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15, avenue de Ségur,
75007 Paris, France.
Tel (Fr) 01 45 51 26 07 - (Int.) +33 1 45 51 26 07
Fax (Fr) 01 45 51 26 32- (Int.) +33 1 45 51 26 32
E-mail: ijdst@europia.org
http://www.europia.org/ijdst

Design strategies for sustainable residential buildings: a quantitative method for morphology optimization

Frida Bazzocchi[*], **Vincenzo Di Naso**[**], **Giuseppe Grazzini**[***] and **Aurora Valori**[****]
[*] University of Florence, Italy. E-mail: frida.bazzocchi@unifi.it
[**] University of Florence, Italy. E-mail: vincenzo.dinaso@unifi.it
[***] University of Florence, Italy. E-mail: giuseppe.grazzini@unifi.it
[****] University of Florence, Italy. E-mail: aurora.valori@dicea.unifi.it

The paper presents some results of a research on the definition of new sustainable residential building types. Starting from the identification of the contributing factors of definition of sustainable buildings, a simplified method for defining the optimal morphology that subsequently, allows us to explore the possibility of designing new building types, is in the phase of being validated. The method is based on a dimensional analysis that allows us to describe and simplify a complex physical system by reducing the number of variables by bringing them together in dimensionless numbers, obtaining a comparable parameter that allows the designer to identify the optimal design solution.

Keywords: sustainable building, green building, building morphology, residential building, energy saving

1 Introduction

Sustainability applied in the field of the construction industry has long been debated in the panorama of contemporary architecture, but in relation to this theme it remains as yet to be fully developed in certain fields of inquiry.

In particular, aspects concerning the overall architectural design of the building, also in relation to the definition of various types of buildings, and in particular in relation to residential buildings, remain to be examined because, at present, the current research is aimed primarily at identifying technological systems and techniques to optimise the energy behaviour.

This paper, aims at presenting the first results of a research relative to the definition of new residential building types, which began from the determination to simplify methods for defining the optimal morphology of these buildings, and that, subsequently, through the application of this instrument, intends to explore the possibility of the development of new building types that implement also the strategies and design criteria, partly consolidated, for to build the environmentally sustainable constructions.[1] [2]

It is the custom in the design of residential buildings to apply principles of sustainability especially in relation to building orientation and adoption of technology systems, building techniques and materials.

It appears evident that in most cases, these buildings present a substantially traditional morphology, that in some cases involves only the application of specific morphological and technological elements such as solar greenhouses, covered courtyards, ventilation stack, shading devices, oriented glass surfaces, etc contributing only to a partial change of the most common forms. Moreover, also the definition of the size of the body of the buildings, in the most usual morpholo-

[1] Although the present study is the result of a common reflection of the authors, the method, adopting dimensionless numbers, was developed by Aurora Valori under the supervision of Giuseppe Grazzini.

[2] This research is carried out, at the Department of Civil and Environmental Engineering, in collaboration with the Department of Energy Engineering "Sergio Stecco", University of Florence. The PhD thesis of Aurora Valori "Methods and techniques of design and construction for sustainable residential buildings" is supervised by Franco Nuti, Frida Bazzocchi, and Giuseppe Grazzini.

gies, currently follows the more traditional logics of design not being considered as closely related to the energy behaviour of the building.

In parallel also the types of buildings have remained almost unchanged, as well as the general organization of the inhabited part of the house and methodology of the joining of housing. Some changes are highlighted in relation: the characteristics of internal organization to homes, where the rooms are distributed taking into account to the main activities carried out inside, to the methods of the organization of the fronts and the empty/full relationship, in connection with the different orientation of the facades and functional to the control of heat gains due to solar radiation. This last point is based more on common sense than on design considerations to control energy efficiency.

Some of the reasons that affect the difficulty of change of building types in our country can refer to factors such as: market logic that requires low-cost housing and therefore the maximum benefit of building capacity; the strict limits imposed by the planning regulations and peculiarities of the urbanized areas; the growing technological development occurring in relation to the need to carry out building work to meet the demands of winter heating and summer cooling, using the minimum energy from exogenous non-renewable sources, connected more easily, for designers, to apply new technologies, especially targeting the envelope of the building, and work presenting a consolidated architectural concept. On the other hand, if work on the form, as a set of geometric and volumetric character of the building, and more generally of the type of building, contributes to improving the overall energy behaviour, less efficient techniques and materials, thereby contributing to a reduction in construction costs could be adopted. To this end, ongoing research, starting from the state of the art, is collecting the founding principles of the design and construction of sustainable buildings, has, to date:

- identified the elements that together define the orientation and the optimal form of sustainable buildings
- identified the types of residential buildings, and the buildings erected, which at present for their characteristics respond, in the optimal way, to meet the requirements of ecological design
- formulated a quantitative method, lied to local bioclimatic conditions, to determine the optimal orientation, the morphology and the optimal dimension of glazed areas to obtain the sustainable residential buildings
- developed an algorithm, in the development phase, which allows for to computerize the identified mathematical approach

This method can be an effective tool for evaluating the energy efficiency of a design model of planar/volume for a given context, also in relation to the definition of the opaque areas and of the glazed areas, allowing us to easily compare multiple ideation, and at the same time can result in a future useful tool to define and evaluate unusual shapes.

The method, of quantitative type, correlates the parameters, such as S/V, orientation, percentage of projection surface and the south facing windows, with the total energy consumption of the building by using an easy to use equation, thus avoiding the calculations according to the UNI-TS 11300-1 of the primary energy need. Thus, it is an indication of the maximum final energy behaviour of the building in a specific place.

To date, it has been decided not to consider the wind in the parameters used in the method that will be described, while recognizing the absolute importance of this element for the energy need of the building and for the determination of its morphology. This choice is due to the increased complexity that the inclusion of this factor would have brought to the algorithm in this first phase. A further implementation of the algorithm that takes into account the effects that the wind has on the definition of the shape of the building will be developed.

2 Methodology

The building morphology is one of the factors that can influence the thermal energy need for the winter heating and the summer air conditioning of a building. The design choices, made by the designer, have an important impact on the environmental pollution, the final consumption of energy and implicitly on the cost of building management. There is a strong correlation between the energy consumption of the building, climate and microclimate of the site of construction, building morphology, its distributive characteristics, the different plant systems and building technologies. These concepts are shown in a lot of national and international studies, such as:

- Olgyay studied the relationship between the optimal shape of the building in different areas and maximum use of solar radiation during cold periods and minimal exposure to it in the overheated periods.[3] He also studied the relationship between the size of the areas with different orientation and the effects on them due to the incidence of solar radiation
- Castelli et al. studied, using the parameter of efficiency of solar form, the relationship between the optimal orientation and the percentage of area of the building projection to the south[4]
- Fanchiotti et al studied the variations of the loss coefficient Cd to understand the relationship between the geometric characteristics and the heat loss through the building envelope[5]
- Balocco and Grazzini devised a method to evaluate the energy consumption of buildings through the use of dimensionless numbers[6]
- Albatici and Passerini studied, through the shape coefficient Cf, the introduction of south exposure coefficient Cfs and of east-west exposure coefficient Cfew, the relationship between the compactness of building, the orientation, the percentage of glazed area and the energy need[7]
- Grosso identified a methodology for finding the optimal configuration plan metric and volume of a group of buildings by analyzing the interaction between the microclimate, the building, the whole buildings complex and the win.[8]

The work presented here describes a quantitative method based on an algorithm that, through easily and uniquely identifiable data, such as climate and microclimate of the site, gives the designer prior useful information on the optimal geometry, morphology and orientation of the building so that it is sustainable.

