

# ACE 21

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ACE: Architecture, City and Environment = Arquitectura, Ciudad y Entorno [en línea]. 2013, Año 7, núm. 21 Febrero P. 117-132

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ISSN: [1886-4805](https://doi.org/10.1080/18864805)

Website access: [http://www-cpsv.upc.es/ace/Articles\\_n21/articles\\_pdf/ACE\\_21\\_SA\\_14.pdf](http://www-cpsv.upc.es/ace/Articles_n21/articles_pdf/ACE_21_SA_14.pdf)

UPCommons Access: <http://hdl.handle.net/2099/13010>

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## URBAN LAYOUT AND FAÇADE SOLAR POTENTIAL: A CASE STUDY IN THE MEDITERRANEAN REGION

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Remisión inicial: 04-01-2013

Remisión definitiva: 16-1-2013

**Key words:** Urban building block, street network orientation, urban canyon aspect ratio, vertical solar potential

### Abstract

The access of direct radiation on building façades and the consequent opportunities for the passive use of solar energy mostly depend on the geometry of the urban canyon. The main factors which affect the influence of surrounding obstructions are the *height to width ratio* of the street section and the *orientation* of the urban pattern.

This study aims to investigate the relationship between the two afore-mentioned parameters with regard to the solar energy gains on the different sides of a courtyard block which is taken as a typological case study. The concept of *vertical solar potential* is a useful tool to compare and assess the response of different urban layouts to the thermal and lighting requirements of a Mediterranean climate, in both quantitative and qualitative terms.

The results of the analysis are expected to provide relevant information when formulating early design solutions to improve the solar performance and energy efficiency of urban patterns.

### 1. Introduction

To date, studies and research on the energy efficiency of contemporary cities mainly focused on the contrast between compact and dispersed models, spotlighting on the concept of *density*. This is a quantitative and measurable indicator which provides a neutral characterisation of a generic entity and allows immediate and objective comparisons between different situations.

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Despite its rigorous scientific character, in a real urban context density itself becomes a fairly relative concept which has strong cultural and geographical roots: there is not an ideal density value since human preferences can change according to temporal and spatial coordinates. Furthermore, density does not exhaustively describe the *urban experience*, because it does not take into account the *qualitative attributes* of the spatial structure that daily supports the inhabitants (Lynch, 1990) and affects individuals' perceptions (Rapoport, 1975).

Several older and more recent studies (Martin, 1972; Cheng, 2010; Berghauer Pont and Haupt, 2010) demonstrate that the same building intensity value may exhibit very different spatial organisations. The *form* of the city is therefore understood as a physical environment that expresses the quality of the space through the design and the structure of the *urban pattern* and is manifested in its typological and morphological characteristics in the 3-D space.

The site layout and the distribution of the built volumes effectively affect the comfort and the environmental behaviour of indoor and outdoor urban spaces, as previous research has demonstrated (Ratti et al., 2003; Robinson, 2006; Cheng et al., 2006), and the concept of building intensity is not exhaustive enough to fully assess and seek these features. Instead, a qualitative and formal approach might provide a more relevant contribution and play a crucial role in improving the energy efficiency of a building cluster, particularly with regard to its ability to exploit solar energy, in terms of technical, individual and social use (Kaiser, 1996).

This study precisely examines the relationship between the morphological structure of a homogeneous urban pattern (in terms of street network orientation and urban canyon geometry) and the potential solar access on the building envelope. The attention is specifically focused on the vertical surfaces, considering their possibilities to receive and passively use direct radiation. The selection of a representative existing case study and the analysis of its different configurations can provide interesting topics to discuss regarding appropriate design solutions, in an effort to improve and regulate the solar gains depending on the climatic needs.

## 2. Street network orientation and urban canyon geometry

Within his studies concerning the efficiency of land use, Martin (1972) identifies the *grid* as the main element generating the urban structure, a framework of reference for the development of the city and of its internal relationships. Actually, the establishment of the street network has always been one of the first acts when founding new settlements.

In the several examples of vernacular villages as well as in the ancient Roman and Greek foundational cities, the planning of the grid was most often guided by direct experience and by religious and strategic factors, but the intentionality and awareness of a specific solar orientation are not completely certain (De Pascali, 2008).

