Solar access in the compact city: a study case in Barcelona

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ABSTRACT

The objective of this work is to analyze the performance of a high-density urban fabric regarding access to solar radiation and to determine the extent to which *urban form* can affect the collection of energy on building envelopes.

A specific case of this study is the *Eixample* district in Barcelona (Spain), a nineteenth-century district that synthesizes the features of a compact and complex city. The attention is here focused on the *fabric orientation*, with the aim of quantifying and comparing the influence of obstructions in different situations.

This analysis is carried out using *Heliodón 2*, a software that simulates real solar paths, providing graphical and numerical information about the evolution and distribution of solar radiation over a surface, and taking into account losses due to cast shadows.

The results provide interesting information on solar radiation performance and the possibilities of formal solutions for improving exploitation of solar energy in an urban context. Furthermore, such an analysis gives the opportunity to explore the possibilities and reliability of comparative processes applied on an urban scale and to extend their application to other study cases.

1. INTRODUCTION

The vast majority of the world's population, business activities, commerce and amenities are located in cities and the energy consumption and environmental contamination that they generate have dangerous effects for present and future human generations.

The urgency of reducing energy demand and the use of fossil fuels first became clear in the 1970s, due to the international oil crisis, when world communities realized that a transformation of the productive, economic and social organization was needed.

Buildings form a major part of the global energy demand, because approximately half of the total amount of energy produced in the world is employed by them only to control interior comfort (Ratti et al. 2005). Moreover, edifices are not isolated and self-dependent entities, but linked parts of a settlement. In an urban area, complicated networks for material transportation, information, communication and services produce *flows* that also require considerable energy resources for their own operations.

The importance of an *urban scale approach* to this problem started to be recognized in the early 1990s, and during the last 20 years many studies have been aimed at creating more sustainable urban models and planning policies in order to reduce energy demand and foster the integration of available natural resources, with special regard to solar radiation.

The *Solar City* concept was created by P. Droege as an International Energy Agency research (2002) and development project aimed at reducing greenhouse gas emissions in urban settlements by introducing a rational use of energy and a renewable energy system (Jenks et al. 2005).

Actually, just before then, C. Winter (1993) had already conceived the city of the 21st century (the Second Solar Civilization) as a solar city, defining it as “an energetically self-contained settlement with solar irradiance as its main energy source” and considering what this big “energy converter” would look like and how it would have to be designed. Though still immature, these observations highlight the importance of the formal aspects of a solar city and the role assumed by architects and planners in dealing with this natural energy source: the sun.

Interaction between site layout and solar penetration is really strict, complex and often conflictive, especially in high-density urban cases. There is a general tendency to recognize a complex and compact model as more sustainable, since it leads to a lesser territorial expansion and reduces global energy demand (Rueda 2002), but it is clear that a strong densification of urban space inevitably reduces the amount of su potentially available as a natural source of energy.

Hence, in what direction is the historic debate between smart growth and urban sprawl evolving, in the age of sustainability? Is it possible to envision a high density *solar city*? What are the most appropriated design solutions that urban designers can choose to optimize individual, technical and social use of the sun (Käiser at al. 1996 and Treberspurg 2008)?

Several studies of the performance of urban environments with respect to solar energy have been carried-out (and many of them are still under way) using different methods of analysis: empirical formulas, algorithms, numerical models, manual, geometric or graphical tools, lighting and thermal simulation software, and so on. Though considerable computational and technical advances have been made during the last few years, the problem is still partially unsolved and the results obtained up to now can by no means be considered exhaustive.

Main problems are related to the big number of inputs interacting at an urban scale. The lack of suitable tools for managing and synthesizing all kinds of variables at once makes the calculation processes long and complicated, often providing output data that are difficult to interpret. Difficulties in creating suitable three-dimensional digital mock-ups and in reproducing sky vault and cloudiness models are two further critical points that can affect the correct estimation of solar access into cities.

The inability of current tools to provide comprehensive and totally exact predictions raises serious questions about the level of accuracy that is really required at an urban scale. Is such a high computational complexity necessary, or can simplified methods and models of analysis suffice and offer more significant results?

