Solar access in densely built urban environments

Formal parameters and comparative methodology in the case of Barcelona, Spain

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ABSTRACT: : In what direction is the historical debate on contemporary cities evolving, in this age of sustainability? How are renewable energies and solar energy in particular being incorporated into urban settlements? To date, researches mainly focused on urban density, while less attention has been paid to the spatial properties of the built environment. In this study, we compare the performance of urban fabrics of similar building intensity in Barcelona (Spain) to investigate the extent to which morphological features of the built environment can affect sun collection on the buildings envelope, in order to define new formal guidelines for a "solar" design of urban planning. The available technical tools for solar radiation analysis are not really suited to an urban scale or to the early stages of the planning process. Therefore, we apply a simplified comparative methodology supported by Heliodón 2 simulation software, we intend to provide a new methodological and operational tool which allows fast interaction between solar radiation and the urban design process. The present paper is an early step in an on-going PhD thesis. In the first section we describe the general approach, the objectives and the method. In the second section, we present the application of this method to the Eixample district and the results. In this preliminary study, we focus on one of the spatial characteristics of the urban fabric in particular - the orientation of the street network.

Keywords: solar access, high-density urban fabric, morphological parameters, comparative analysis, Heliodón 2

1. INTRODUCTION

The rapid and uncontrolled sprawl of contemporary cities has environmental and social costs that have become unsustainable and it is now widely recognized that large-scale approach to this problem and a new urban model are required [1].

The following two factors have a bearing on this issue. Firstly, scarce land availability leads to densification of the city. Secondly, as there is an urgent need for a reduction in fossil fuel consumption, natural energies must be considered. The sun is the main source of natural energy, due to its size and the fact that it is pretty uniformly available in space and time,

Many studies have been carried out on the integration of solar energy into cities. In 2000, the International Energy Agency created the Solar City® program which is a model of development that promotes the systematic integration of renewable energy technology into urban communities [2].

Before this official initiative, the solar issue had already caught the attention of architects and engineers. In the 1970s, P. Soleri, strongly criticized the waste of energy in of megalopolises and introduced the concept of Two Suns Arcology, a specific exploration of solar effects in relation to urban and architectural design [3].

About 20 years later, C. J. Winter described solar city as "an energetically self-contained settlement with solar irradiance as its main energy source" and considered what this big "energy converter" would look like and how it would have to be designed [4]. In others words, he wondered what the aesthetics and spatial organization of the urban fabric would be like in a solar city and which formal solutions would most optimize the individual, technical and social use of the sun [5].

The relation between site layout and solar access is strict and complex and, obviously, becomes more conflictive in urban situations in which building is more intense. Studies of the morphological structure of urban fabric and its solar radiation performance could provide important new input for the design process from a solar perspective.

Solar issues should be fundamental requisites for architects and urban designers from the first steps in the design process. To achieve this, suitable operational instruments are needed. Although considerable computational and technological advances have been made in recent years, previous studies on solar performance at urban scale show that further research is required in this area.

The current study aims to provide new formal materials as well as specific tools for developing a new conception of solar urban design.

2. BACKGROUND

2.1. Physical density and urban form

Since the nineteenth century, the debate on cities focused on the difference between compact and dispersed models. The concept of density has been stressed in particular, and has become one of the main operative parameters in the planning process. Less attention has been paid to urban form, i.e. the spatial structure that supports the inhabitants and their activities [6]. The morphology and typology of the urban fabric are an interesting topic to study as an additional tool in the design process [7].

In general, density is a ratio that expresses the mass of some entities in a given environment. It is a point measure of the quantitative characteristics of the city, such as population, the number of trees or dwellings and the land occupation, normalized by some measure of the area they occupy [8]. In this paper, we refer to density as built mass intensity as this is the only aspect that affects the study of solar access.

However, built mass intensity does not fully describe an urban environment, since it does not take into account the physical characteristics. In fact, we can easily demonstrate that areas with a similar building density may have a highly variable spatial layout.

