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# How environmental and energy issues shape the cities: a case-study in Barcelona, Spain.

### 1. Urban models and energy sources in city history

The current environment and energy conditions need reflection on the energy-intensive behaviour of the City on territory. The deep relationship between urban morphology and energy supply directly affects both the urban energy balance and the environmental comfort of areas where we live. This one-to-one connection historically led to the growth or collapse of urban models: if, on the one hand, the development and decline of the energy source enabled the growth of the man-made environment, on the other hand, land usage for residential and production purpose has determined the development and permutation of energy sources.
From this perspective, the entire city history highlights how urban form has changed during different epochs with relation to the function of energy sources. City models moved from early discrete villages, constrained within a compact and self-sufficient form fed on wood and animal muscular power, to the contemporary city, labelled by F. Butera as the energy and environmental *black hole*[1].
Inside this evolution, every crisis caused by an energy source generated a mutation of the previous city's shape. An example are *Coke-towns*: technological innovations, especially in infrastructure, pushed production and consumption sites away from the mines. Industry begot the quick growth of urban expansion in a process wherein «industrialization and urbanization phenomena appear inextricably linked»[2]. Saturated city-centres became unable to satisfy social and economic requirements, generating a new untidy building belt around the city: suburbs.
The nexus between production and consumption site, still active in this model, will be broken down later with electricity, which has had great importance on future urban form thanks to two main features: the introduction of a new supply technology, based on a broadly distributed network system, and the vertical development of buildings, enabled by elevators. Today the *Vertical City* symbolizes governmental economic power, yet skyscrapers reveal themselves as energy-hungry machines «which can consume easily up to 1.000 $kWh/m^2$/year, a value 8-12 times higher than normal construction»[3]. Similar to former circumstances, the advent of oil has once again modified the previous city-types toward a sprawling and *'dilute'* urban model strongly linked to individual car utilization. The limit of this urban model, already found in excessive land use, revealed itself during international oil crisis of Seventies. The oil embargo, in fact, has led scholars to reintroduce in their research energy-saving and efficiency issues, while also studying the improved urban design[4]. In this way, all 'physical' parameters which had been entrusted to technology and which directly affect the city's energy behaviour (density, H/W ratio, volume ratio, orientation, etc.) came back to the core of debate on efficient and self-sufficient urban form, strengthened by M.K. Hubbert's theory on peak of oil and the following *Green Apocalypse*[5].

### 2. Objectives

In light of this historical relationship between urban structure and energy sources, the current urgent requirement to switch-over towards new renewable sources make us wonder about the shape of future Renewable City. This requirement constrains designers to pay attention from the early stage of the process to the weather and environmental conditions in which the design will exist, in order to define it according to its energetic and environmental behaviour. The importance of working at an urban scale is confirmed by international and European commission which assigns great importance to the city action, suggesting urban design as the ideal tool to reach urban sustainability's main goals: «The way land is used in an urban area is fundamental to a town or city's character, its environmental performance and the quality of life it provides for its citizens [...] Sustainable urban design will therefore be a key element of the thematic strategy for the urban environment»[6].

Most recent research addresses the size of the building in order to shorten the planning process and to facilitate the ease of construction, but an interesting study[7] shows how, in the long run, results achieved in this way lose their efficiency, demanding a jump of scale toward that of a city. In fact, a building has a confined capability and is unable to solve prior urban design mistakes. Today, advancements in informatics systems provide designers useful software to estimate energy and environmental performance of a given urban form. Software supports designers without replacing them: it provides quantitative data and trend analysis, but it is unable of expressing the quality of space which remains architect's task and responsibility.
Consequently, the transition towards a more efficient urban form involves energy-environment parameters and quality of urban space, both of which are contained within the urban fabric unit: the block. The latter gains importance in sustainable design, due to its scale half-way between city and building size, and works at the same time on buildings and public space, improving both the quality of urban space and the energy performance of cities.
The paper applies these topics on a case-study in Barcelona; the main objectives of this study are to:
- Demonstrate how the environmental performance of the urban texture is related to the dimensional and morphological characteristics of the fabric, with specific regard to the streets orientation and the proportions of the urban canyon.
- Provide guidelines to improve energy performance and environmental comfort both in new and existing urban area through urban design.

