Sustainable Urban Block Design through Passive Architecture

A tool that uses urban geometry optimization to compute energy savings

EUGENIO MORELLO[1,2], VIRGINIA GORI[3], CARLA BALOCCO[3], CARLO RATTI[1]

[1]Senseable City Lab, Massachusetts Institute of Technology, Cambridge MA, USA
[2]Human Space Lab, Politecnico di Milano, Milan, Italy
[3]Department of Energy Engineering "Sergio Stecco", Università di Firenze, Florence, Italy

ABSTRACT: The aim of this study is to assess the impact of urban geometry in the overall energy balance of indoor spaces. Buildings are not analysed as single entities, but are considered as components of the urban fabric at the wider scale of the block and the neighbourhood. The hypothesis is that significant energy savings in indoor spaces can be achieved by controlling urban geometry variables (shape, orientation, height and density of buildings, glazing ratio) typically defined in the initial stages of master-planning design. The authors propose a tool for quantifying energy contributions of both lighting and heating, revealing the energy-based implications of formal design choices. The results of this study outline the impact of different energy contributions in the total energy balance of buildings considered in their urban environment. Whereas heating energy consumption depends relatively little on the arrangement of the urban shape – mainly due to solar gains – the energy consumption for lighting reveals itself to be more affected by urban geometry. An efficient mix of natural and artificial lighting with a sustainable energy urban design offers effective challenges to obtain significant energy savings and less environmental impact.
Keywords: daylighting, Digital Elevation Models, sustainable urban design, urban morphology

INTRODUCTION

The proper use of available natural illumination reveals itself to be fundamental in order to reduce thermal losses and electrical power in buildings and improve the environmental quality of indoor spaces (thermal and visual impact on occupants' psychology and comfort). This issue is particularly important in high density urban areas, where reciprocal obstructions caused by buildings significantly reduce solar admittance. Furthermore, the exploitation of daylighting is essential in tertiary buildings, where energy consumption for lighting often overcomes consumption for heating or air conditioning. Hence, the approach to energy conservation and environmental quality in buildings has to start with urban design considerations, with the aim to achieve the best arrangement of the urban fabric to admit the solar radiation needed to satisfy lighting requirements. At a second stage, a proper designed urban fabric can benefit from the application of energy savings technologies and equipments at the scale of the building. For instance, specific lighting systems that are able to integrate natural and artificial light conditions are convenient in the case of good solar admittance.

A lack in design tools that account these issues at the urban scale limits to explore energy conservation in the initial phase of site layout planning. Especially urban planners have often no clues about the energy implications of the proposed design schemes. If it has to be decided among alternative solutions, a quantification of the energy performance would be very helpful to legitimate the final choice.

What we propose here is a first basic design tool aiming at providing urban planners a very rough but trustful information about estimated energy consumptions of the urban fabric under normal use conditions of buildings. The tool is particularly useful for decision making in the planning of new urban developments, but it can also be applied for calculating and comparing energy performances of existing urban layouts.

Some schematic urban layouts based on the urban block as structural units are the case study to test this model. According to sustainable urban design trends [1] these schemes offer the maximum extension of built fronts on street, thus supporting a liveable and active public realm. Blocks have an internal courtyard, streets are 12 m wide and buildings have a depth of 12 m. Several configurations of urban blocks are investigated in order to find a sustainable design solution for a settlement located in a temperate climate in Europe (in this case Milan, Italy, 45° latitude, was chosen).

The model calculates several indicators related to urban solar admittance. First, it computes the solar admittance through the assessment of the percentage of shadowed areas on the urban facades. Second, it assesses the solar potential of the urban fabric by summing all intercepted irradiances on buildings. Third, it calculates daylighting conditions inside the building and estimates the supplementary energy consumption for artificial lighting. Finally, it calculates the general energy consumption for heating according to the European Standards.

Moreover, we are interested in extracting some correlations between urban morphology indicators and environmental parameters. Among the morphological indicators the population density plays a major role in understanding the delicate relationship existing between sustainability and the compact city and could help in future to assess design guidelines oriented to land use optimisation strategies.

RESEARCH CONTEXT

The question we pose has been deeply investigated in the past years [2, 3]. Especially passive architecture addresses design principles based on the exploitation of free energy gains from nature and daylighting is surely the first parameter to take into account. Solar architecture provides guidelines based both on empirical experience (vernacular architecture and novel design solutions) and on calculation (digital simulations and measurements) [4].