Research into the links between quantitative and qualitative properties of the urban fabric explores additional possibilities of action in relation to challenges from the new sustainable urban vision.

2.2. Digital tools for solar analysis at urban scale

Solar radiation analysis at city level is a research area that can be considered pretty recent.

The main problems are related to the high number of variables that interact at urban scale and to the consequent difficulty in reproducing, drawing up and combining all of them in a concise and reliable way. For example, some kinds of approximations need to be made, as it is difficult to create precise digital mock-ups of the urban environment and to reproduce sky vault and cloudiness models [9] [10].

Furthermore, most of the solar simulation software that is used today come from the field of digital graphics and aims to create a completely realistic representation of lighting effects on the scene, while aspects related to the design are of secondary importance [11]. In practice, such programs require a large amount of specific input data and take a long time to draw up and calculate.

Clearly, this kind of approach cannot be used in the early stage of the planning process when the design has not yet been fully defined and different options still need to be compared and evaluated. Therefore, it is essential to define new operative instruments that allow fast interactive handling of solar radiation and urban design decisions [12].

3. OBJECTIVES

3.1. Urban morphology and obstructions

The first general goal of this study consists in evaluating how and how much the geometry of the urban fabric affects the potential use of solar radiation to establish the “operating margins” and the contribution of the architects who work on sustainable designs.

Firstly, the aim is to identify the morphological parameters that influence solar access in the city and to study their behaviour and mutual relations. This operation leads to the definition of a general conceptual framework for the project, a reference “database” of formal tools that can easily be used and adapted to different environmental situations.

At the same time, the specific information that is deduced from the analysis of existing cases will be used to draw up morphological and typological guidelines and specific design solutions for new solar urban interventions in Barcelona or in other geographic locations with similar climates.

3.2. Definition of new methodological references for the urban project

The second objective of this research is closely related and complementary to the previous one. In this step, the aim is to introduce a new operational and methodological protocol for the design of solar settlements.

More specifically, the potentiality and the reliability of a comparative analysis will be improved trough a solar radiation study performed at urban scale, using a specific simulation software. This kind of approach enables us to reduce the input data, to simplify the calculation process and to focus on the formal aspect of the problem only. In practice, we aim to check whether these operational features affect the rigour and usefulness of the final results.

The last goal is draw up a general method that can guide and support formal decisions during the early phases of the solar design process and that can be used repeatedly in generic urban cases.

4. APPROACH AND METHODOLOGY

This research is based on a comparison of different homogeneous urban fabrics in Barcelona, whose solar performance is studied using Heliodón 2, software that has been specifically developed as a decision tool for designing with daylight availability [13]. The method is divided into 3 main steps. To date, we have fully developed the first of these steps.

4.1. Selection of cases to study

To reduce the number of variables to the formal parameters only, the analysis needs to be limited to comparable urban fabrics, i. e. cases that have the same or similar building intensity. This characteristic was evaluated using the Floor Space Index (FSI), which quantifies the amount of floor space in relation to the gross land area [14].

Using the same approach, Compagnon studied the solar and daylight availability of an urban area in Fribourg (Switzerland). He kept the FSI (here called the plot ratio) constant and checked performance of different hypothetical configurations [15].

Using these assumptions, we identified 4 homogeneous sectors in Barcelona (in the Eixample, Ciutat Vella, Poble Sec and Gracia districts), that all have a FSI between 2.65 and 3.13 (Fig. 1). The maximum difference between the highest and the lowest value was 0.48 points, a gap that was acceptable for the scale of the study.

Solar shading analysis and calculations will be only carried out for a suitable sample of each homogeneous area. For each sample, we created a 3D digital mock-up, using the cadastral information available.