At present, two important questions concerning the study of solar radiation performance within cities need to be solved. Firstly, from the sustainability point of view, the influence of morphological parameters on solar radiation access in buildings and open spaces takes on a special role in high-density urban environments and therefore needs to be studied specifically.

Secondly, the definition of suitable and accessible research tools and processes seems to be one of the most urgent needs, in order to get a more flexible and practical knowledge and to achieve a rational management of all the information available.

2. OBJECTIVES

2.1 General objectives

This study represents the first step of a current research project regarding sun availability and radiation control in high-density urban fabrics. By studying and comparing the performance of different built environments, it intends to obtain information about formal features of the city that affect solar access and its exploitation.

By focusing attention on the geometrical aspects of the question, it also aims to improve the possibilities of *comparative analysis* at an urban scale. This methodology is based on a digital simulation and aims to reduce the number of variables taken into account, in order to obtain faster computations and more synthetic results that can be used to inform the urban planning process.

This method is here applied to the case of the *Eixample's district.*

2.2 Specific objectives

2.2.1 The influence of obstructions

The first step is to evaluate the effect of obstructions to access of solar radiation and the percentage of energy loss due to the mutual shadows cast by neighbouring buildings, in order to determine the previously performance of the existing situation.

2.2.2 Urban fabric orientation and solar access

With specific reference to the direction of the urban pattern, Eixample's regular grid is therefore studied with two different orientations with respect to the North, in order to compare shadows projected by surrounding buildings in various situations. Changeble evolution of solar radiance throughout the year is really important to relate correctly geometrical characteristics and solar access in the urban context. For this reason, number of sunny hours and amount of energy collected by exposed surfaces are separately calculated in summer (21/06-20/09) and winter (21/12-20/03).

2.2.3 Tool and methodology evaluation

Through the operations previously described, we also wish to test the efficacy of the specific methodology and digital simulation process proposed in comparison with other tools usually applied for solar radiation analysis at an urban scale.

The aim is to check the level of accuracy provided by the software, in order to determine whether the results can be considered reliable to guide formal urban planning decisions.

3. METHODOLOGY

3.1 Identification and selection of the study case: Barcelona's Eixample

Barcelona is located in the central coast of Catalonia, Spain, at 41°23'N and has a mean elevation of 4 m above sea level. The climate is Mediterranean, with an annual average temperature of 15.5ºC, a daily temperature range of 15 degrees and an annual average solar radiation of 14.4 MJ/m^2*day, according to the *Servei Meteorològic de Catalunya* and to the *Atles climàtic digital de Catalunya*.

A population of about 1,600,000 people reside today in the urban area that covers an area of 100 km^2. The formal organization of the city is the result of both its history and the natural geographical boundaries.

The Eixample covers an area of 748.5 hectares and houses about 16.5% of Barcelona's inhabitants. It is one of the smallest districts in Barcelona, but one with a very high population density, 35,082 inh/km^2, well over twice the average for the whole city (data source: *Department de Informatica del Ajuntament de Barcelona*, 2007).

The demographic data clearly reflect the morphological and functional features of the site layout: a dense and mixed texture, in which private residential use is combined with public activities. In the 21st century, the Eixample still works as a dynamic and heterogeneous district, though its formal organization dates back to 150 years ago.

Ildefons Cerdà's 1859 Plan for the Eixample proposed a regular formal organization, constituted by an array of quadrangular chamfered blocks (*manzanas*) with sides 113.3 m long, defined by a grid of orthogonal streets 20 m wide (one central lane 10 m wide for vehicles and 2 lateral pedestrian sidewalks). Buildings, whose height was limited to 16 m, should have occupied only two edges of the block, in order to give access to the central patio consisting of public green areas. Unfortunately, during successive phases of building speculation, the general buildings rose to a height of 20-24 m (1 or 2 floors more) and occupied almost the whole manzana (Fig.1).