More conscious and specific studies concerning the relationship between the planning and design choices and the solar performance of an urban pattern have been developed since the 20th century thanks to the previous knowledge accumulated coupled with the availability of modern techniques to measure and calculate solar radiation.

During the twenties, Rey et al. (see Montavon, 2010) developed a theory based on the relationship between the daylight hours and the corresponding air temperature; more specifically, the *heliothermic axis* was determined as the direction which is supposed to bring the maximal solar thermal contribution and which is defined, therefore, as the optimal orientation of the urban pattern<sup>3</sup>.

About 15 years later, Vinaccia (1943) proposed a different approach aimed at providing an equal amount of sunshine to all four façades of a cubic building. The author demonstrated that to achieve this condition in temperate regions the street network orientation should match the direction of the sunrise on the summer's solstice.

Based on the empirical demonstration by Heiligenthal, Gropius (1977) claimed that a north-south orientation is more desirable than a 45° tilted one because it allows a lower value of height to width ratio (1.5 versus 2), ensuring the same conditions of solar exposure to the façades (2 hours of direct radiation on the winter solstice) while occupying less land. The experiments were implemented and assessed with regard to the city of Frankfurt (50° North latitude), where the analysis refers to a specific type of urban block, namely the row, and the main priority was to get the maximum solar gains throughout the whole year.

Later, in the eighties, Knowles (1981) stressed the importance of the street orientation as one of the main components in the framework for future urban growth aimed at improving the use of solar energy and the quality of life in cities. By comparing the Jeffersonian and Spanish grids in Los Angeles (34° North latitude), the author claimed that the *solar envelope*<sup>4</sup> over a city block oriented on the cardinal points would contain more developable volume than a block built over a diagonal orientation, but that the latter would ensure a more homogeneous distribution of solar radiation within the urban pattern.

Most of the later studies and handbooks generally recognise the N-S orientation, with small deviations of +/- 25-30° (Chrisomallidou, 2001; Littlefair, 2000, as optimal because it provides a large south-facing surface which receives the most solar radiation during the cold season and is easy to shade in summer. This is true in general terms, but what about the condition of the other building façades, such as the east and west facing ones in temperate and hot regions? In this regard, Olgyay (1998) embarked upon a meticulous study of the incident radiation on a vertical surface, considering different orientations at intervals of 30 degrees, in order to assess the optimal exposure (summer/winter) at different latitudes.

Another important consideration to bear in mind is that, in a building cluster, the effective solar gains on a vertical surface are also affected by the presence of facing obstructions. The cast shadowing, in fact, can change significantly according to the spatial configuration of the surrounding streets and buildings along with the variable position of the sun. In other words, not only the street network orientation but also the *urban canyon geometry* have a significant influence on a façade's effective solar potential. The strict and complex interconnection between these two parameters is a key topic worth studying and analysing.

<sup>3</sup> The work quoted by Montavon is: A. Rey, J. Pidoux and C. Bardet (1928). *La science des plans de villes. Ses applications à la construction, à l'extension, à l'hygiène et à la beauté des villes, orientation solaire des habitations.*

<sup>4</sup> Knowles defines the solar envelope as a "container to regulate development within limits derived from the sun's relative motion. Development within this container will not shadow its surround during critical periods of the day".

Compagnon (2004) proposed an interesting method to assess the potential exposure of differently-oriented façades by means of a polar diagram that displays the amount of vertical surface area in each direction weighted by its corresponding sky view factor. The *orientation rose* is an useful tool to evaluate and compare the influence of the obstructions with regard to diffuse radiation, even if the direct solar contribution from different cardinal points is not taken into account.

More recent studies (Strømmandersen and Sattrup, 2011; Van Esch et al., 2012) discuss the effects of the urban canopy design on solar access in northern European regions, highlighting the complexity and relevance of this topic with regard to a building's passive energy use.

This study fits in with this branch of research and aims to assess the solar potential of the building façades within a homogeneous urban fabric, taking into account the joint influence of the grid orientation and the urban canyon *aspect ratio*, the latter being the proportional relationship between its height and its width, as defined by Erell et al. (2011). The purpose of the experimental analysis is to find a *tendential* relationship between these two parameters in order to identify common building performances and formulate tentative guidelines for solar urban design, with particular attention to the Mediterranean climate's seasonal requirements.