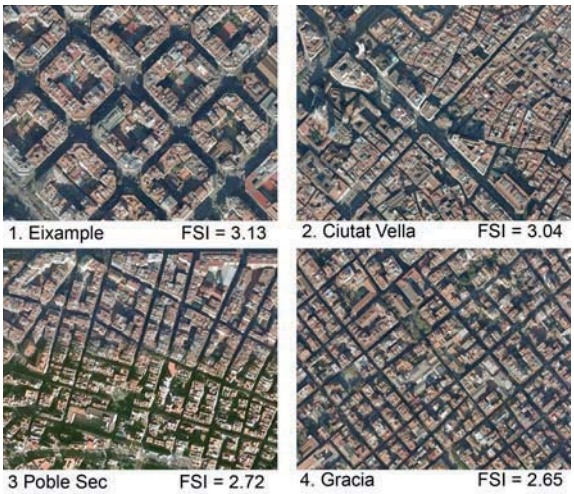

Figure 1: The study cases and their FSI

4.2. Solar radiation simulation process

Heliodón 2 is a program that simulates the sun's paths at a specific geographic site and provides graphical and numerical information about the evolution and the distribution of solar radiation over exterior buildings surfaces, taking into account the shadows cast by neighbouring obstructions.

Compared with other lighting and thermal simulation software, Heliodón 2 does not refer to theoretical sky models or requires meteorological data, as solar radiation is determined by a calculation algorithm based only on the direct component and corresponding to clear sky days [13]. In fact, Heliodón 2 has no diagnostic aim, but provides absolute information that is closely linked to the geometry of the objects.

The performance of the 4 samples will be compared separately in the summer (21 June-20 September) and in the winter (21 December-20 March). The potential contribution of solar radiation is computed by Heliodón 2 through a long series of data on instantaneous solar radiance (kW) at specific points of the envelope. The mean values are then integrated for the previously established interval to obtain the cumulative distribution of solar energy collected (kWh) by the whole envelope and the amount of sun flux (kWh/m^2) on every single element of the building. The program also provides information about the distribution of daylight hours (h) received by every external surface.

The element of reference will be the central block of the sample area, while the rest of the built environment simply will act as an obstruction.

Overall data referring to the whole block are complemented by specific data on the solar performance of single portions of the envelope, i. e. façades and roofs, according to their orientation or position. Various pieces of Information, such as the lighted surface ratio (%), the hour-by-hour evolution of solar radiance (kW) and of solar energy collected (kWh) describe the qualitative distribution of incident radiation and enable us to identify specific aspects.

A comprehensive picture of the solar performance of the different urban plots can then be obtained by comparing the overall and local results.

4.3. Data analysis and methodology review

An analysis and comparison of data from the 4 samples will allow us to identify common points and tendencies related to the spatial properties of the urban fabric. Using the suitable devices, we will transpose the information from the specific to the general case, in order to draw up a “catalogue” of morphological variables that are classified according to their performance and interaction with solar access.

Within this general scope, specific design solutions, typological and dimensional, standards and application examples will be provided for Barcelona. These guidelines will constitute a practical and basic “handbook” to guide architects and urban designers in the early decision steps of the design project.

The final methodological review will be used to make any adjustments that will be needed to optimize the comparative analysis process applied to urban design. Sequential steps of the general methodology will then be specifically illustrated and collected in a “user guide” that, together with the conceptual and formal references described above, will complete the “solar tool box” that this study aims to provide.

5. PRELIMINARY CASE STUDY: EIXAMPLE

In this section, we present early results that refer to the case of the Eixample's urban fabric. This is a preliminary study to check the comparative approach at urban scale and to assess the suitability of the simulation software.

The Eixample district occupies a surface area of 748.5 hectares. It is one of the smallest districts of Barcelona, but with an FSI of 3.13, it is the densest built sector of the city.

Cerdà’s 1859 Plan for the district involved a regular formal structure, consisting of an array of quadrangular chamfered blocks (called manzanas) with sides 113.3 m long defined by a grid of orthogonal streets 20 m wide. The buildings, whose height was limited to 16 m, should only have occupied two sides of the block, to provide 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 and occupied almost the entire manzana.