The proposed method is based on an dimensional analysis. The main elements considered are the solar radiation and the total energy behaviour of the building. For simplification the behaviour related to wind energy actually was excluded. It was chosen to perform dimensional analysis since it allows us to describe and simplify the description of a physical system by reducing the number of vari-

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[3] **Olgyay V.** (1981). Progettare con il clima, Franco Muzio & C., Pavia

[4] **Castelli L.** ed (2008). Architettura sostenibile, UTET, Trofarello (TO)

[5] **Fanchiotti A.** et al (1988). Confronto delle prestazioni energetiche di tipologie edilizie, in Atti del 43° Congresso Nazionale ATI, 43° Congresso Nazionale ATI, Ancona pp.177-185

[6] **Balocco C.** & **Grazzini G.** (2000). Thermodynamic parameters for Energy sustainability in urban areas, Solar Energy, 69: 351-356

[7] **Albatici R.** & **Passerini F.** (2011). Bioclimatic design of buildings considering heating requirements in Italian climatic conditions. A simplified approach, Building and Environment, 46: 1624-1631

[8] **Grosso M.** (2008). Il raffrescamento passivo degli edifici in zone a clima temperato, Maggioli Editore, Santarcangelo di Romagna

ables of the system through dimensionless numbers. When phenomena are very complex this method is effective in that the dimensionless numbers allow us to describe the problem no matter what system of reference, its size and its scale. However, one should start by saying that the use of this method allows us, in an approximate way, to understand the physical phenomenon analyzed because it equally represents but does not replace the physical laws that govern it, even though the dimensionless numbers that allow us to define certain uniquely, albeit general, relationships among variables. A method which uses dimensionless numbers has been adopted as the desired objective is to obtain a comparable parameter giving the magnitude of the problem and allows the designer to identify, through the use of a limited number of initial parameters uniquely and easily measurable, the optimal design solution.

The primary energy consumption is one of the basic parameters for the determination of sustainability in construction and for this reason the method aims to correlate, using a mathematical equation, the primary energy consumption with the geometric parameters and the building orientation which affect this value:

- the S/V ratio which allows us to determine the compactness of the building
- the glazed area Sv which affects the amount of the free solar gains and the thermal dispersions
- the opaque area Sop which affects the thermal dispersions
- the β angle of inclination to the horizontal area
- the γ angle azimuth than in the south, identifies the orientation of the building.

After the identification of the geometric parameters and orientation that affect the morphology of the building the method for defining the dimensionless parameters among those found in present literature was identified. The tool chosen is the Buckingham theorem also called π theorem.[9] The analysis of the physical system and the identification of physical parameters related to the shape and orientation of the building allowed for a choice of the variables that describe the behaviour. These have generated a series of dimensionless numbers determined according to the diagram shown in Figure 1.

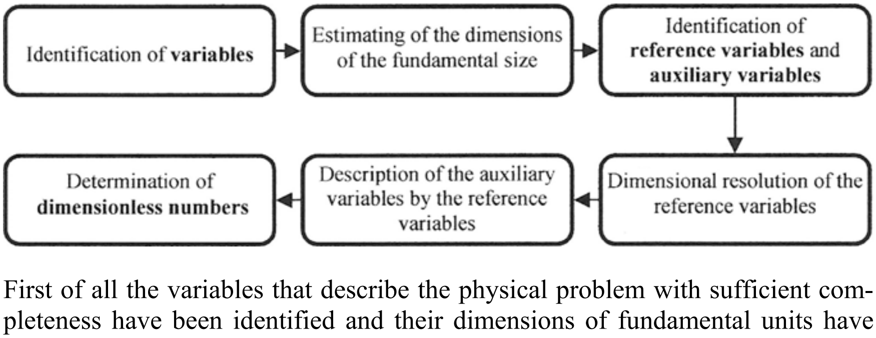

Figure 1 Synthesis of the steps to be carried out to determine the dimensionless numbers

First of all the variables that describe the physical problem with sufficient completeness have been identified and their dimensions of fundamental units have been estimated. Then the reference variables and the auxiliary variables have been defined: the first is the fundamental quantities whose fundamental units of measure are primary quantities while the second is secondary variables that will be expressed in terms of the reference variables because the fundamental dimensions are derived quantities or are equals to those of reference. The reference variables for the calculation of transmission losses and heat input are: the opaque

[9] **Barenblatt G.I.** (1987). Dimensional Ana-lysis, Gordon and Breach Science Publishers

area Sop [m2], the glazed area Sv [m2], the transmittance of the opaque area Uop [W/m2K], the transmittance of the glazed area Uv [W/m2K], the azimuth γ [°], the angle β of inclination to the horizontal area [°], the sol-air temperature Tsa [K], the internal set-point temperature Ti [K], the primary energy need for heating and cooling Q [J], the time τ [s], the solar irradiance I [W/m2], the volume flow V*r [m3/s], the volume capacity ρa*ca [J/m3K]. After these steps, π theorem, has been applied: the dimensional resolution of the reference variable was made, the auxiliary variables by the reference variables have been described and the dimensionless numbers were determined. We obtained the following dimensionless numbers:

$$N_{1t} = \frac{S_{op} \cdot I \cdot \tau}{Q} \quad N_{2t} = \frac{S_{op}}{S_v} \quad N_{3t} = \frac{I}{U_{op} T_i} \quad N_{4t} = \frac{U_{op}}{U_v} \quad N_{5t} = \frac{\gamma}{\beta}$$

$$N_{6t} = \frac{T_i}{T_{sa}} \quad N_{7t} = \frac{S_{op}^{3/2}}{V \cdot r \cdot \tau} \quad N_{8t} = \frac{I \cdot \tau}{S_{op}^{1/2} \cdot T_i \cdot \rho_a c_a} \tag{1}$$

Which are related by means of the following approximate relationship

$$N_{1t} = a_{1t} \cdot N_{2t}^{a_{2t}} \cdot N_{3t}^{a_{3t}} \cdot N_{4t}^{a_{4t}} \cdot N_{5t}^{a_{5t}} \cdot N_{6t}^{a_{6t}} \cdot N_{7t}^{a_{7t}} \cdot N_{8t}^{a_{8t}} \tag{2}$$

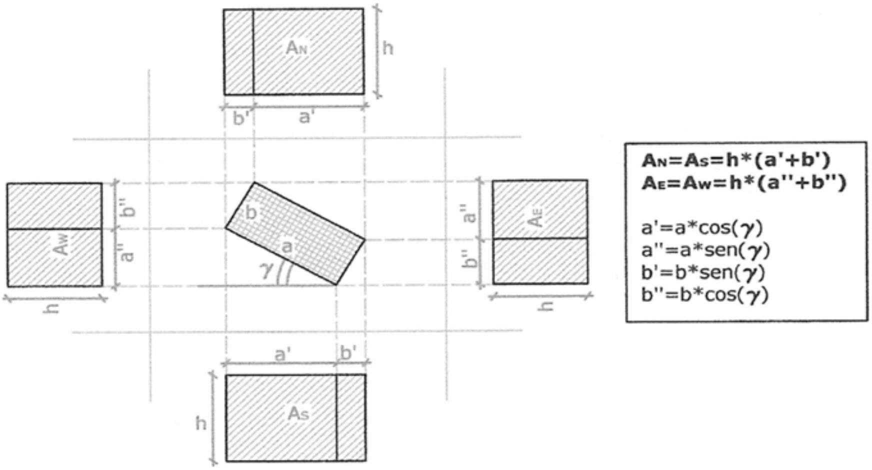

Figure 2 Identification of projection areas according to the four compass points

Once are determined the correlation coefficients of equation (2) it is possible to calculate the value of N1t and estimate the geometric configuration and the orientation of the building to reduce the energy need.

Since this method is shown to have a large number of dimensionless parameters it was at present to make the following simplifications in order to obtain a smaller number:

- the values of the transmittance of the opaque and glazed area have been considered constants and have been used, in implicit way, for the Q calculation
- the values of set-point temperature, of volume capacity and of volume flow in the calculation of the energy need for heating and cooling have been considered in an implicit way

– the sol-air temperature in the computation has been not considered

– the areas used in the calculation of solar heat input are the projection of the lateral area of the building according to the four compass points (Figure 2)

The variables considered by applying the simplification are: the demand for primary energy need for heating and cooling Q [J], the solar irradiance in the south I [W/m2], the total area of the building S [m2], the total volume of the building V [m3], the total area projection to the south A [m2], the glazed area projection to the south Av [m2], the time τ [s].

The choice to determine the dimensionless numbers through explicit variables related to the south comes from the fact that this approach in most cases, in the northern hemisphere, it appears to be the best both for the winter and summer: in fact, a area facing south receives more solar gains in winter and lower summer overheating.