To develop the proposed model we refer to basic energy consumption calculations for heating and daylighting.

Heating consumption is calculated according to European Regulations (CEN EN 832:1998 [5]). In addition, the proposed tool specifies a more precise calculation for defining mutual obstructions by buildings. Beam and diffuse irradiances collected on the facades and roofs with 8 different orientations are computed referring to solar geometry [6]. This calculation enables to estimate thermal energy stored by opaque and transparent surfaces, taking into account if those surfaces are in shadow or not.

Considering daylighting, it is necessary to build up a model that reproduces the case study in order to simulate indoor illuminances. Sophisticated software refers today to two main approaches: the ray-tracing technique and the radiosity technique [7]. These techniques, even if very accurate, are time consuming and have a level of detail which is too precise for an estimation of energy consumption at the urban scale.

A simplified method is based on the calculation of the Daylight Factor DF [4], defined as the ratio of total daylight flux incident on the working plane, expressed as a percentage of the outdoor illuminance on a horizontal plane. The method refers to the CIE overcast sky (the worst condition where direct sunlight is discarded) and does not consider any dynamic situation related to the actual sun path and sky conditions. The DF provides information on the parts of the building that are bright or dark. Longmore [8] defined an average daylight factor DF_{av} to indicate the visual adequacy of daylighting in space as a whole rather than at any particular point.

Another useful factor we refer to is the Daylight Autonomy DA [9], defined as the percentage of time that one can expect to reach a certain light level (usually this threshold is expressed by illuminance values) just using daylight. In this case the computation runs on a hourly basis and considers the changeability of solar radiation.

Moreover, the authors refer also to the distinction between passive and non-passive zones as defined in the LT-Method implemented by Baker and Steemers [10]. Passive zones are those areas that can benefit from natural environmental conditions in terms of energy savings, whereas non-passive zones require constantly mechanical equipments (basically HVAC and artificial lighting) to guarantee indoor comfort and functionality.

METHODOLOGY

The construction of the model is based on image processing techniques which input is the simple raster representations of built volumes [11, 12, 13]. These images are named 2.5 digital urban models DUMs, or more generally Digital Elevation Models DEMs. In these models the intensity value of each pixel contains the information about the elevation. Today’s increasing availability of 3-D information from user generated contents and remote sensing surveys, makes this technique promising and very useful for a general understanding of the energy performance of our cities.

As case study for this investigation we focus on the compact urban texture and in particular on simplified urban blocks’ configurations based on the courtyard typology. These urban prototypes are analysed in terms of morphology, solar admittance and daylighting performance. We argue that evident savings on energy consumption can be achieved by simply disposing the built volumes in a proper way. Six configurations with different block geometries and urban densities are investigated (Fig. 1). From results we deduce the parameters related to the central block to avoid the edge effect. So we can evaluate the general performance of a prototypical block located in a homogeneous environment.

The proposed technique computes energy consumption, taking into account lighting and heating contributions separately. The urban fabric is sliced into several horizontal sections at 3 meters intervals to simulate typical heights of storeys. This subdivision enables to assign different types of indoor spaces uses, thus considering specific energy demands (households, offices).

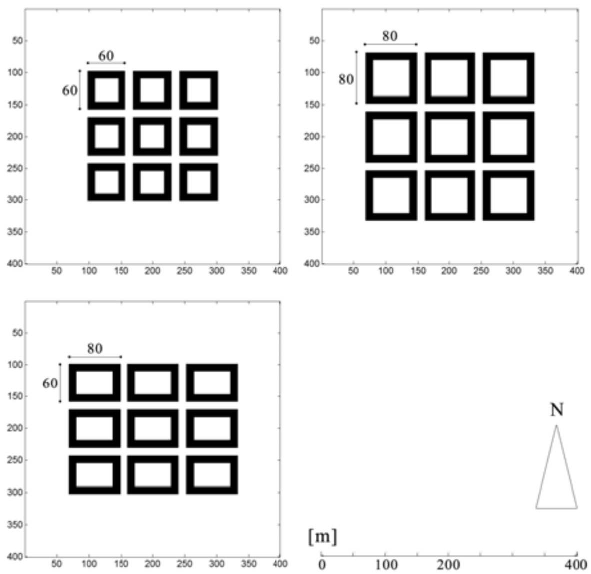

Figure 1: The analysis investigates 6 urban blocks configurations. Above the 3 basic layouts that were also analysed with a rotation of 45°. Blocks are 12 meters high.