The street canyon geometry and pattern orientation established by Cerdà (NO-SE and SO-NE) were devised to control shading by surrounding buildings and thus ensure that all dwellings received enough daylight and natural ventilation. Therefore, Cerdà’s city concept recognized the importance of sunlight and daylight availability in an urban context [16] and consequently, we tested the performance of this urban fabric with respect to solar access.

5.1. Street network orientation analysis

In the preliminary case, we focused on the street network orientation, as this is one of the specific and clearest characteristics of the Eixample. We compared two different cases, in the summer (situation a) and in the winter (situation b):

1) The real case (urban fabric orientation NO-SE and NE-SO)

2) A hypothetical case with a rotation of 45 degrees (urban fabric orientation N-S and E-O)

Due to the regular structure of the Eixample, it was easy to select a study sample area of 9 blocks symmetrically placed in a 3 x 3 square (Fig. 2).

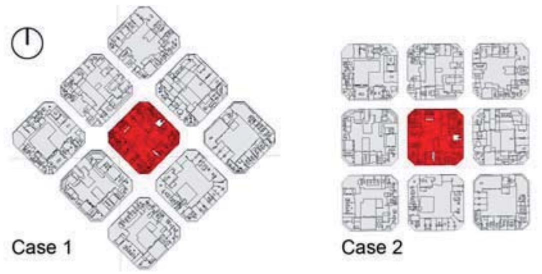

Figure 2: The two orientations of the street network.

5.2. Quantitative overall results

A first observation of overall results (Tab. 1) shows that the hypothetical situation appears to be the most efficient. In fact, the numerical values demonstrate that a 45-degree rotation of the Eixample's grid produces an overall increase in solar energy gain in the winter (+4%). This is because a larger vertical surface faces exactly south with the N-S and E-O orientation, and works as a large energy collector. The maximum values of sun flux (304 kWh/m^2) were detected on the same façade, due to the steep inclination of the sun's rays (23 degrees at 12:00 h at the winter solstice) (Fig. 3).

Table 1: The two orientations of the street network

Cases	Overall gain (Mwh)	Max sun flux (kwh/m^2)	Max sunny hours (h)
1a	8194	567	1289
2a	8133	567	1289
1b	3090	304	921
2b	3213	304	921

In the summer, we detected contrasting performance, since the seasonal gains fell slightly from 8194 MWh in Case 1a to 8133 MWh in Case 2a (about -1%). Actually, this decrease was almost inappreciable as the greater angle of incidence of the sun's rays (72 degrees at 12:00 h at the summer solstice) meant that highest energy contributions were made by horizontal surfaces, never affected by shadows from surrounding buildings (Fig. 3). In fact, the maximum values for the sunny period were detected just above the roofs both in the summer (1289 h) and in the winter (921 h) (Fig. 4 and 6).