### 3. The case-study

The *Eixample* district (Fig.1) is a representative synthesis of the features of the compact and complex Mediterranean urban model. The interest in this case-study depends not only on its particular morphology, but also on the approach and the design process developed by Ildefons Cerdá, which guided the transformation of Barcelona from a walled town into a modern city (1859).
One basis of the planning method was the knowledge of the city real estate as the main reference to understand the actual needs and the future perspectives of development. Cerdá reports the insalubrious living conditions and the inadequacy of Barcelona to integrate the upcoming energy sources (*i.e.* the steam engine) and recognizes public health and universal mobility as the main objectives of the urban renovation process.
The second step of the planning process is the principle of equality, aimed at ensuring respectable quality of life (in terms of residential standards and hygienic conditions) as well as uniform accessibility to urban services and infrastructure (public and green spaces, transportation, supplies).
The formal structure of the *Eixample* is defined and sized through a mathematical formula which constitutes the scientific application of the previous principles[8]. The result is a quadrangular chamfered block (*illa*) with sides 113.3 m long and a 60x60 m inner garden (patio). At first, the buildings should have been 16 m high and occupy only two sides of the *illa*, but the pressure of private owners and the postwar speculation led to much more intensive edification.
The disposition of the blocks according to a regular array defines a grid of streets 20 m wide, formed by a central driveway and two lateral sidewalks with plane tree rows. *The street canyon geometry* and the 45° network orientation established by Cerdà are devised to ensure adequate exposure of the main sides of the block to solar radiation and to healthy winds .

### 4. General approach and methodology

The methodology refers to the conceptual frame defined by Cerdá which might be considered a operating tool to establish appropriate strategies for the forthcoming transformation of contemporary cities[10], but takes advantage of the digital tools available today.
The research is developed through the design of a generic virtual model based on the typological structure of the pattern, in order to avoid the specificities of a real urban context which might make the understanding of its environmental behaviour difficult. The average measures to build an abstract but reliable mock-up are determined referring to the *SpaceCalculator*[11] (Fig.2).
Within the homogeneous fabric, a sample of 9 blocks laid out in a 3x3 array on a site area of 400x400 m is appropriate to provide correct information that can be extended to the whole sector. The analysis is implemented in two steps with the support of specific simulation software:
1) Assessment of the environmental performance in outdoor spaces by means of *Envimet* program[12], considering the climatic parameters which affect the conditions of well-being:[13]
– Temperature (K°)
– Relative humidity (%)
– Wind speed (m/s)
– Solar flux ($W/m^2$)
2) Examination of the solar collection above the building envelope, by means of the *Heliodon* program[14]. In this phase, more specific indicators are calculated:
– Solar potential ($Wh/m^2$),
– Energy gains (kWh)
– Sunlight hours (h)
The digital simulation is implemented at winter (case A) and at summer (case B) solstices, in order to provide a complete picture of the site's climatic performance. The required weather inputs are obtained from the *EnergyPlus* database[15] (Fig.3).