The street canyon geometry and grid orientation originally established by Cerdà (NO-SE and SO-NE, the same chosen by the Romans for the foundation of the first settlement in the 1st century BC), were justified by the intention of controlling shadowing by surrounding buildings, in order to guarantee that all dwellings would receive sufficient daylight and natural ventilation.

Cerdà's city concept seems to express the features of a compact and complex supposedly sustainable city (Rueda 1998) and also to recognize the importance of sunlight and daylight availability in an urban context. It is therefore interesting to study the performance of the Eixample in order to test the effectiveness of a dense fabric with respect to solar access.

An analysis of the whole area would be unnecessary and not significant for the aim of this work because the peculiar regularity of the fabric easily allows one to consider only a part of it and to extend the results to the whole. Hence, an area formed by 9 blocks symmetrically placed in 3 x 3 square on the left side of the district was selected as a study sample (Fig.2)

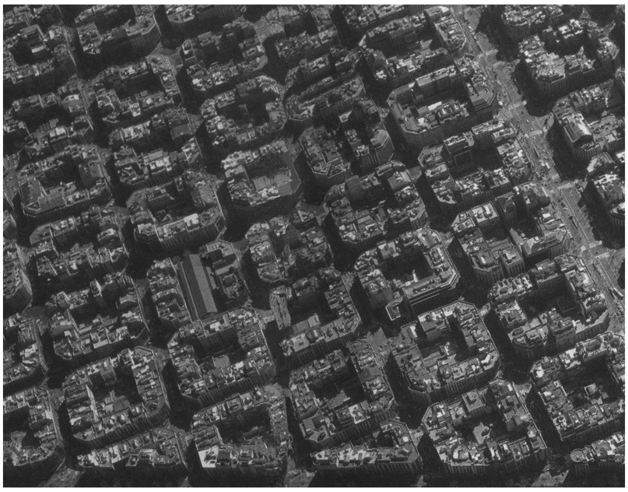

Figure 1: Bird's eye view of Eixample

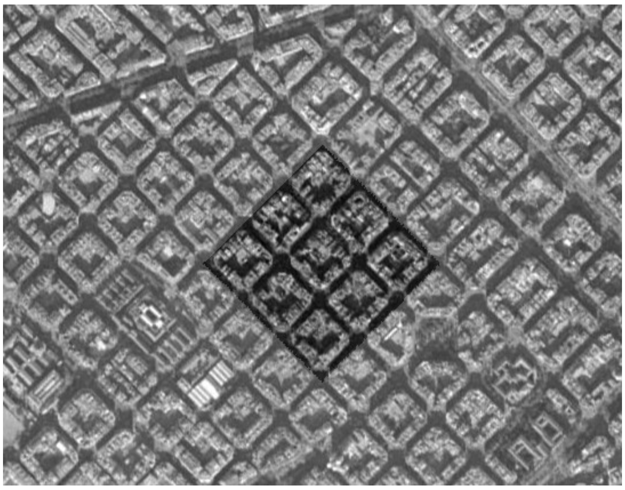

Figure 2: The portion of the district object of calculation

3.2 Construction and approximation of the model

The 3D digital mock-up of the selected area necessary for digital simulation requires a careful process of preparation and simplification. In this study, we used a three dimensional model prepared by the *Laboratorio de Modelización Virtual de la Ciudad* (LMVC) of the Universitat Politèecnica de Catalunya.

Small-scale construction details on the building envelopes (like openings, balconies, chimneys, decorations, mouldings, and so on) were omitted from the model, since their contribution is irrelevant to solar gain at an urban scale and their presence can considerably reduce the computation speed. The main volumes were taken from a 2D topographic plan of the Eixample; the number of floors of each building was known and 3 metres were counted for each one to build their volumes.

Volumes within the same manzana were then merged together (in the scene there will be 9 objects in total), in order to eliminate adjacent overlapping surfaces and to obtain a less complex shape. The vector model built as a DWG file is finally exported as an STL format that reduces the enclosing envelope of the previous volumes to a "list" of triangles identified by coordinates of its 3 vertexes and of its perpendicular.