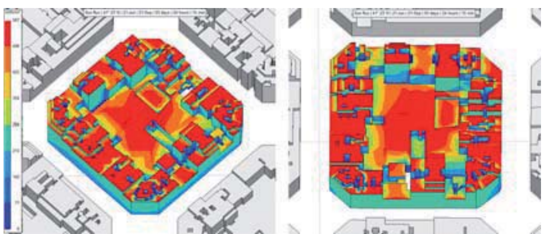

Figure 3: Distribution of sun flux(kwh/m^2) in Cases 1a-2a

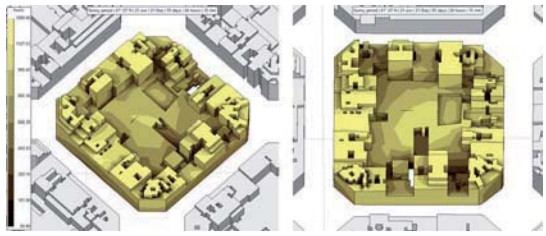

Figure 4: Distribution of sunny hours in Cases 1a-2a

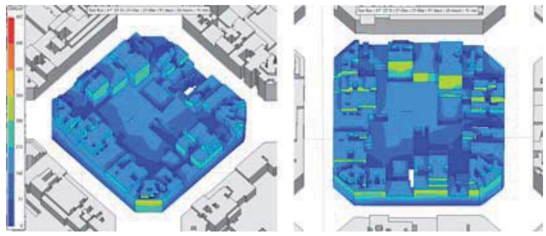

Figure 5: Distribution of sun flux(kwh/m^2) in Cases 1b-2b

Figure 6: Distribution of sunny hours in Cases 1a-2a

5.3. Distribution of radiation on external façades

If we consider now data for single portions of the block, we observe that the exterior façades (F.1-F.4) and chamfers (C.1-C.4) are more affected by the influence of obstructions with a 45-degree rotation.

In 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 drops from 617 to 469 hours, which means that this side of the buildings has less possibilities of enjoying direct radiation. However, the final energy contribution of this façade is higher than that of the previous case (259 versus 97 MWh), due to the larger surface available to radiation.

The most unfavourable situation was found for the north sides of the block which do not receive any direct radiation in the winter. If we consider that many of the Eixample's flats only have one exterior facing, this means that a certain percentage of occupants will have no individual use of the sun.

In general, the amount of solar energy stored by the exterior façades is 7% lower in Case 2b than in Case 1b. If we assume, as observed before, that the behaviour of roofs is fairly constant, we can affirm that the greater overall gain of solar energy in Case 2b must come from the extra contributions of interior façades.

In the summer, the solar access in Case 2a was lower on the east and west façades. In fact, the sunny hours decreased from 511 to 394 and from 549 to 428 respectively, even though the final energy contributions were still consistent. The north side was more exposed, while in other parts of the building local flux was almost constant.

The energy contribution of all exterior façades in Case 2a was 14% overall lower than in Case 1a. In other words, the influence of external obstructions was more notable in the summer than in the winter. However, also in Case a the internal façades compensated for energy losses due to shadowing.

Table 2: Solar radiation on exterior façades. Case 1a

F	m^2	Exp.	Daylight (h)	Mwh/m^2	Mwh
F.1	1733	SO	613	0.22	380
F.2	1394	SE	614	0.22	307
F.3	1759	NO	357	0.08	152
F.4	1240	NE	306	0.09	94
C.1	357	S	829	0.22	77
C.2	239	N	108	0.01	1
C.3	335	E	511	0.21	70
C.4	461	O	549	0.21	99
	Overall energy gain (Mwh)				1181

Table 3: Solar radiation on exterior façades. Case 2a

F	m^2	Exp.	Daylight (h)	Mwh/m^2	Mwh
F.1	1733	O	428	0.16	281
F.2	1394	S	890	0.22	307
F.3	1759	N	272	0.01	24
F.4	1240	E	394	0.15	185
C.1	357	SO	655	0.24	86
C.2	239	NE	337	0.08	20
C.3	335	SE	602	0.22	75
C.4	461	NO	336	0.08	38
	Overall energy gain (Mwh)				1016

Table 4: Solar radiation on exterior façades. Case 1b

F	m^2	Exp.	Daylight (h)	Mwh/m^2	Mwh
F.1	1733	SO	462	0.15	254
F.2	1394	SE	450	0.14	198
F.3	1759	NO	121	0.01	12
F.4	1240	NE	112	0.01	8
C.1	357	S	617	0.27	97
C.2	239	N	0	0	0
C.3	335	E	310	0.07	24
C.4	461	O	253	0.06	26
	Overall energy gain (Mwh)				618

Table 5: Solar radiation on exterior façades. Case 2b

F	m^2	Exp.	Daylight (h)	Mwh/m^2	Mwh
F.1	1733	O	428	0.06	113
F.2	1394	S	890	0.19	259
F.3	1759	N	272	0	0
F.4	1240	E	394	0.05	67
C.1	357	SO	655	0.19	68
C.2	239	NE	337	0	1
C.3	335	SE	602	0.19	65
C.4	461	NO	336	0	1
	Overall energy gain (Mwh)				573

6. FEASIBILITY OF THE STUDY AND FUTURE PERSPECTIVES

The analysis of the Eixample that is presented here works as a preliminary test of the formulation, the method and the technical tools used in the on-going research. In this early step, the strengths and weaknesses of the process have been revealed, so that the next stages of the investigation can be optimized. Below, we describe aspects that merit particular attention.