### 5. Results and discussion

#### 5.1 Environmental performance of outdoor spaces

The overall results refer to the pedestrian level (Fig.4 and 5).
*Temperature* (T) and *relative humidity* (Hr) are two interrelated air properties which affect thermal comfort and can be analysed together . In this case-study, the form of the urban fabric does not seem to directly affect the spatial and temporal variation of these parameters whose performance is probably influenced by the boundary's effects on the sample area. In both [A] and [B], temperature is fairly uniform in streets, crossings and courtyards and sporadic differences are found between shadowed and sunny areas. A similar tendency is detected with regard to relative humidity: only during the early afternoon of the 21st June, the Hr in courtyards is higher than in streets, due to the different degrees of closure of these spaces.
Contrary to the previous parameters, the *wind* performance is closely related to the morphological features of the built environment. The dominant North wind is symmetrically diverted in the direction of the streets, due to the 45° orientation of the grid. The street canyon geometry produces a *channelling effect* with air paths parallel to the long sides of the blocks. The vectors allow identification of a *skimming flow* regime in the street section, while, within the courtyards, the draughts are definitively weaker (V=0-1 m/s in A and B). The wider distance between opposite internal sides of the block results in an isolated *roughness flow* regime, with disturbed and contrasting wakes[17].
The only windward façade is the North chamfer, while the other sides are sheltered thanks to their own orientation. Almost stagnant zones are locally generated next to the corners, due to their position with respect to the main air flows; in the crossings, wind temporally recuperates its original direction, but with a speed reduction.
Solar simulation is run for a cloud-free sky conditions[18] which allow the best insight into the daily evolution of solar access. Only the *direct solar flux* is analysed.
In case A, all the streets have some hours of direct radiation, thanks to the diagonal orientation: the SE-NW axis are well-lit and warm between 9:30 and 11:00 h, while the SW-NE ones receive the sunlight from 15:00 to 16:00 h. Shadows cast by plantings along sidewalks are negligible because planes are deciduous trees. Courtyards are sunny in the North sector around midday, while the South portion does not get any direct radiation throughout the all day.
In case B, streets are fully exposed to solar radiation between 12:00 and 15:00 h, while sidewalks are partially sheltered by the trees, whose cast shadows reduce the incoming solar flux by about 60%. During the rest of the day, at least one side of the street is shadowed by the surrounding buildings. Crossings and courtyards are almost constantly exposed to solar radiation, due to the greater spatial openness and the absence of plantation.

#### 5.2 Solar accessibility on the block envelope

Within the homogeneous portion of the Eixample, the study is limited to the central block while the surrounding buildings act as obstructions. Solar analysis is implemented with regard to vertical (chamfers, inner and outer façades) and horizontal (roofs and patios) components of the envelope (Fig.6, 7 and 8).
On the 21st of June (sun's altitude is 72° at 12:00 h), roofs have the highest solar potential and provide the maximum energy gains (58% of the total amount), due to a large and unobstructed surface area[19]. During the winter solstice, the general trend is the same, but the distribution of solar gains is more uniform.
With specific regard to solar access on vertical surfaces, in case B the average sunlight hours and the solar potential display a similar behaviour in outer and inner façades. The width of the courtyard would forecast a greater collection potential with respect to the external sides, but, in the first case, the shadowing of the transversal orthogonal façades have to be considered[20].
The different influence of h/w and h1/c ratios appears clear in [A], when sun rays are lower (23° at 12:00 h) and solar potential decreases of 28% from the internal to the external façades.
The 45° rotation of the street network allows all the sides of the block to receive some amount of solar radiation during the winter solstice and protects them from the direct East and West incoming solar flux during summer.

### 6. Conclusions and further development

The *Eixample* case-study demonstrates how to deal with energy and design issues at an urban scale and shows the great opportunities provided by the urban project. The conscious analysis of environmental parameters led to discovery of general relationships which can aid architects in renovations and new interventions.
The spatial and temporal control of climatic variables is fundamental to making the best planning decisions: each formal solution has to fit within a specific environmental context and to other specific morphological parameters. Concerning this, the simulation software might provide a fundamental technical support, but the designer still keeps a principal role in interpreting and elaborating the results.
In a Mediterranean climate, the diagonal orientation of the grid is a rational arrangement which provides equal solar exposure in winter and good protection in summer both on the façades and on the streets. Actually, its effectiveness is related with the urban canyon geometry: in this situation, the H/W ratio is constant in all directions, but the variation of this proportion according to the orientation might be an interesting topic to improve solar performance.
Similar considerations can be done with regard to air flow. The 45° rotation shields the buildings from the North wind, without substantially affecting its original velocity: the requirements of comfort in the streets[21] are therefore fully satisfied in summer (V=2-3 m/s), but not in winter (V=4-5 m/s). A narrower section would attenuate the air movements and flows, but would become uncomfortable in the warm season.
The solution can be researched in the typology of the urban block: the patio is a "buffer zone" between the exterior and the interior which offers the possibility to control the microclimate. In winter, it might become a "shelter" to enjoy free sunlight and moderate ventilation, while adequate protection from solar radiation could be provided by the vegetation in summer. Furthermore, the partial opening of the block would ensure the public accessibility, provide air renewal and reduce the relative humidity inside (over 80% in B)[22].
With regard to the "individual" comfort, the central courtyard allows dwellings to have a double opposite aspect and to take advantage of passive daylight and ventilation; concerning the technical use of the sun, the homogeneous height of the blocks would make it possible to exploit the roofs for solar active applications.
On the whole, the results show how, by paying attention to the local conditions, urban design can reduce energy costs which usually fall on buildings behaviour (lighting, heating and cooling system, etc.), improving dweller's environmental comfort. The interconnection between the urban and the architectural scales is confirmed, therefore, as a fundamental tool to achieve positi-