3.3 Simulation process

With reference to the sample area of the Eixample previously selected, assuming that all the manzanas have the same area of exposure, we only analyse the performance of the central one, while the other blocks simply act as obstructions. Sun paths are simulated in summer (situation a) and in winter (situation b) in 3 different cases (Fig.2):

1) A case of maximum radiation: the surrounding buildings are removed from the scene in order to calculate the *daylight hours* and *potential energy* received with complete absence of obstructions.

2) The real case (urban fabric orientation NO-SE and NE-SO): computation is now performed

including shadows projected by neighbouring buildings.
3) A hypothetical case (urban fabric orientation N-S and E-O): the same process of analysis is repeated, considering the Eixample's grid with a rotation of 45 degrees clockwise with respect to the original one.

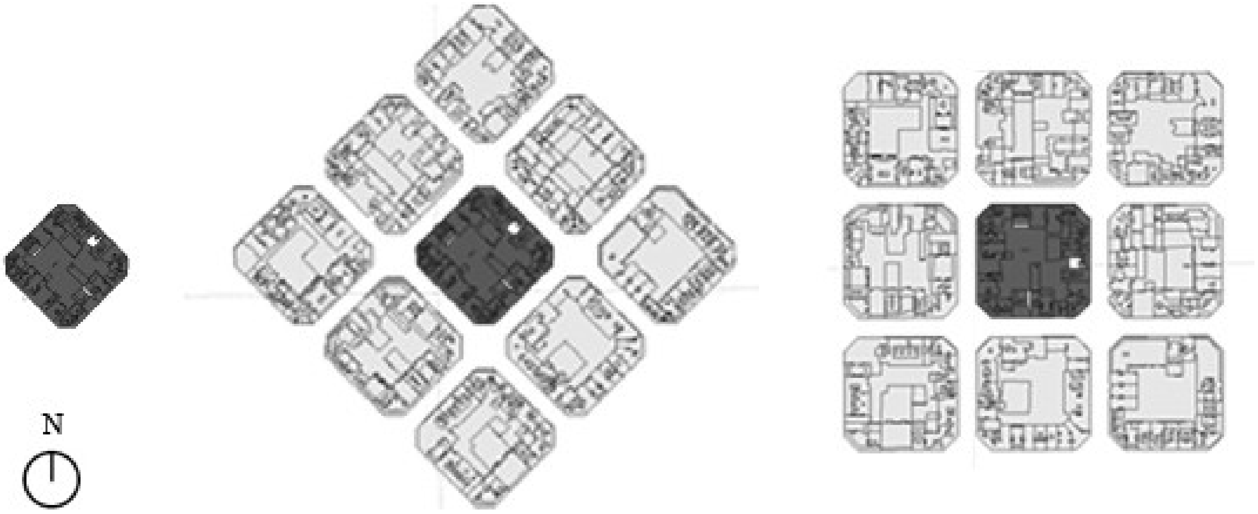

Figure 3:The 3 situations analyzed, from the left case 1, 2 and 3

3.3.1 The Heliodon 2 software

The digital tool we improved is *Heliodón 2*, a solar path simulation software that allows fast interactive energetic and visual control of natural lighting, providing clear and immediate information about spatial and temporal distribution of radiation on building envelopes at a specific geographic site defined by latitude and altitude (B. Beckers and L. Masset 2009).
The program considers direct and diffuse components of illumination separately. Reflection factors of surface materials are not specified, which means that specular and diffuse indirect contributions due to the surrounding elements are not taken into account.
With respect to the direct component, Heliodón 2 considers maximum balances of incident radiation, without subtracting any losses due to cloudiness, but acting as if the sun were shining during the whole year. In this study, the attention will focus only on this component of the sun.
Compared with other lighting and thermal simulation software, this one does not refer to theoretical sky models or require climatic data to be entered, but instead it provides absolute information strictly linked to the geometry of the objects. Therefore, the statistical input data inserted are reduced and the calculation is simplified in terms of time and technical costs. Herein lies the versatility and robustness of the product.
Evidently, hours of exposure and values of collected energy are therefore very optimistic and do not correspond to reality. Actually, Heliodon 2 has no diagnostic aim, but is rather aimed at making *comparisons* between situations. Consequently, the assumptions described above do not affect the reliability of the final results.
Heliodón 2 uses an *isochronal projection* to represent solar provision in a specific scene: while stereography provides only instantaneous information, in these graphics hours (X axis) and months (Y axis) are equidistant. This property allows solar flux (kW/m^2) to be integrated during an interval defined by the user, in order to obtain corresponding balances of solar energy (kWh/m^2). The accuracy of the final results depends on the frequency of calculation in the given duration; in this case, the default value of 15 minutes represents a good compromise between precision of output data and technical tools available for computation.

