new index S_{south}/V , i.e. south façade area/ volume.

Representation of points characterized by determined values of heating demand in a graph (S_i/V ; S_{south}/V) gives some interesting information. Moreover, spreadsheets based on a monthly method (like the one in standard EN ISO 13790:2008) give results with a good level of accuracy with low calculus time and easily to be used by designers.

A future research should analyze the relationship between buildings shape and energy requirements considering also summer conditions, in which results could be very different. Indeed, low compactness and low exposition to solar radiation are disadvantageous during winter season but could be advantageous during summer season (in particular, low compactness is an advantage during summer season if hourly external temperature is lower than inner temperature for a certain period so to allow heat dispersion). A calculation of energy requirements considering the whole year could be made by means of dynamic software (e.g. EnergyPlus or TRNSYS) also to take into account other environmental elements such as wind, orography and so on, influencing not only external shape but even the inner space distribution. Moreover, in this way human inner comfort conditions could be considered, not only energy aspects.

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