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**Notes**

[1] Droege, 2006
[2] P.H.Derycke, 1972 (De Pascali, 2008).
[3] De Pascali, 2008
[4] Among the most remarkable publications: S. Owens (1986); R.L. Knowles, (1974); L. Martin and L. March (1975); R. G. Stein (1977)
[5] The events that raised the Ecological Issue: the ozone hole discovery (1985) and the global warming (1986-88). Ingersoll, 2009
[6] Towards a thematic strategy on the urban environment. Eu, 2004.
[7] De Pascali, 2008
[8] The side of the block is the ratio among building height, street section and courtyard width. Serratosa, 2008
[9] Martín Ramos, 2010
[10] The urban dynamics have changed, but the way to work with them is the same. Busquets 2009
[11] A set of basic indicators of density and urban form. Berghauser Pont, Haupt, 2010
[12] http://www.envi-met.com/
[13] Serra Florensa, 1995
[14] By B. Beckers and L. Masset. http://www.heliodon.net
[15] http://apps1.eere.energy.gov/buildings/energyplus/cfm/weather_data.cfm
[16] Serra Florensa, 1999
[17] The flow regimes are functions of h/w and h/l ratios. Santamouris, 2001
[18] Both *Envimet* and *Heliodon* provide potential values of solar flux
[19] Roofs are located at the same height and not affected by obstructions
[20] Courtyards are not actually urban canyons described by a single cross-section. Erell, 2011
[21] Air speed values until 3.5 m/s are acceptable in outdoor spaces. Serra Florensa, 1995
[22] Values of Hr higher than 75% are out of the comfort zone. Olgyay, 1998

**8. Bibliography**

Berghauser Pont M., Haupt P., *Spacematrix. Space, density and urban form*, Nai Publishers, Rotterdam, 2010.

Busquets J. and Centre de Cultura Contemporània de Barcelona, *Cerdà i La Barcelona Del Futur: Realitat Versus Projecte*, Cccb, Barcelona, 2009.

Compagnon, *R. Solar and Daylight Availability in the Urban Fabric*, in «Energy and Buildings», n. 4, vol. 36, 2004

De Pascali P., *Città ed energia. La valenza energetica dell’organizzazione insediativa*, Franco Angeli, Milano, 2008.

Droege P., *The Renewable City. A comprehensive guide to urban revolution*, Wiley&Sons, Chichester (GB), 2006.

Erell, E., Pearlmutter D., Williamson, T., *Urban Microclimate: Designing the Spaces between Buildings. Earthscan*, London; Washington, D. C., 2011.

Ingersoll R., *Questione ecologica in architettura*, in «Lotus» n.140, 2009.

Knowles R., *Sun rhythm form*, MIT Press, Cambridge Massachusetts, 1981.

Martín Ramos Á. et al., *El Efecto Cerdà: Ensanches Mayores y Menores*, Escola Tècnica Superior d’Arquitectura, Barcelona, 2010.

Olgyay V., *Arquitectura y Clima: Manual De Diseño Bioclimático Para Arquitectos y Urbanistas*, Gustavo Gili, Barcelona, 1998.