External surfaces in the scene are discretized by a regular virtual mesh of points, whose mutual distances can be regulated manually. In the current example, a width of 1.4 m seems to be sufficient for the scale of the project. According to the fixed frequency, Heliodón 2 computes a long series of data about instantaneous solar radiance at the nodes; mean values are then aggregated and elaborated to obtain a *cumulative distribution* of daylight hours (h), local flux (kWh/m2) and total energy (kWh).

3.4 Overall quantitative comparison and qualitative cross-analysis

Potential contribution of direct solar radiation is quantified and compared in the 3 different cases using graphical and numerical values of *sunny hours* and *energy* collected for the whole block.

The overall results are then complemented by specific information on the evolution of solar radiance and the percentage of energy loss in significant single portions of the envelope, such as external and internal façades and roofs. These data express the *qualitative distribution* of incident radiation and allow us to find more specific relations between position, dimensions and other formal features of exposed surfaces and their orientation, in both winter and summer.

4. RESULTS

Table 1: Global results; enegy and sunny hours collected by the whole block in winter and summer

	Overall energy gain (Mwh)	Overall energy gain (GJ)	Maximum sun flux (Kwh/m²)	Maximum sun flux (MJ/ m²)	Maximum sunny hours (h)
Case 1a	8412	30284	567	2041	1289
Case 2a	8194	29500	567	2041	1289
Case 3a	8133	29280	567	2041	1289
Case 1b	3390	12203	304	1094	921
Case 2b	3090	11123	304	1094	921
Case 3b	3213	11567	304	1094	921

4.1 Solar radiation distribution and influence of cast shadows

Comparing case 1 with case 2 (Table 1), it was foreseeable to find that the presence of obstructions in the immediate surroundings of the block represents a concrete obstacle to solar access that reduces total energy gains. Losses are greater in winter (-8,9%) than in summer (-2,6%) because of the different height of the sun on the horizon (in Barcelona, 23 and 72 degrees at 12.00 h at the winter and summer solstices, respectively).We also observe in the Figures 4 and 6 that the highest values of solar flux are always detected above horizontal surfaces during the summer (567 kWh/m^2) and above south-facing vertical surfaces during the winter (304 kWh/m^2). This is because radiation always depends on the angle of incidence: at 0 degree angles no radiation corresponds, while for 90 degrees ones the maximum value is received.

The Table 1 also show that both sun flux and sunny periods on roofs and internal façades are the same, regardless of external obstructions. Actually, the only parts of the envelope affected by shadowing of surrounding blocks, in both seasons, are the exterior façades of the *manzana*; of course, amount of radiation received is proportional to the height of the building (Figures 4 and 6).