6.1. Spatial and temporal relations

The study of solar access at urban scale does not simply involve a general cumulative analysis. The influence of obstructions cannot be evaluated only in terms of overall amounts of energy or sunny hours: the quantitative values are by no means exhaustive as information has to be temporally and spatially related.

In terms of temporal aspects, the relationship between solar radiation and the built environment changes during the year, which is why it is essential to study the evolution in different seasons separately. Moreover, depending on the location, radiation may or may not be perceived as advantageous by the citizens. In a Mediterranean climate such as that of Barcelona, a reduction in sunlight and overheating of the building are generally required in the summer, which means that the presence of obstructions is not always considered negative.

With regard to spatial features, it is essential to know the effective distribution of solar radiation above the envelope, in other words the “quality” of solar access. The preliminary case shows that, despite the higher winter solar gains in the hypothetical situation, a whole façade is totally shaded throughout the season. Thus, we can conclude that a 45-degrees rotation of the network definitely does not fit in with the rest of the Eixample’s morphological structure.

6.2. The scale of the urban block

The previous analysis shows that the proportions within a single manzana are the main factors responsible for the solar performance and potential exploitation of radiation in the urban fabric.

In the case of the Eixample, the relation between the height of the buildings and the distance of opposite sides of the block functions similarly to the height to width ratio (H/W). In this sense, it represents a key parameter for controlling shadows on interior façades. In addition, the “ziggurat” shape [17] along the outer profile of the manzana (due to a height difference of 1-2 floors) affects the solar exposure of the roofs. A regular number of layers of adjoining buildings would ensure that the maximum surface was potentially available for active use of the sunlight.

In general, the urban block combines all the three-dimensional characteristics of an homogeneous urban fabric (such as the street network, the footprint and the height of the buildings). Thus, the urban block can be considered as the fabric's most representative and significant element [18] and we can focus on the scale of it.

The strict relationship between formal parameters with regard to their solar performance is another important aspect that needs to be properly taken into account, particularly in the definition of specific guidelines and standards for the project.

6.3. Digital mock-up

In the case of the Eixample, we found that too advanced a level of detail in the digital model did not really contribute to the purpose of the research at the scale used. In addition, it was not suited to the computational capacities of Heliodón 2.

Consequently, small-scale details of the building envelopes (such as chimneys, openings decorations and mouldings) were omitted from the mock-up and only the main volumes were included. This kind of approximation does not affect the final results, since the contribution of minor elements in terms of cast shadows and energy collection is not really relevant. We used the same criterion to build the models of the other cases selected.

6.4. Evaluation of tools and methodology

With regard to the simulation software, we must consider several aspects. The simplicity of the process, the speed of computation and the immediacy of the results demonstrate the real potential of Heliodón 2. However, as mentioned above, we must always take into account the fact that the values of solar radiation provided by the program are absolute and not real.

Therefore, the researcher must act to take advantage of these aspects which, if wrongly interpreted, could affect the rigour of the whole study. In this respect, the comparative approach responds perfectly to the possibilities offered by Heliodón 2.

7. CONCLUSIONS

The results of this preliminary comparative analysis were fairly positive and reliable and provide interesting opportunities for the next studies.

More specifically, the study confirms that this method can be used to compare the performance of different urban fabrics to obtain useful tips for future planning decisions.

8. ACKNOWLEDGEMENTS

Supported by the Spanish MICINN under project ENE2009-11540.

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