More specifically, the main objectives of this study can be summarised as follows:

- To study the growth/decline rate of a building façade's solar potential with regard to its progressive rotation, in the absence of obstructions.
- To evaluate the relative and changing impact of the height-to-width ratio (in terms of percentage of solar radiation loss due to obstructions) according to the different orientations of an urban canyon.

### 3. Case study and methodology

This research deals with the Mediterranean climatic region and the peculiar pattern of the *Eixample* district in Barcelona, Spain (41° 23' north latitude) which has been selected as a representative example of the courtyard block prototype (Figure 1).

Figure 1. Bird's eye view of the *Eixample* district in Barcelona

Source: <http://www.bing.com/maps/>

The configuration of the *Eixample* is characterised by quadrangular chamfered blocks (*illas*) closed along all four sides and accessed by streets. The average height of the front façade along the perimeter of the block is about 20 m. Originally, the courtyard (*pati*) was supposed to be used as a semi-public garden, but the pressures from private owners and building speculation during the sixties led to the construction of one-storey structures in the interior space. The regular layout of the blocks defines a network of streets 20 m wide with a 45° north orientation. The street canyon geometry is fairly regular in all directions and it is characterised by an average height-to-width ratio of about one. This parameter, as well as the other average dimensions of the urban pattern, were determined according to the *Spacecalculator*. The latter is defined as a system of variables calculated using mathematically related experimental data (Berghauer Pont and Haupt, 2005) that is a very useful tool in describing the built space. The numerical values are summarised in the Table 1.

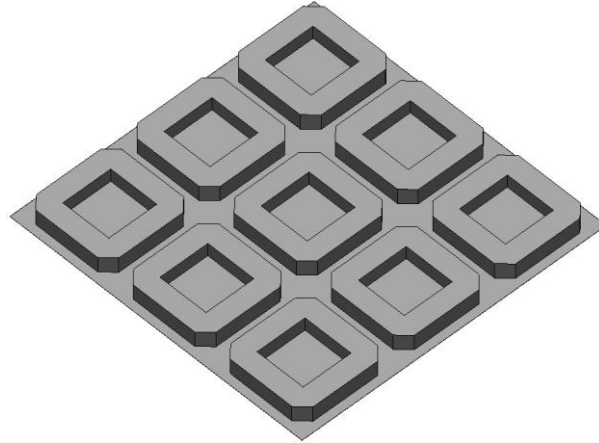
Table 1. Main dimensional features of the *Eixample* urban fabric

Variables	Units	Symbol	Average value
Floor Area Ratio	-	FAR	3,12
Side Length	m	L	113
Front Façade Height	m	H	20
Street Width	m	W	20
Height-to-Width Ratio	-	H/W	1

Source: Authors' own.

In order to avoid all the specificities and morphological irregularities found in a real urban context, which might make the understanding of its solar behaviour difficult, a 3-D digital mock-up (a cluster of nine blocks occupying an area measuring 400x400 m<sup>2</sup>) was built with reference to the typological structure and average measurements of the selected sample (Figure 2).

Figure 2. Axonometric representation of the layout extrapolated



Source: Authors' own.

This research is based on a comparative analysis implemented by means of *Heliodon2*, a simulation software which provides potential data about the cumulative distribution of solar energy collected by the building envelope, taking into account the influence of surrounding obstructions (Beckers and Rodríguez, 2009). In this case, only direct radiation on the external vertical envelope is considered.

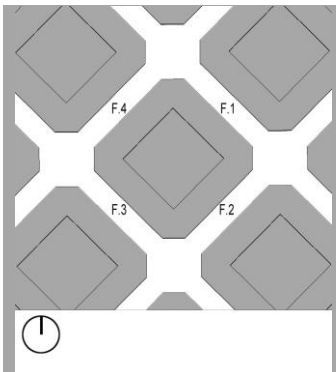
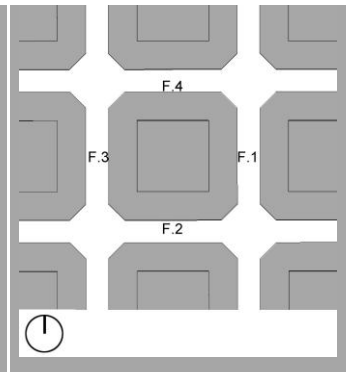
In this case study, the street network orientation was modified, while keeping its height-to-width ratio constant. Two different configurations of the same urban pattern were compared:

- Configuration A: the actual diagonal orientation (N-E/S-W; N-W/S-E)
- Configuration B: a hypothetical orthogonal orientation (N-S; E-W)

Within the selected 3x3 layout, the solar gains for the central block were assessed and its performance was evaluated in both summer (from 21/06 to 20/09) and wintertime (from 21/12 to 20/03). In the first phase of the analysis [1], the simulation was implemented in the absence of obstructions, while, in the second step [2], the surrounding blocks were taken into account in order to estimate the weight of their cast shadows on the façades of the central block.