Using the π theorem were determined following four dimensionless numbers:

$$N_{1s} = \frac{A \cdot R}{Q} \quad N_2 = \frac{A}{S} \quad N_3 = \frac{S}{V}\sqrt{S} \quad N_4 = \frac{A_v}{A} \tag{3}$$

Where R = ΣIτ or rather the sum of monthly average solar radiation according to the south, N1S represents the percentage the incidence of solar energy on the south area of the total energy consumption of the building, N2 represents the percentage of the area projection to the south regarding the total, N3 provides useful information concerning the compactness of the building (greater values of N3 correspond to less compact buildings) and N4 represents the percentage of glazed area projection to the south. Considering N1S as the ratio between solar gains and the energy need, we decided to change the formulation of N1S to determine two equations that describe, firstly the winter behaviour of the building and secondly the behaviour of the building in the summer. The two new dimensionless numbers N1i and N1e are derived as the ratio between heat gains and the primary energy need for heating or cooling.

$$N_{1i} = \frac{Q_{gn,inv}}{Q_{tot,inv}} \quad N_{1e} = \frac{Q_{gn,est}}{Q_{tot,est}} \tag{4}$$

The dimensionless numbers (3) and (4) are correlated with the following approximate equations:

$$N_{1i} = a_{1i} \cdot N_2^{\,a_{2i}} \cdot N_3^{\,a_{3i}} \cdot N_4^{\,a_{4i}} \tag{5}$$

$$N_{1e} = a_{1e} \cdot N_2^{\,a_{2e}} \cdot N_3^{\,a_{3e}} \cdot N_4^{\,a_{4e}} \tag{6}$$

where a1i, a2i, a3i, a4i are the winter correlation coefficients and a1e, a2e, a3e, a4e are the summer correlation coefficients.

The transition from the equation (2) to the equations (5) and (6) allows us to simplify the methodology. However the transition from the eight to the four dimensionless parameters can lead to the loss of information. In fact, neglecting this parameters from the procedure, specific phenomena linked to the excluded elements can not be evaluated. However we believe that these simplifications allow us to make the general reasoning on the energy behaviour of the building in relationship to its morphology.

The optimal geometry and orientation of the building will be those for which N1i is maximum and maximum N1e. When N1i is maximum then the primary energy demand for heating is minimal and the solar heat gains and internal cover part of the heat loss due to transmission and ventilation or the heat dispersions are minimum. For this reason, acceptable values of N1i are positive values less than 1. Instead, when N1e is maximum, the energy need for cooling is minimum and improves the energy behaviour of the building because the thermal gains are minimum or the thermal dispersions for transmission and/or ventilation are augmented.

Subsequently it was decided to combine N1i and N1e to obtain an equation that simultaneously consider the behaviour of the building in winter and summer. Combining (5) and (6), the relationship is obtained, thus:

$$N_1 = N_{1i} \cdot N_{1e} = \left(a_{1i} \cdot a_{1e}\right) \cdot N_2^{\left(a_{2i}+a_{2e}\right)} \cdot N_3^{\left(a_{3i}+a_{3e}\right)} \cdot N_4^{\left(a_{4i}+a_{4e}\right)} \qquad (7)$$

Analyzing the expression of (7) it can be understood that for a very high value of N1 will have a better energy behaviour and therefore geometry and an optimal orientation of the building.

The use of this apparently more complex methodology to determine the correlation coefficients, allow us to compare few design solutions and to individuate the optimal geometry and orientation for a sustainable buildings on chosen site.

3 Modelling phase

The first application of the method was carried out on a rectangular plan model of the building for the climatic data of Bolzano, Florence and Messina, because of their geographic positions and heating periods are different (Table 1).[10] Varying the three dimensions of the building, the orientation and the percentage of the glazed area of the building envelope, the same statistical universe of cases for each of them was generated, using Matlab and Excel.

Table 1 Data of referenced cities

	Altitude (m)	Latitude	Longitude	Heating period from	to
Messina	3	38° 11’	15°32’	01/12	31/03
Florence	40	43° 41’	11° 15’	01/11	15/04
Bolzano	262	46° 29’	11° 21’	15/10	15/04

The statistical universe of cases using the following hypothesis was generated:

- the energy behaviour of the building has been evaluated by the calculation of primary energy need for heating and cooling of the building as reported in the UNI EN ISO 13790 and UNI TS 11300-1
- the calculation of solar heat input has been evaluated only according to the four directions of the compass points
- the areas used in the calculation of solar heat input are the projection of the lateral area of the building according to the four compass points. In this way it implicitly takes into account the azimuth of the areas
- the primary energy need for heating and cooling with quasi-steady-state method has been calculated
- the average monthly climatic data such us to define in UNI 10349 have been used

[10] **Bazzocchi F.** et al (2011). A method for shape optimization in sustainable residential buildings, in Atti del convegno internazionale EuropIA13, Roma 8-10 Giugno 2011, pp. 203-215

- the values of the transmittance of the opaque components and windows were considered equal to the minimum required by the regulations law D.lgs.311/2006 as regards the year 2010
- the set-point of the internal temperatures have been estimated to be the same as the numbers listed in UNI TS 11300-1
- the stairway in the heated volume has been considered
- the four fronts have the same windowed areas percentage
- the external walls of the building have been chosen to be medium weight
- absence of thermal bridges
- absence of shading devices on walls with windows
- absence of shadows on the building from surrounding buildings and/or tall trees

The correlation coefficients of the equations (5) and (6) have been determined by the least squares optimization on the generated statistical universe of cases. In calculating N1i and N1e the negative values of Qtot,inv and of Qtot,est have been discarded. Once calculated the coefficients a1i, a2i, a3i, a4i, a1e, a2e, a3e, a4e (Table 2) it has been possible to explain the (5), the (6) and (7) through them and check the progress of these equations to range of N2, N3 , N4 with graphics.

Table 2 Values of the correlation coefficients determined by the first application of the method to the cities of Messina, Florence and Bolzano

	a_{1i}	a_{2i}	a_{3i}	a_{4i}	a_{1e}	a_{2e}	a_{3e}	a_{4e}
Messina	10.211	0.266	-0.138	0.842	2.164	-0.033	-0.289	-0.317
Florence	3.926	0.272	-0.083	0.782	1.826	-0.067	-0.248	-0.417
Bolzano	3.345	0.280	-0.071	0.789	1.214	-0.239	-0.266	-1.121

Have been made, the diagrams that show the evolution of the three equations N1i, N1e, N1, in terms of N2, N3, N4 to the climatic data of Messina, Florence and Bolzano. From Figure 3 to 11 are shown, for example, through a three dimensional graph, the trend of N1i, N1e, N1 to N4=0.15 and N4=0.30 for all cities examined.