Ratti C., Raydan D., Steemers K., *Building form and environmental performance: archetypes, analysis and an arid climate*, in «Energy and Buildings», n. 35, vol. 1, 2003.

Santamouris M., *Energy and Climate in the Urban Built Environment*, James & James, London, 2001.

Serra Florensa R., *Arquitectura y Climas*, Gustavo Gili, Barcelona, México, 1999.

Serra Florensa R., Coch Roura H., *Arquitectura y Energía Natural*, Edicions UPC, Barcelona, 1995.

Serratosa A., *Attualità dell’Eixample di Barcellona*, in *La città reticolare e il progetto moderno*, CittàStudi Edizioni, Torino, 2008.

**9. Legend**

Fig.1 The Eixample: the street and the chamfered blocks.

Fig.2 Typological model and morphological features of the urban fabric: plan and section

Fig.3 Monthly average weather data provided by Energyplus (A_June; B_December)

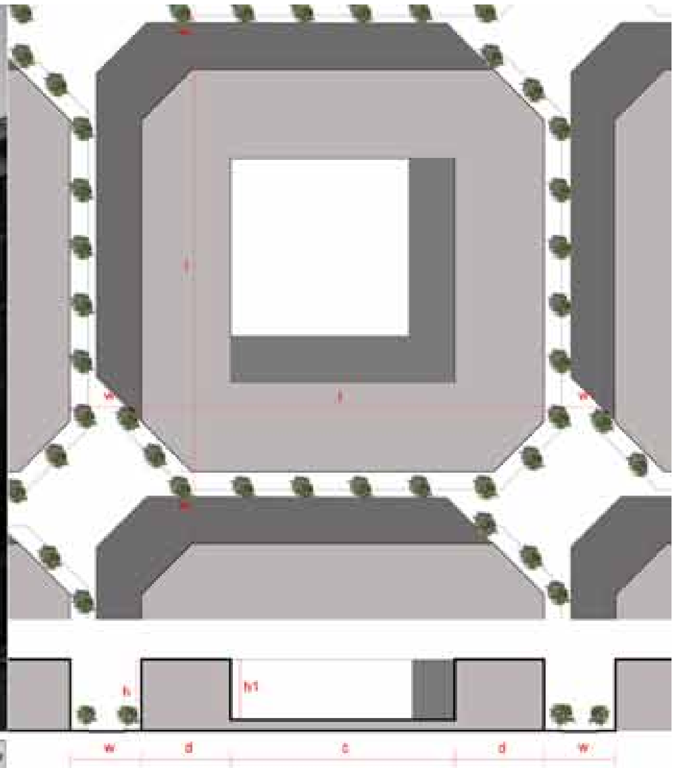
Fig.4 Daily evolution of climatic parameters on winter’s solstice (Case A)

Fig.5 Daily evolution of climatic parameters on summer’s solstice (Case B)

Fig.6 Graphical representation of sunlight time distribution in case A (right) and B (left)

Fig.7 Graphical representation of solar flux in case A (right) and in case B (left)


fig. 1




| FSI | l | d | c | w | h | h1 | h/w | h1/ |
|---|---|---|---|---|---|---|---|---|
| 3.15 | 113 m | 25 m | 63 m | 20 m | 20 m | 17 m | 1 | 0.27 |

fig. 2

| INPUT CLIMATIC DATA | Average temperature (K) | Wind speed (m/s) | Wind direction | Relative humidity (%) | Specific humidity (g water/Kg air) |
|---|---|---|---|---|---|
| Case A | 283 | 4,4 | N | 66 | 8 |
| Case B | 294 | 2,6 | N | 77 | 11 |