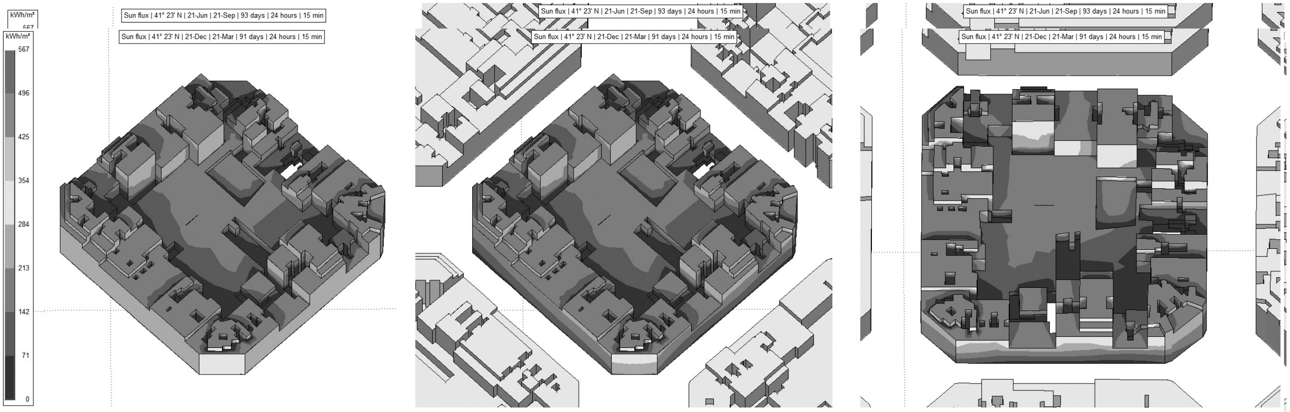

Figure 6: Distribution of sun flux in the cases 1b, 2b, 3b. View from the South

The large surface of the central patio, provides the most consistent contribution to solar energy gain, though it is partly shaded by high surrounding buildings. Distribution of solar flux and sunny periods are inhomogeneous, with maximum values concentrated in the centre and progressively decreasing toward the lateral parts.

4.2 Influence of urban fabric orientation

Numerical results (Table 1) demonstrate that a 45-degree rotation of the Eixample's urban fabric produces an overall increase in solar energy gain in winter (+4%), when energy and daylight demand is higher in Barcelona. In fact, with the N-S and E-O orientation, a larger vertical surface is facing exactly south and, despite the presence of obstructions, it works as a energy collector. On the other hand, in case 3b (Figures 6 and 7), one of the long sides of the manzana is exposed to the north, which means that 23% of total surface of the exterior façades receives no direct radiation throughout the whole season (sunny hours = 0).

In summer, a different process is instead detected: for the same block, seasonal gains fall slightly from 8194 MWh in case 2a to 8133 MWh in case 2b (about -1%).

Actually, this decrease is almost inappreciable because, as stated above, during the hot season greater amounts of energy are provided by horizontal surfaces, which are not affected by shadows of surrounding buildings even in this situation: the graphical distribution shows, in fact, that maximum values of sunny period (1289 hours) are detected above the roofs in both cases (Figures 5 and 7). Positive or negative contributions of the other portions of the envelope probably have a secondary importance, which is why the overall balance is almost unchanged.

4.3 Distribution of solar flux on the external façades

Tables 2, 3, 4 and 5 show results for the sunny period and total energy on the 4 long sides and the 4 chamfers of the manzana, according to their surface and orientation. We immediately observe that with a 45-degree rotation , exterior façades are definitely more affected by the influence of obstructions compared with case 2, in both summer and winter (cases 3a and 3b) .

During the winter, the average local flux on the south façade falls from 0.27 to 0.19 MWh/m^2, and the average sunny period from 617 to 469 hours (Tables 4 and 5). This means that this side has less possibilities of enjoying direct solar access, even if its final contribution in terms of energy is higher than that of the previous case (259 versus 97 MWh), thanks to the surface available to radiation, which is about 4 times bigger than before. A similar performance is detected on the east façade, while the SO and SE sides show an opposite process (more sunny hours, but a smaller area exposed).

The total amount of solar energy stored by the exterior façades is 7% lower than in the real situation. If we assume, as mentioned above, that the behaviour of horizontal surfaces is fairly constant, how can we explain the overall increase obtained in case 3b (Table 1)? We deduce that the highest gains come from interior façades, especially from the south-facing one, whose contribution not only compensates for losses by the exterior vertical envelope, but also gives an extra provision of solar energy.

In summer (Tables 2 and 3), solar access in the hypothetical situation (case 3a) is instead reduced on the east and west façades with respect to the real situation (case 2a). In fact, sunny hours decrease respectively from 511 to 394 and from 549 to 428, even if their final energy contributions are still consistent.