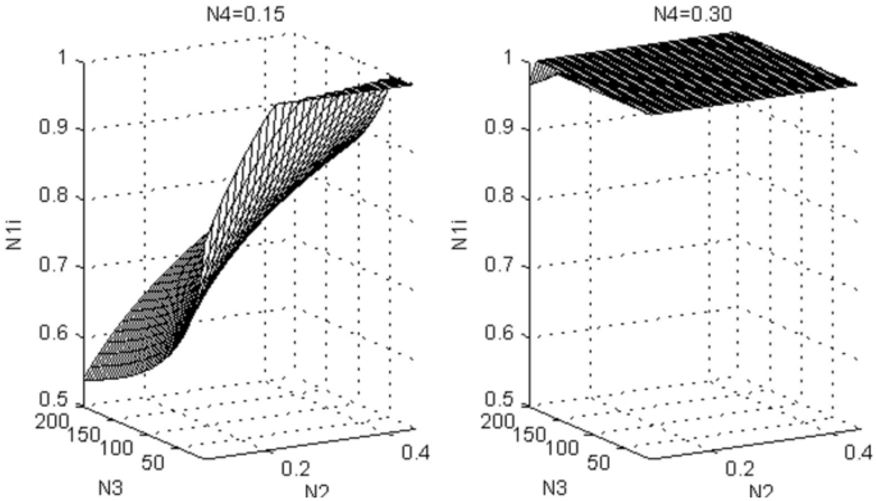

Figure 3 Comparison N_{1i} to N_4=0.15 and N_4=0.30 for the city of Messina

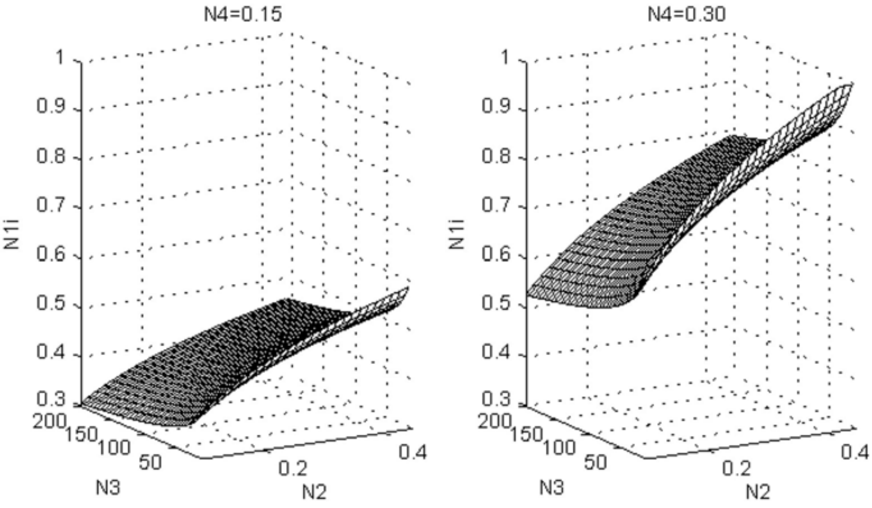
N4=0.15
N4=0.30

Figure 4 Comparison N_{1i} to N_4=0.15 and N_4=0.30 for the city of Florence

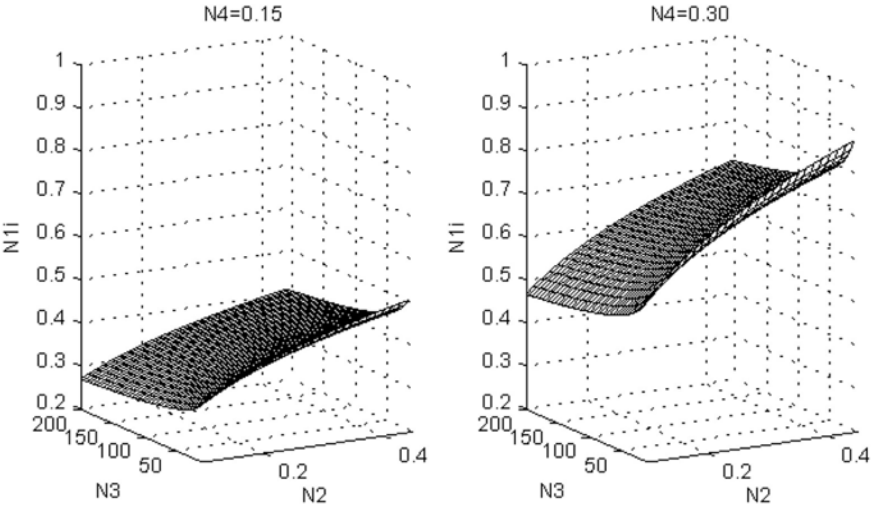
N4=0.15
N4=0.30

Figure 5 Comparison N_{1i} to N_4=0.15 and N_4=0.30 for the city of Bolzano

Figures 3, 4 and 5 show how an increase of the percentage of south glazed area, that is N4 parameter, from 15% to 30%, determines greater values of N1i and therefore the winter energy behaviour improves while maintaining the same variation of the ranges of N2, in relation to the percentage of area projected to the south, and N3, relative to building compactness. The diagrams of the cities of Florence and Bolzano show how a decrease of the percentage of south area (least N2) or a decrease of the compactness (greater N3), determine a worsening of winter energy behaviour (least N1i). Moreover, it can notice how the surfaces, for N4=0.30, have a greater slope compared to those for N4=0.15. Therefore, from this it follows that the variations of the compactness and the area projection to the south have more importance, increasing the percentage of glazed area projection to the south. The greater difference noted between the diagrams in Figure 4 (for Florence) and those in Figure 5 (for Bolzano) is in the surface slope: in the first case the surfaces have a greater inclination and for this reasons, for the city of Florence, small variations of the area projection to the south and/or of the compactness determine greater changes in the winter energy behaviour if compared to the city of Bolzano. Instead, Figure 3 shows the trend of N1i for the city of Messina: when N4=0.15 the surface has a steep inclination, therefore, in this case, both the compactness and the percentage of area projection to the south have much influence in determining the winter energy behaviour in that, at small variations of N2 and N3, greater variations of N1i result; moreover, analyzing the two diagrams, it can be noted how a small variation of the south glazed area increases the numbers of cases in which it is possible to turn off the heating plant because the primary energy need is balanced by solar and internal gains (N1i=1).