THE PROCEDURE OF CALCULATION

For natural lighting simulation, we need some initial information. The required inputs of our model are: (a) the geometry of the case-study area (to calibrate the DUM we need to know the depth, the width of the site layout and the height of the tallest object); (b) the geographic position of the site, which in this case is located in Milan (Italy; 45° latitude); (c) climatic data of the specific location: in this case we used monthly irradiance values (beam and diffuse) on the horizontal plane (according to the Italian Standard UNI 10349:1994 [14]).

The simulation runs during the winter season and takes into account a time span from 9 AM to 5 PM to compute useful daylighting contributions.

The first step is to calculate the solar irradiances for the specific location. Referring to solar geometry formulae [6] it is possible to derive the hourly values of the sun altitude and azimuth. This allows us to process the image and cast the shadows on the model, hour by hour, thus distinguishing among lit and shadowed pixels [11] (Fig. 2a). It is important to note that the model is sliced building by building at every storey (intervals of 3 meters) in order to differentiate the shadowing conditions of vertically aligned pixels. Then, the percentage of shadowed surface is computed on each facade and can be visualized to give a general idea of the solar admittance in the urban texture (Fig. 2b).

So we take into account the influence of urban geometry. Then hourly solar irradiance values are derived from the monthly irradiance values on the horizontal plane. Using simple *Sobel* filters for image processing, the model detects 8 orientations for the vertical surfaces of buildings. For each orientation and the horizontal direction, the calculation of hourly values of beam, diffuse and total irradiances are computed for the typical day of each month (please, refer to [15] for details).

Once we obtain the annual array with the hourly irradiance values, it is possible to assign to each facades' pixel, its intercepted solar irradiance. The beam contribution of irradiance is summed to the diffuse, only for lit pixels, as previously determined (Fig. 2c).

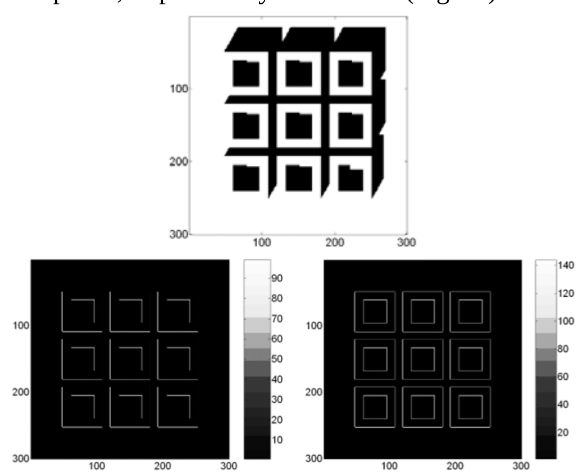

Figure 2: On the top: (a) Shadows' map. Bottom left, (b) percentage of direct solar radiation and right (c) collected on each facade on 10 December at 2PM (W/m^2).

The next action is to convert irradiance values (W/m^2) into illuminance values (lx). We assume a luminous efficacy of 100 lm/W as the multiplier for an array where all irradiance values on the vertical urban surfaces are stored. Then we get a matrix with the illuminances on the buildings facades.

From now on, a simplified method for take into account daylighting in the model is presented. We assume some simplifications. First, the geometry of openings is defined by a glazing ratio GR of 30%, applied to all orientations. In particular, we suppose that openings run uninterruptedly along all the perimeter of the buildings. E.g. if the storey is 3 meters high, the window itself is 1 meter high, according to the GR. Second, we input default window factors (maintenance factor M=0.90, glass transmittance G=0.85, framing factor B=0.80). These parameters can be changed according to the design input.