The north side is more exposed (272 versus 108 hours of direct radiation), while on the other parts the values of local flux remain almost constant. The highest energy losses are basically recorded on the SO and SE chamfers, due to their small surface area. The balance of energy contributions provided by all vertical exterior components in case 3a is overall 14% lower than in case 2a. In other words, in summer, the influence of external obstructions is accentuated and the internal façades fail to compensate for energy losses due to shadowing.

Table 2: Sunny hours and energy gain on exterior façades (Case 2a)

Façade	Surface(m^2)	Orientation	Sunny hours (h)	Energy gain (Mwh)	Energy gain (GJ)	MWh/m^2	GJ/m^2
F.1	1733	SO	613	380	1368	0,22	0,79
F.2	1394	SE	614	307	1105	0,22	0,79
F.3	1759	NO	357	152	549	0,09	0,31
F.4	1240	NE	306	94	338	0,08	0,27
C.1	357	S	829	77	278	0,22	0,78
C.2	239	N	108	1	5	0,01	0,02
C.3	335	E	511	70	252	0,21	0,75
C.4	461	O	549	99	356	0,21	0,77
Overall energy gain				1181	4250		

Table 3: Sunny hours and energy gain on exterior façades (Case 3a)

Façade	Surface (m^2)	Orientation	Sunny hours (h)	Energy gain (Mwh)	Energy gain (GJ)	MWh/m^2	GJ/m^2
F.1	1733	O	428	281	1012	0,16	0,58
F.2	1394	S	890	307	1106	0,22	0,79
F.3	1759	N	272	24	87	0,01	0,05
F.4	1240	E	394	185	666	0,15	0,54
C.1	357	SO	655	86	309	0,24	0,87
C.2	239	NE	337	20	73	0,08	0,3
C.3	335	SE	602	75	269	0,22	0,8
C.4	461	NO	336	38	136	0,08	0,29
Overall energy gain				1016	3656		

Table 4: Sunny hours and energy gain above exterior façades (Case 2b)

Façade	Surface (m^2)	Orientation	Sunny hours (h)	Energy gain (Mwh)	Energy gain (GJ)	Mwh/m^2	GJ/m^2
F.1	1733	SO	462	254	913	0,15	0,53
F.2	1394	SE	450	198	712	0,14	0,51
F.3	1759	NO	121	12	43	0,01	0,02
F.4	1240	NE	112	8	30	0,01	0,02
C.1	357	S	617	97	348	0,27	0,98
C.2	239	N	0	0	0	0	0
C.3	335	E	310	24	88	0,07	0,26
C.4	461	O	253	26	92	0,06	0,2
Overall energy gain				618	2225		

Table 5: Sunny hours and energy gain on exterior façades (Case 3b)

Façade	Surface (m^2)	Orientation	Sunny hours (h)	Energy gain (Mwh)	Energy gain (GJ)	MWh/m^2	GJ/m^2
F.1	1733	O	304	113	406	0,06	0,23
F.2	1394	S	469	259	932	0,19	0,67
F.3	1759	N	0	0	0	0	0
F.4	1240	E	249	67	241	0,05	0,19
C.1	357	SO	524	68	245	0,19	0,69
C.2	239	NE	44	1	3	0	0,01
C.3	335	SE	518	65	233	0,19	0,7
C.4	461	NO	51	1	5	0	0,01
Overall energy gain				573	2064		

5. CONCLUSIONS

5.1 Importance of temporal and spatial distribution of solar radiation

Studying solar access at an urban scale does not simply mean carrying out a general cumulative analysis. Influence of obstructions cannot be evaluated only in terms of overall amounts of energy or sunny hours: these quantitative “absolute values” are important, but by no means exhaustive, because information also needs to be organized in relation to *space* and *time* in order to be really significant.