fig. 3

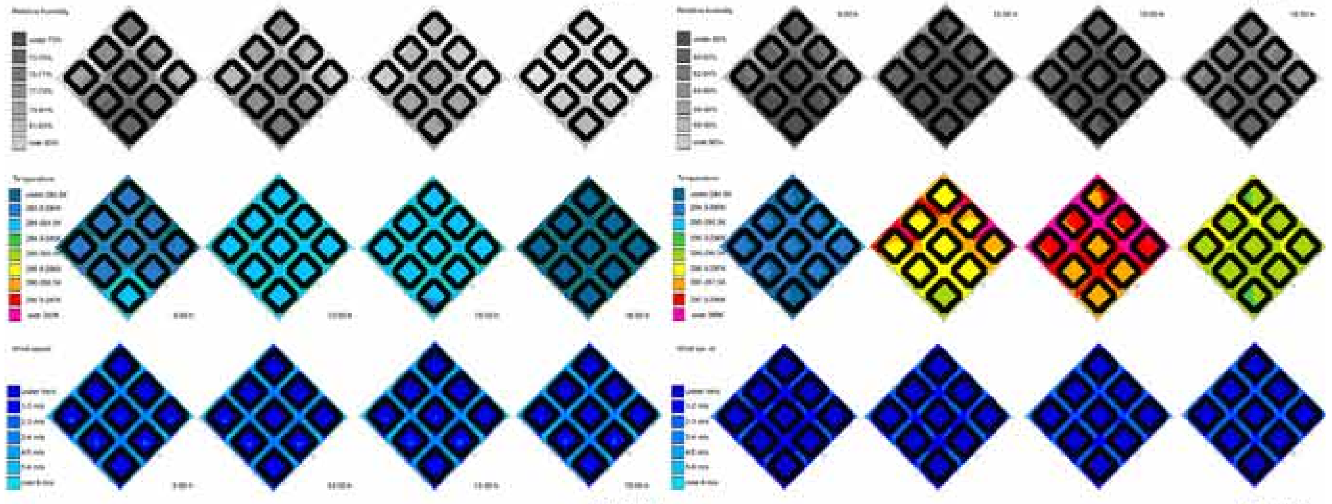


fig. 4 (A) fig. 5 (B)
fig. 6 fig. 7

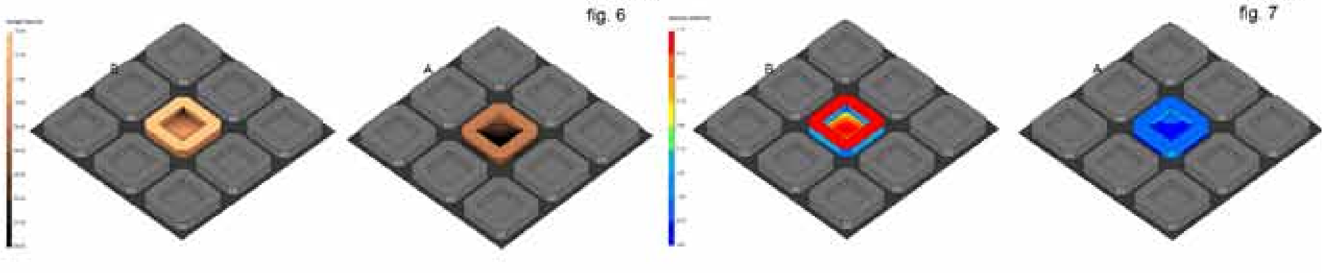



fig. 8

| Envelope | Surface | Area (m²) | Sunlight time B (h) | Sunlight time A (h) | Total energy B (kWh) | Solar flux B (kWh/m²) | Total energy A (kWh) | Solar flux A (kWh/m²) |
|---|---|---|---|---|---|---|---|---|
| Horizontal surfaces | Roofs | 8400 | 15 | 9 | 59731 | 7,11 | 9584 | 1,14 |
| | Patio | 3969 | 7,7 | 1,4 | 20620 | 5,20 | 1176,4 | 0,30 |
| Vertical surfaces | Inner façades | 4283 | 5,85 | 2,75 | 7607 | 1,78 | 3349 | 0,78 |
| | Outer façades | 6776 | 6 | 2,75 | 12235 | 1,81 | 3810 | 0,56 |
| | Chamfers | 1600 | 6,225 | 2,7 | 2793 | 1,75 | 1204 | 0,75 |