Hence, referring to the total flux method [16], the luminous flux φ_t (lm) entering the room can be calculated by the product of the illuminance on the plane of the window E_w , times the window's area A_w.

$$\varphi_t = E_w * A_w$$

To consider the constrains of windows, we calculate the effective flux φ_e(lm).

$$\varphi_e = \varphi_t * M * G * B$$

The daylighting level dramatically drops with the increase of distance from the openings. In the next step we derive a basic method for spreading the previously computed luminous flux on the window plane inside the considered room. Since the proposed model is meant to be a support tool for designers at the urban scales, many details in the calculations can be skipped. First of all we refer to literature (digital simulations and measurements) to derive simplified daylight factor's profiles (or daylight design diagrams) in indoor spaces and we assume these identical over all orientations [17]. The reflectance properties of walls, floors and ceilings, and the reflectance properties of outdoors elements are not necessary as input.

Through some operations on the model, we offset the illuminances E_i into the room and decrease their values according to the following equation (Fig. 3):

$$E_i = \frac{\varphi_e * DF_{av}}{d * e^{-1.35}}$$

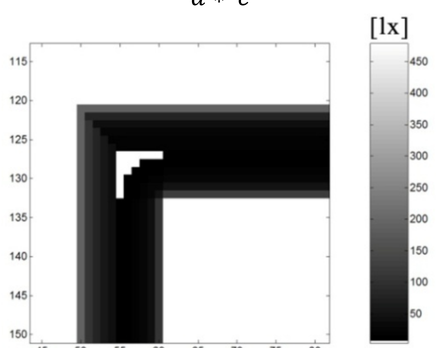

Figure 3: Detail of one building showing the estimated illuminances (lux) distributed indoors on the 15th of April at 5 PM. Note the non-passive zones in the middle of the corner.

where DF_{av} is the average daylight factor (we assume DF_{av} = 10% on the plane of the window alone when the external illuminance enters the room) and d represents the distance from the window. We calculate internal illuminances on the passive zones only [10, 12]. In this case, we define as passive zones the floor areas within a distance to the external perimeter that is twice the height of the ceiling, hence e.g. 6 meters.

Once the patterns of indoor illuminance levels are mapped, the integration of natural and artificial lighting has to be assessed. A threshold of minimum illuminances over the work plane have to be guaranteed, otherwise artificial lighting has to be provided. We assume 100 lux as the minimum illuminance that has to be reached on every point of space. Even if 100 lux do not represent a high level of illuminance and is usually provided in spaces that do not require specific visual tasks, though it constitutes a good average limitation if spread out on all points of the building. Knowing the needed gap of illuminance to fulfil the condition of 100 lux, it is possible to estimate the overall wattage that has to be provided with artificial lighting. The lighting solutions design goes beyond the interests of this work and implies numerous factors (among others: the geometry of the space, the type of luminaries and their layout in the room). Moreover, sophisticated lighting systems that precisely integrate natural and artificial light are expensive and can not be assumed as a general design condition. Therefore, we prefer to estimate the amount of artificial luminous power that is needed to compensate natural lighting lacks.

The luminaries assumed in this study are standard white fluorescent lamps with a lamp power of 0.050 W/m^2lx. The model computes the average hourly energy consumption in Wh/m^2 over the passive zones that require the integration of artificial lighting, whereas it assumes 5 W per m^2 as the general electrical consumption for artificial lighting in the non-passive zones where full electric lighting system is always provided: this value is calculated considering a 100 W lamp that covers an area of about 20 m^2 whereby also unlighted floor areas occupied by furniture or facilities are included in this estimation. Synthetic results show the energy consumption for lighting at each storey.

The energy consumption for heating is estimated referring to the CEN EN 832 Standard [5]. The model computes the energy requirement building by building on the average day of each month for the whole heating period, taking into account the effects of mutual shadowing by the urban fabric. Results are stored in a data structure and they can be visualized either for the whole case-study area or for each building, or for each storey of the same building. We slice the buildings at intervals of 3 meters: this subdivision is useful because it allows assigning different uses to spaces. In this case we can distinguish between households and tertiary buildings. The idea is to build up a function that calculates thermal losses and gains trough the external surfaces of a single storey and then to repeat it for every slice of every building. The heating period is defined by the climatic zone depending on the base of the heating degree days (HDD) where Milan is located, according to UNI 10379:2005 [18]. Constant internal climatic conditions for the heating period are set as 20°C temperature and 50% relative humidity, as suggested in CEN standards for indoor air quality [19].

The required input data for the simulation, besides the urban geometry of the case-study, are the following: (a) thermal parameters of different materials (the transmittances of horizontal and vertical opaque and glazed surfaces, the transmittance of the ground floor, the conductivity of the ground, the solar transfer coefficient of the window glasses, the thermal capacity of the wall), (b) some constructive characteristics of the buildings (glazing ratios, external wall thickness). When accurate data are not available, the minimum values are set according to the standards.