Concerning the aspect of time, of course solar radiation changes during the year, as does its relationship with the built environment, so it is essential to study its evolution in different seasons separately. Moreover, according to the location, radiation may or may not be perceived as appreciable by the citizens: in fact, in a Mediterranean climate like that of Barcelona, reduction of sunlight and building overheating are generally required in summer. Consequently, in the Eixample, the presence of obstructions is not always considered to be negative.

It is also important to know the effective spatial distribution of solar radiation above the envelope. In the study case, shadows concentrate on exterior façades, while solar access on the roofs and on the interior surfaces is not affected by external obstacles.

This behaviour immediately allows one to recognize some of the typical formal features of the Eixample's urban fabric: the height to width ratio and the regular skyline of the blocks ensure total exposure of the roofs, which offer a large surface potentially exploitable for an active use of the sunlight.

If we move instead from the urban overview to the scale of a single manzana, we individuate a “ziggurat” shape (Busquets, 1992) along its outer profile, due to the difference of 1-2 floors between adjoining buildings. Losses of solar energy due to this smaller-scale formal detail may be irrelevant with respect to overall gain, but become determinant—and must be taken into account—if, for example, it is desired to install technical solar devices.

Dimensional and formal proportions within a single manzana also affect the performance and potential exploitation of its envelope. The relation between the height of the buildings and the distance between opposite sides of the block, similarly to the H/W ratio, represents a key formal parameter for controlling interior shadows. The central patio could recover its original function as a public, green, sunny space or adopt one of technical use of the sun, while the vertical façades could provide an equitable daily amount of direct radiation to the interior spaces.

Issues regarding solar access in the Eixample district highlight the importance of checking both general and specific situations and maintaining a continuous *transversality between the different scales of the project*—in this case the urban fabric, the single block and its individual components.

Such an approach is not only valid for this specific case, but can also be considered as a general criterion of analysis, aimed at achieving a thorough understanding and a correct interpretation of solar energy phenomena within the urban fabric.

5.2 Fabric orientation and façades exposure in different directions

In terms of overall energy gain, the hypothetical configuration seems to be particularly suitable in both winter and summer. Actually we also demonstrated that this is not true at all, because the entire north side of the block (exterior and interior) is completely shaded during the whole cool season.

If it were possible to transfer the concept of manzana from an urban to an architectural scale, in other words if the manzana were a single dwelling, this situation would be positive, because lack of direct radiation on the north side would be compensated by that on the other façades. However, the apartments in the Eixample often do not have a double external façade, so individual passive use of sunlight would be denied to all north-facing dwellings.

The orientation defined by Ildefons Cerdà's Plan was precisely aimed at ensuring that all the façades (except, of course, the small north chamfer) receive at least one hour of direct radiation on 21 December and this is still true, despite the strong densification of the urban texture that occurred during the years of building speculation.

The new direction of the streets definitely does not fit with the Eixample's morphological structure, but this does not mean that it could not work instead in another situation: combined, for example, with a different articulation of the volumes or with a differently-sized urban fabric, the N-S and E-O orientation can offer very good results with respect to solar access.

In the early phases of the planning process, calculation of façade surface area in each direction (Compagnon, 2004) and its relation to the corresponding energy potential offers important additional information that is helpful for evaluating solar performance and determining

5.3 Observations about tools and methodology

The application of the Heliodón 2 software has given a fairly positive and reliable feedback in this first step of the research. Of course, some points of the method need to be refined—especially regarding construction and management of a three-dimensional model, which should be more accurately simplified—in order to obtain more specific and versatile results.

Moreover, we also have to keep in mind that the amounts of collected energy calculated by the program are potential theoretical values; they are useful for evaluating and comparing different scenarios, but in practical applications they need to be suitably translated into effective quantities, taking into account real meteorological data. This point needs to be more investigated and represents another interesting issue of the research.

Overall, the *comparative methodology* seems to offer interesting opportunities for research at an urban scale. The simplicity of the process, the speed of computation and the immediacy of the information provided suggest the possibility of extending its application to other high-density cases and considering other morphological variables, in order to compare performances of different urban forms with respect to solar availability and to obtain useful tips for future planning decisions.

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