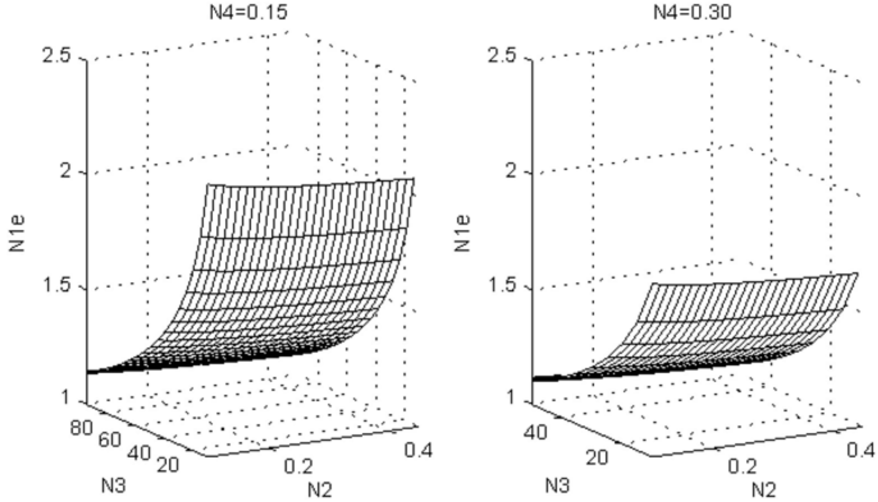

Figure 6 Comparison N_{1e} to N_4=0.15 and N_4=0.30 for the city of Messina

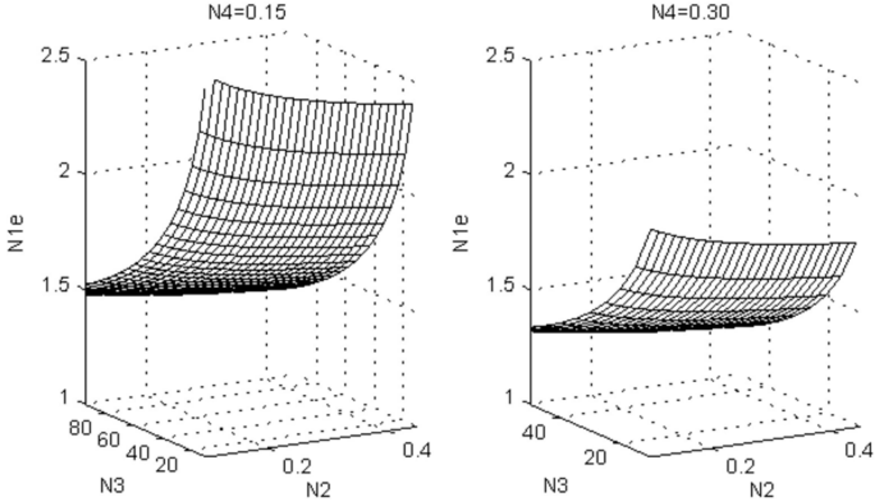

Figure 7 Comparison N_{1e} to N_4=0.15 and N_4=0.30 for the city of Florence

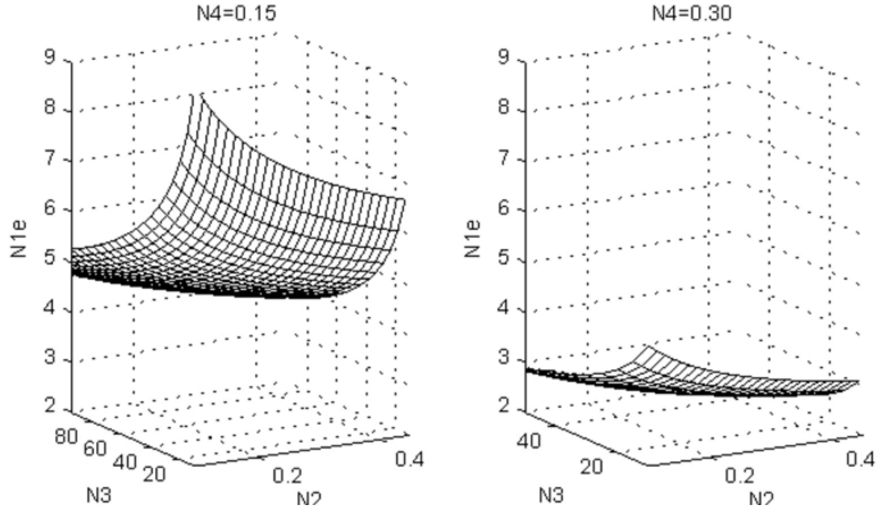

Figure 8 Comparison N_{1e} to N_4=0.15 and N_4=0.30 for the city of Bolzano

Figures 6, 7 and 8, show how an increase of the percentage of glazed area projection to the south (from N4=0.15 to N4=0.30), determines lower values of N1e and therefore a worsening of the summer energy behaviour of the building for all cities examined. The diagrams, also, show how increasing the percentage of area projection to the south (greater N2) or decreasing the compactness (greater N3), for constant values of south glazed area, a worsening of winter energy behaviour is determined (least N1i). Moreover, it can be noticed how the surfaces, for N4=0.30 for all cities, have a lower slope compared to those for N4=0.15. Therefore, it follows that the variations of the compactness and the area projection to the south have less importance, when increasing the percentage of south glazed area.

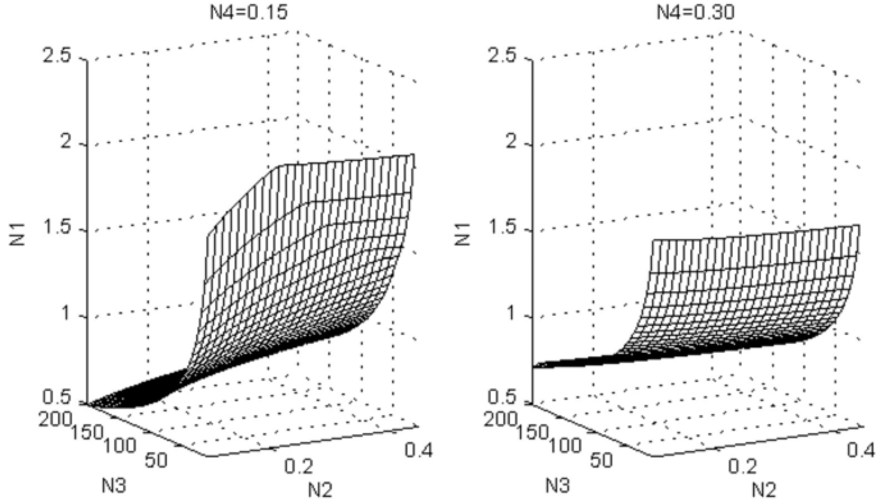

Figure 9 Comparison N_1 to N_4=0.15 and N_4=0.30 for the city of Messina

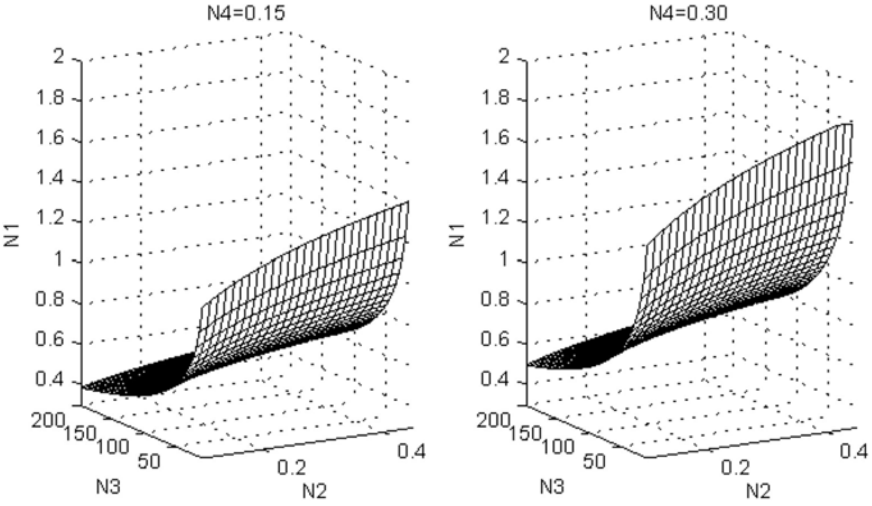

Figure 10 Comparison N_1 to N_4=0.15 and N_4=0.30 for the city of Florence

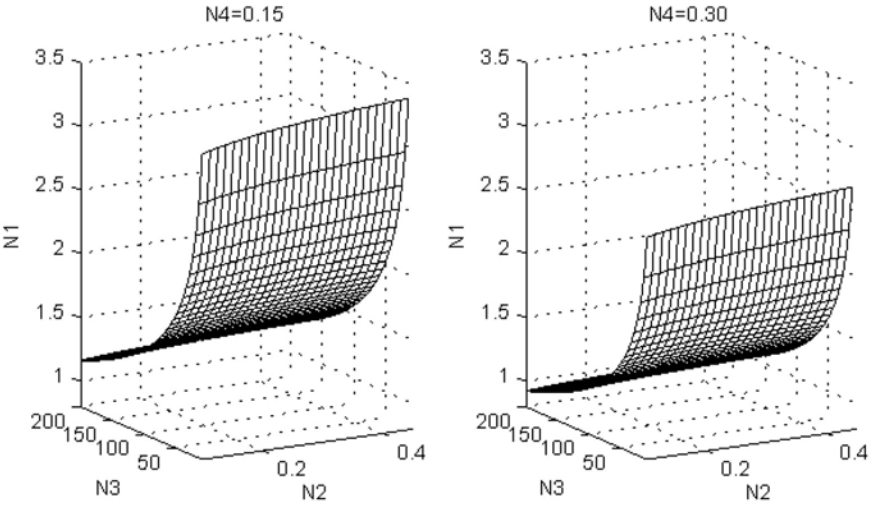

Figure 11 Comparison N_1 to N_4=0.15 and N_4=0.30 for the city of Bolzano

Table 3 Individuation of the actions of design to carried out to obtain the best energy behaviour for the cities of Messina, Florence, Bolzano

	Best energy behaviour	Compactness (N3)	Area projection to the south (N2)	Glazed area projection to the south (N4)
MESSINA N1i<1	Winter (N1i)	greater	greater	greater
	Summer (N1e)	greater	least	least
	Annual (N1)	greater	greater	least
MESSINA N1i=1	Winter (N1i)	greater	greater	greater
	Summer (N1e)	greater	least	least
	Annual (N1)	greater	least	least
FLORENCE	Winter (N1i)	greater	greater	greater
	Summer (N1e)	greater	least	least
	Annual (N1)	greater	greater	greater
BOLZANO	Winter (N1i)	greater	greater	greater
	Summer (N1e)	greater	least	least
	Annual (N1)	greater	greater	least

The diagrams from Figure 9 to 11, show how an increase of the percentage of glazed area projection to the south from value 15% to 30% (N4=0.15 and N4=0.30), determines a worsening in the total energy behaviour of the building for the cities of Messina and Bolzano (least N1) and an improvement for the city of Florence (greater N1). The diagrams show how, with an equal amount of glazed area projection to the south, for all three examined cities, with the exception of Messina (N4=0.30), a better total energy behaviour is obtained by increasing the area projection to the south (greater N2) and/or the compactness (least N3). Instead, in the case of Messina with N4=0.30, by increasing the compactness (least N3) and/or reducing the area projection to the south (least N2), an increase of the value of N1 is obtained.