The first step is to calculate some geometrical quantities of the DUM. For each building, indeed, it is possible to derive the floor area, the volume and the lateral surface just using some simple techniques of image processing and making some simple matrix operations.

The second step is to calculate thermal gains and losses of the lateral walls, the ground floor or the top floor. Dispersions are provided by heat losses both caused by transmission and ventilation through external surfaces. Thermal gains can be split into internal and solar gains: internal gains depend on the use (residential or tertiary) and the floor area (we refer to UNI 10379:2005, Appendix B [18]). Solar gains connected to both opaque and glazed surfaces, depend on the solar radiation intercepted by the external building envelope. These gains depend mainly on the orientation of the surfaces and on the presence of surrounding buildings that can cast shadow on them. A 3-D array stores the information concerning the percentage of how many times each pixel is obscured by the surrounding buildings.

The next step consists in computing the energy balance for all the buildings. The monthly and seasonal energy requirements for the heating period are determined as the difference of the total heat gains (multiplied by a utilization factor) and the total thermal losses. Considering the energy balance of each building, if monthly gains are greater than losses, the building energy requirement for the considered month is set to zero. Finally, by multiplying the energy requirement by the intermittency and the efficiency of the heating system, it is possible to estimate monthly and seasonal energy consumption of each building and storey, and then of the urban area.

RESULTS

The models proposed in this paper were applied to schematic and typical urban configurations. They reveal themselves to be useful tools for evaluating the energy efficiency of existent different urban areas. Lighting and heating energy consumption are compared for the analysed configurations and then put in relation to different urban density parameters (Tab.1).

Results show that for office buildings lighting consumption is higher than heating, increasing twofold in some cases. Due to the initial strict conditions imposed by building energy performance standards (EPBD, Energy Performance of Building - Directive 2002/91/CE), the most energy savings are possible today concerning heating (20 kWh/m^{2}yr corresponds to 'A class' energy performance standards). On the other hand, a proper integration of daylight and artificial lighting does not guarantee as much energy savings. Therefore, if lighting represents such a strong issue in the overall energy balance of buildings, a proper arrangement of the urban form is fundamental in order to improve solar admittance in the built environment.

Moreover, a contradiction between lighting performance and heating performance of building emerges. As a matter of fact, the 45° rotated schemes have better heating performance due to a more homogeneous solar exposure. In this situation, in terms of daylighting, the reduction of south oriented surfaces compromises the available light indoors and represents a worse scenario.

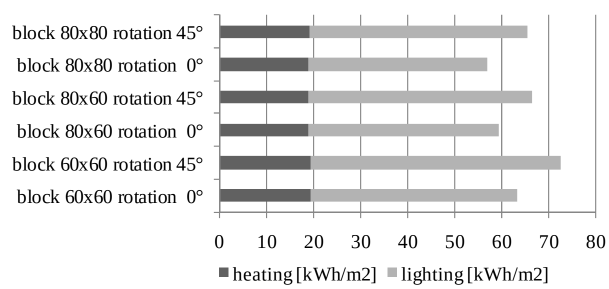

Table 1: Energy consumption for lighting and for heating during the winter season, in case of tertiary buildings.

Concerning the relationship between indicators of density and energy consumption it emerges that heating consumption does not increase with higher densities. On the opposite, lighting consumption increases with higher levels of density. Thus, it could be possible to estimate the energy consumption of the design scheme by simply defining the urban density and buildings' typologies *a priori*.

Finally, as a preliminary suggestion for urban designers, a block orientation with the longer axis facing the south is recommended. This meets the optimal condition for energy savings, since consumption for lighting is more dependent on the orientation of the block as opposed to heating.

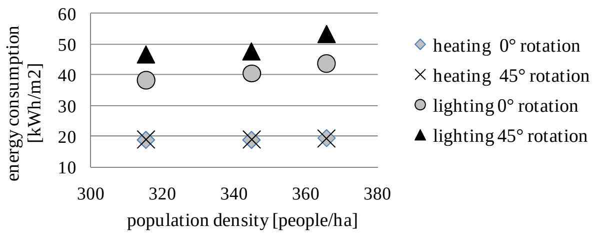

Table 2: Comparison between energy consumptions and urban density.