To summarize, by analysis it emerges that (Table 3):

- Winter energy behaviour (N1i): the parameter which has greater effect is N4 relative to glazed area projection to the south because by increasing its value the energy behaviour significantly improves (greater N1i). In fact, the percentage of glazed area has a great effect on the winter energy behaviour because it is the element that determines the amount of free solar gains and the thermal dispersions. Therefore, for all three cities, by increasing the compactness (least N3) and/or increasing the area projection to the south (N2) and/or increasing the glazed area projection to the south of the building (N4), the best winter energy behaviour is obtained.
- Summer energy behaviour (N1e): the percentage of glazed area projection to the south (N4) is the parameter that has greater effect on the summer energy behaviour in that by increasing its value, the solar gains, the danger of overheating of the interior and the demand for the cooling of the rooms increase. Increasing the compactness (least N3) and/or reducing the area projection to the south (N2) and/or reducing the south glazed area (N4), for all examined cases, the best summer energy behaviour is obtained. In fact this allows us to reduce the solar gains through the windowed areas and to reduce the heat absorption due to solar radiation by external walls.
- Annual energy behaviour or total energy behaviour (N1): N4 is the parameter that has the greatest effect. An increase of glazed area projection to the south, for the cities of Bolzano and Messina determine worse annual energy behaviour of the building, while, for the city of Florence, it determines an improvement. In Bolzano the annual energy behaviour worsens because totally the benefits obtained by means of the winter solar gains are less than summer solar gains that produce the overheating of interior because, in the proposed model, the shading devices are absent. The energy behaviour in Messina worsens because the increase of glazed area determines the interior overheating in the summer season. Finally in Florence, where the winters are less severe than in Bolzano and the summers are less torrid than in Messina, the annual energy behaviour of the building improves. Therefore, in these studied cases, the best annual energy behaviour is obtained, for Bolzano and in the case of Messina (N1i<1), by increasing the compactness (least N3) and/or increasing the area projection to the south (greater N2) and/or reducing the glazed area projection to the south (least N4). In the case of the city of Messina with N1i=1, the annual energy behaviour coincides with the summer behaviour and then what has

been stated for the latter applies. Finally, for the city of Florence, by increasing the compactness (least N3) and/or increasing the area projection to the south (greater N2) and/or increasing the glazed area projection to the south (greater N4) the best annual energy behaviour is obtained.

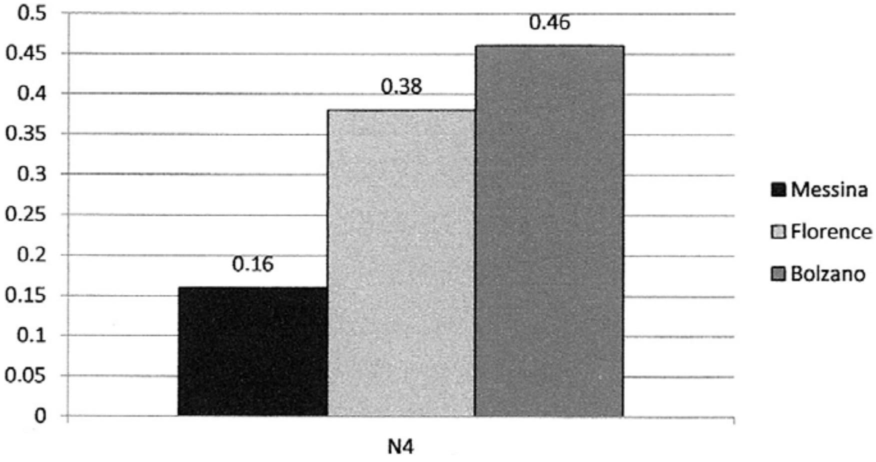

Figure 12 Maximum value of N4 for which N1i<1 for the cities of Messina, Florence and Bolzano

Table 4 The incidence percentage of parameters N4, N2, N3 on N1i, N1e, N1 for the base case examined

	N2		N3		N4		N1i			N1e			N1		
	Min.	Max.	Min.	Max.	Min.	Max.	N4	N2	N3	N4	N2	N3	N4	N2	N3
Messina	0.09	0.26	13	22	0.10	0.16	63.4%	33.9%	2.8%	50.8%	2.5%	46.6%	34.0%	33.4%	32.5%
Florence	0.09	0.26	13	22	0.10	0.38	96.3%	3.5%	0.2%	92.1%	1.9%	6.0%	80.9%	11.0%	8.1%
Bolzano	0.09	0.26	13	22	0.10	0.46	97.6%	2.4%	0.0%	94.4%	4.5%	1.1%	86.4%	0.8%	12.8%

4 Sensitivity analysis

The analysis of the diagrams of N1i, N1e, N1 showed how these parameters are strongly affected by the change of the three dimensionless parameters N2, N3, N4; moreover, the way in which the influence of these parameters changes in relation to the climatic characteristics of the city where the method has been applied, has been shown.

Therefore the results were controlled through the sensitivity analysis of the method. This study allows us to understand how the mathematical model behaves changing the values of the input variables by evaluation of the relative weight of the single parameter on the final output values. The analysis, as example, on a base configuration comparing, only for the dimensional characteristics, to a tenement block of dimensions b=25 m, p=10 m, h=14 m, V=3500 m2, compactness S/V=0.423 1/m and values of dimensionless parameters N2=0.236 that corresponds to a orientation $\gamma=0°$ to the south, N3=16.628, N4=0.15 defined by the analysis of ratio between glazed areas and opaque areas of existing traditional tenement blocks, has been carried out. After N2, N3 and N4 have been changed. The range of variation of N2 is between 0.09 and 0.26 in order to consider a change of building orientation $0°<\gamma<90°$ and the variations of the dimensions of the area projection to the south. The range of variation of N3 is between 13 and 22 that correspond to a variation of the compactness of the building $0.35<S/V<0.51$ (1/m): the value 0.35 corresponds, only for compactness, to the squat tower block and 0.51 to the row house. The corresponding range of N4 is between 0.10 and a maximum value for which N1i<1 because in this way only the period with running heating plant is evaluated (Figure 12). Table 4 and in Figure 13 show the results of the sensitivity analysis.

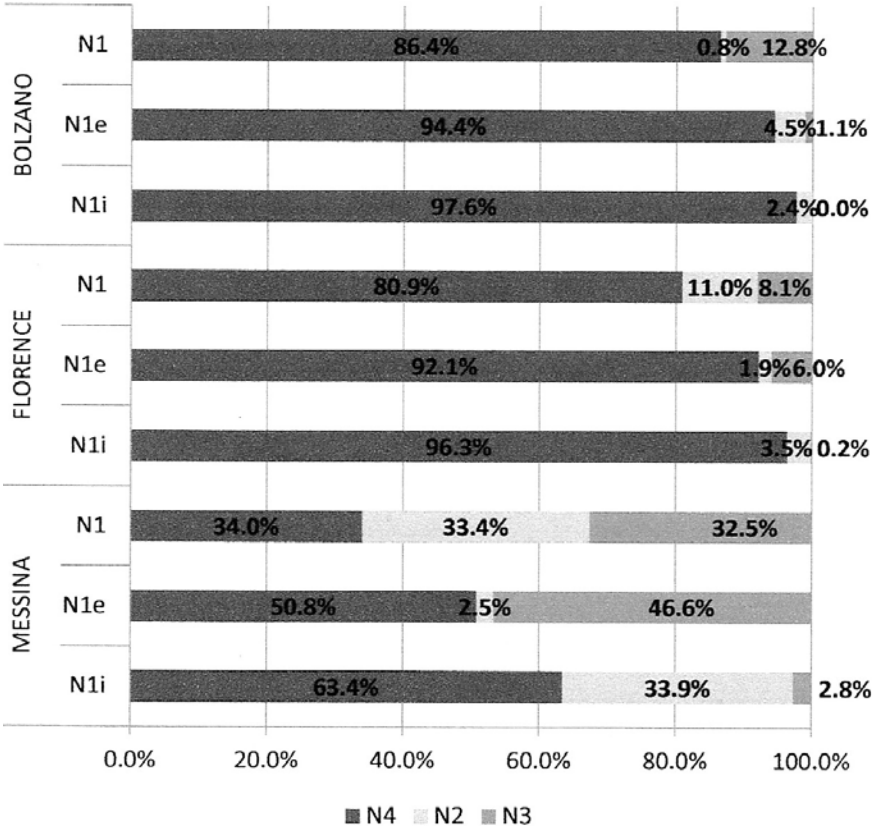

Figure 13 Diagram of the incidence percentage of parameters N4, N2, N3 on N1i, N1e, N1 for the base case examined

Table 5 Geometric parameters of the four models used

Model	b*(m)*	p*(m)*	h*(m)*	floors	V(m^3)	S/V *(1/m)*
A. Tenement block	25	10	14	4	3500	0.423
B. Deck access	36	7	14	4	3528	0.484
C. Row house	42	12	7	2	3528	0.500
D. Squat tower block	16	16	14	4	3584	0.393

In particular the following has emerged:

- the percentage of glazed area projection to the south is the element that affect significantly the value in output of N1i, N1e, N1: the influence of N4 is lower in the cities with less severe winters and shorter heating periods because the overall dispersions through the glazed area are lower
- the variation of the orientation and the compactness of the building are completely irrelevant compared to the dimensional variation of the glazed area projection to the south for the city of Bolzano
- for all cities the N2 parameter has greater influence than N3 in the computation of N1i: an appropriate value of area projection to the south compared to compactness has a greater effect on the winter energy behaviour of the building

- the variation of the area projection to the south has less importance in comparison with to the compactness of the building when considering N1e for Messina and Florence
- the variation of the orientation, of the percentage of glazed area and of the building compactness affect, in the same way, the total energy behaviour of the building in Messina because none of these three parameters has a very determining role on the annual energy behaviour of the building

Therefore the sensitivity analysis though limited to this specific case allows us to confirm what was expected during the construction of the method and modelling phase.

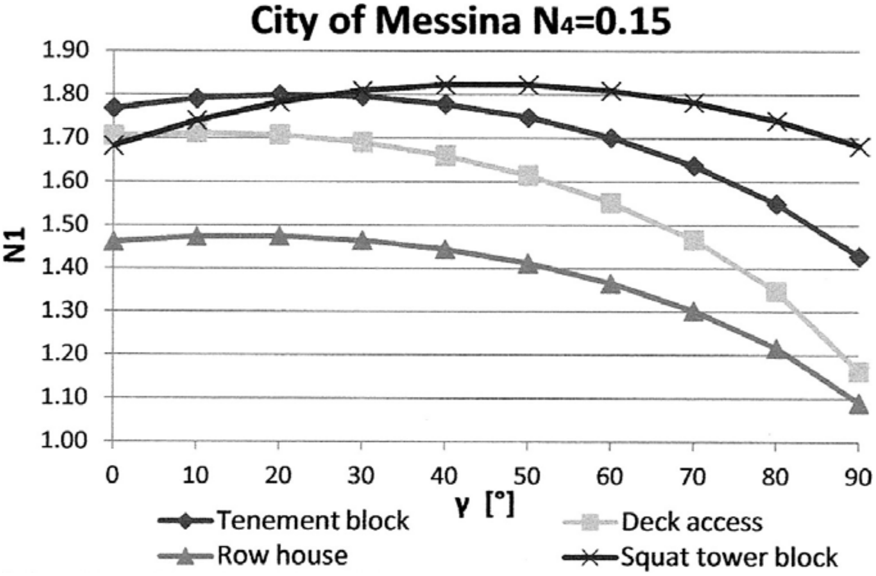

Figure 14 Values of N1 related to orientation for N4=0.15 (City of Messina)

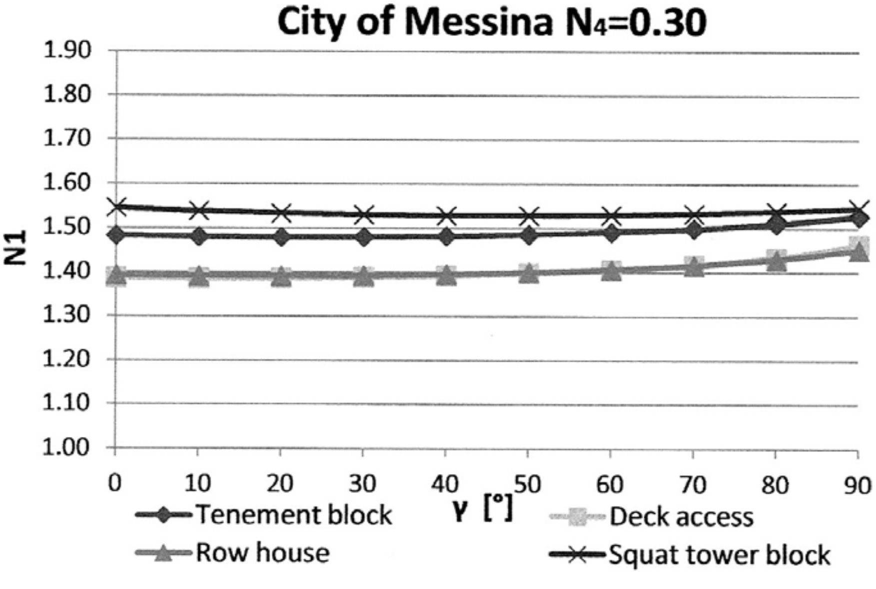

Figure 15 Values of N1 related to orientation for N4=0.30 (City of Messina)

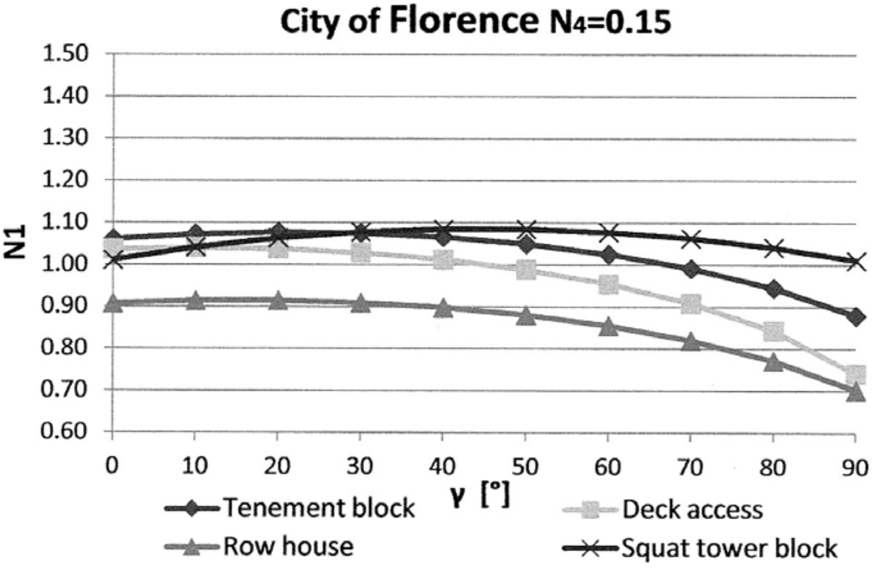

Figure 16 Values of N1 related to orientation for N4=0.15 (City of Florence)

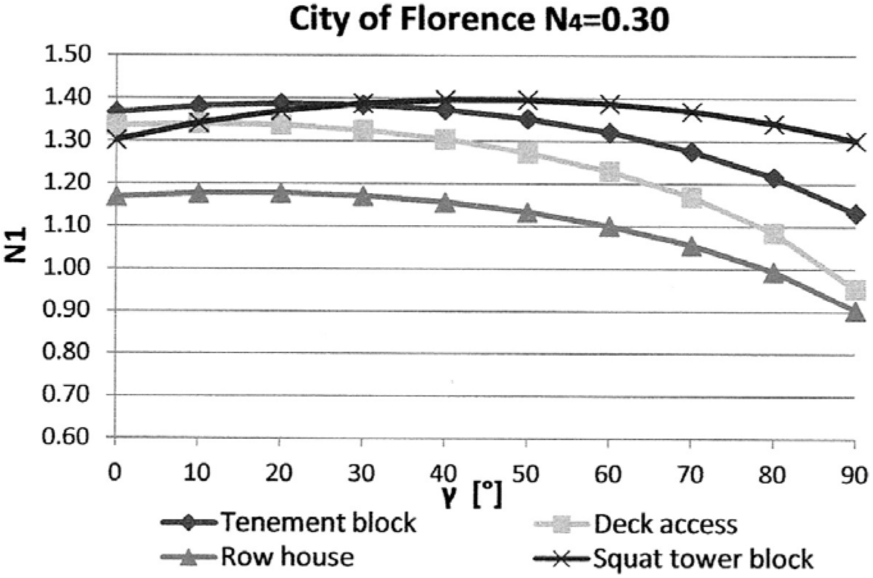

Figure 17 Values of N1 related to orientation for N4=0.30 (City of Florence)

5 Application of the method

The method is applied, for the chosen sites, to four models of buildings with similar volume (Table 5). The four models refer, only for size and shape, for traditional building types, respectively to tenement block, to deck access, to row house and squat tower block. Therefore, these models have different three-dimensional configurations.