CONCLUSION

The results of this study outline the impact of different energy contributions in the total energy balance of buildings taking into account the features of the urban environment. Whereas heating energy consumption depend relatively little on the arrangement of the urban shape – mainly due to solar gains – the energy consumption for lighting reveal themselves to be more affected by urban geometry. An efficient and optimal mix of natural and artificial lighting, also with an environmental conscious design of the built fabric, offers effective challenges to obtain significant energy savings.

Finally, future work will include the following considerations: first, the model accuracy has to be improved, using simplified boundary conditions and simplified involved variables into the algorithms. Second, the possibility of using this tool over existing urban areas makes it promising for urban planning and design applications. Third, the model should consider the annual energy balance of buildings, taking into account all-weather. In particular it is difficult to cope both with winter and summer requirements, because these have often divergent implications concerning the formal layout of design schemes. For instance, daylighting in the summer season is mostly excluded to avoid glare and overheating. Thus, shading solutions have to be taken into account in the model. This issue is an exciting occasion to rethink and propose a new reconfigurable architecture that adapts itself depending on seasonal conditions.

Anyway, the proposed model can be utilized for comparative studies to assess the changes among different situations. As a matter of fact, the prototypes processed in the present work, are samples for testing the model. The technique is fast and accurate and works with more complex urban geometries as well.

REFERENCES

1. Farr, D. (2007). *Sustainable Urbanism: Urban Design With Nature.* Hoboken, NJ, USA: Wiley & Sons.
2. Owens, S. E. (1986). *Energy, planning, and urban form.* London: Pion.
3. Jenks, M., Burton, E., & Williams, K. (Eds.). (2000). *Achieving Sustainable Urban Form.* London, UK: E & FN Spon.
4. Littlefair, P. J. (1991). *Site layout and planning for daylight and sunlight: a guide to good practice.* London: BRE.
5. CEN EN 832:1998. *Thermal performance of buildings - Calculation of energy use for heating - Residential buildings*
6. Duffie, J. A. (1980). *Solar engineering of thermal processes.* New York: John Wiley & Sons.
7. Tsangrassoulis, A., & Bourdakis, V. (2003). Comparison of radiosity and ray-tracing. *Renewable Energy , 28*, 2157–2162.
8. Longmore, J. (1975). Daylighting: a current view. *Light and Lighting , 68*, 113-119.
9. Reinhart, C. F., & Walkenhorst, O. (2001). Dynamic RADIANCE-based Daylight Simulations for a full-scale Test Office with outer Venetian Blinds. *Energy & Buildings , 33* (7), 683-697.
10. Baker, N., & Steemers, K. (2000). *Energy and Environment in Architecture.* London: E&FN Spon.
11. Ratti, C., & Richens, P. (2004). Raster analysis of urban form. *Environment and Planning B: Planning and Design* (31:2).
12. Ratti, C., Baker, N., & Steemers, K. (2005). Energy consumption and urban texture. *Energy and Buildings , 37.*
13. Morello, E., & Ratti, C. (2007). Raster Cities: image processing techniques for environmental urban analysis. In: K. Thwaites, S. Porta, & O. Romice (Eds.), *Urban Sustainability through Environmental Design: approaches to time, people and place responsive urban spaces* (pp. 119-122). London, UK: Spon Press.
14. UNI 10349:1994. *Heating and cooling of buildings. Climatic data.*
15. Carneiro, C., Morello, E., Ratti, C., & Golay, F. (2008). Solar radiation over the urban texture: LIDAR data and image processing techniques for environmental analysis at city scale. In: J. Lee, & S. Zlatanova (Eds.), *3D Geo-information Sciences* (Lecture Notes in Geoinformation and Cartography ed.). Berlin: Springer.
16. Szokolay, S. V. (2004). *Introduction to architectural science: the basis of sustainable design.* Amsterdam, Boston: Elsevier, Architectural Press.
17. Krarti, M., Erickson, P. M., & Hillman, T. C. (2005). A simplified method to estimate energy savings of artificial lighting. *Building and Environment , 40*, 747–754.
18. UNI 10379:200. *Buildings heating - Conventional normalized energy requirements*
19. CEN - prENV 1752 (1996). *Ventilation for buildings. Design criteria for the indoor environment.*