For every model N1i, N1e, N1 have been calculated, changing the percentage of the glazed area projection to the south and also the plan orientation. N1i=1 has also been used for values N1i>1. From Figure 13 to 18 the results of applying the method related to calculation of N1, assuming N4=0.15 and N4=0.30, for the cities of Messina, Florence and Bolzano are shown.

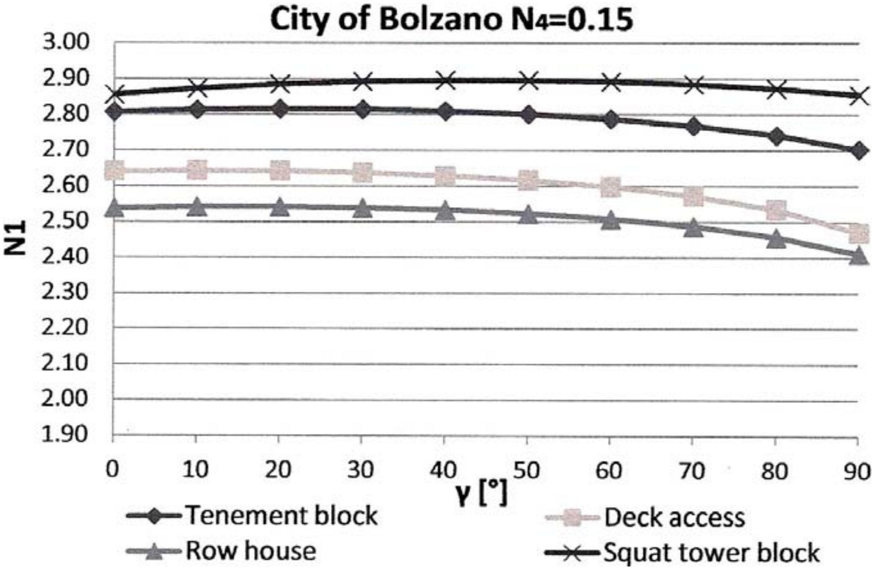

Figure 18 Values of N1 related to orientation for N4=0.15 (City of Bolzano)

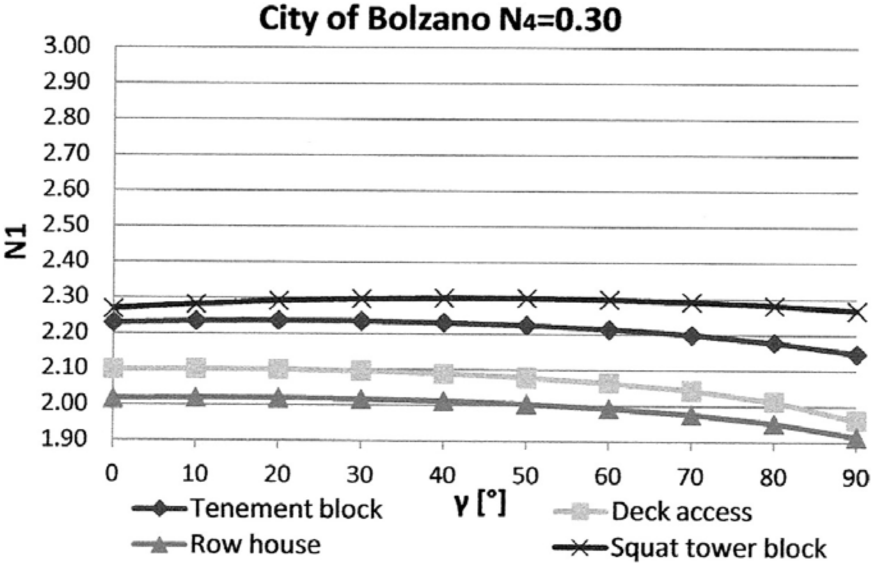

Figure 19 Values of N1 related to orientation for N4=0.30 (City of Bolzano)

From the analysis of the diagrams drawn as a result of this first application, it emerges that:

- the building with the greater compactness (least N3), in particular the building comparable in morphology to the tenement block, has the best energy behaviour (greater N1) among the buildings which are rectangular in plan
- for buildings rectangular in plan the optimal orientation is about 20°

- buildings of a square plan have better energy behaviour for Bolzano and for α> 30° for the cities of Messina and Florence because the glazed area projection to the south increases considerably; in this case, with all sides windowed, the buildings have a more uniform behaviour
- in Florence by increasing the percentage of glazed area projection to the south, for all the buildings, the energy behaviour improves. Instead, in Bolzano and Messina the energy behaviour worsens

Using this methodology allows the designer to have some useful information on the compactness, orientation, and the percentage of glazed area to be used so that the building has optimal energy behaviour and that means is energetically sustainable. From these first considerations become clearly necessary to define new types of buildings or in part attributable to traditional types. In fact, for instance, it is clear that the best morphology is that similar to tenement block or to squat tower block. These typologies of buildings, however, for organization and aggregation of flats, certainly do not appear to be the most efficient.

6 Conclusions

The analyses carried out have allowed for the definition of the limitations, the potentials and the ambit of the methodology presented in this paper. The method defines in quantitative way the energy quality of the building by means of a mathematical algorithm and is a flexible instrument capable of adapting to the climatic characteristics of the site of the intervention being the correlation coefficients obtained using the national reference standards for the calculation of energy need. The climatic data of the site, the values of the transmittance of the building envelope relative to the climatic zone of reference and to the duration of heating period of the country are used. The method, therefore, has general validity because, by varying these elements, it can be applied everywhere. These characteristics could be used to create a computer program with a simplified interface which the designer could use to define the morphological characteristics of the sustainable residential building in its preliminary phase and to compare a number of design solutions. This software could also be used at an academic level as an instrument for the learning of design strategies to be applied to the construction of sustainable buildings. In this regard future developments could be the implementation of the algorithm by means of the other plan configurations (buildings at L, C, at court, etc.) and the inclusion of parameters relative to shadows and shading due to the surrounding environment.

The method does not have a direct impact on the development of new technologies, but can be a valid tool to use in parallel with advanced building technologies for the construction of more energy efficient and sustainable buildings: therefore the disciplines that can benefit from the use of this methodology are those connected to the sustainable design and the energy assessment of the buildings.

The greater criticality is that linked of the UNI TS 11300-1 use: in effect this national standard contains_inadequacies related to the calculation of the energy need because it is based on the conventional criteria, it evaluates the thermal energy need in stationary condition by assuming this to be constant over a twenty-four hour period, and it is based on average monthly climatic data and also the summer calculation use a quasi-steady-state method. Thus the use of this standard, in this particular application, does not appear to be completely adequate for the energy need calculation.

Therefore the simplifications made in the method development and the inadequacies of the standard produce some loss of information and in some cases the method is not suitable for describing the physical system in a complete way. However it is believed that the proposed methodology, with the due corrections, could be a valid tool in the preliminary phase of projection for the definition of the optimal geometry, orientation and percentage of glazed area to ensure the minimum energy consumption for the heating and cooling and to compare other design solutions.

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