In summary, the analysis was extended to eight case studies which are listed in Table 2.

Table 2. Summary of cases being studied

A	B	Case study	Layout	Temporal interval	Obstructions
		1.AS	A	Summer	No
		2.AS			Yes
		1.AW		Winter	No
		2.AW			Yes
		1.BS	B	Summer	No
		2.BS			Yes
		1.BW		Winter	No
		2.BW			Yes

Source: Authors' own.

Three parameters are chosen to assess and compare the influence of the grid orientation and of the H/W ratio on the façades' solar potential:

- 1) The *Sun factor* -  $S_f$  (kWh/m<sup>2</sup>) which is the ratio of the direct incoming radiation on a façade and its surface area. The  $S_f$  is used to express the vertical solar potential in each direction.
- 2) The *influence of obstructions* -  $I_o$  (%) which expresses the losses in potential solar energy due to the shadows cast by the neighbouring blocks.
- 3) The *energy gains* -  $E_s$  (MWh) and their distribution on the different front façades of the block.

#### 4. Results

We focused our attention on the long sides of the block (identified as F.1 - F.4) as the chamfers overlook the intersections, central spaces which cannot be described or considered as urban canyons (Erell et al., 2011). Furthermore, the solar collection on the lateral façades is much more considerable than on the chamfers, thanks to the side façades' larger exposure surface (1.694 m<sup>2</sup> each one). The overall numerical results are reported in Table 3.



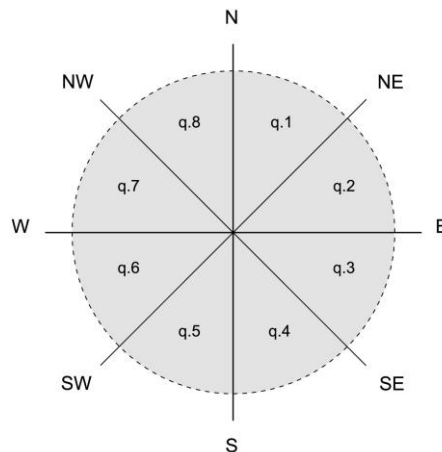
Table 3. Overall results: Winter (left) and summer (right) season

Parameter	Case study	F.1	F.2	F.3	F.4	Parameter	Case study	F.1	F.2	F.3	F.4
		Orientation	NE	SE	SW			NW	Orientation	E	S
Sun factor (S <sub>f</sub> )	1.AW	9	219	219	9	Sun factor (S <sub>f</sub> )	1.AS	108	249	249	108
	2.AW	7	145	145	7		2.AS	86	227	227	86
Energy gains (E <sub>s</sub> )	1.AW	15	371	371	15	Energy gains (E <sub>s</sub> )	1.AS	184	422	422	184
	2.AW	13	246	246	13		2.AS	146	385	385	146
Influence of obstructions (I <sub>o</sub> )		14	34	34	14	Influence of obstructions (I <sub>o</sub> )		14	34	21	21
Sun factor (S <sub>f</sub> )	1.BW	88	297	88	0	Sun factor (S <sub>f</sub> )	1.BS	222	215	222	16
	2.BW	64	199	64	0		2.BS	164	215	164	15
Energy gains (E <sub>s</sub> )	1.BW	150	504	150	0	Energy gains (E <sub>s</sub> )	1.BS	376	364	376	27
	2.BW	108	337	108	0		2.BS	278	364	278	25
Influence of obstructions (I <sub>o</sub> )		28	33	28	-	Influence of obstructions (I <sub>o</sub> )		28	33	26	0

Source: Authors' own.

The outcomes of the analysis are summarised and displayed through a polar diagram model which is divided into eight circular sectors (q.1-q.8) with the same angle extension of 45 degrees and corresponding to different solar orientations (Figure 3).

Figure 3. The polar diagram model



Source: Authors' own.

#### 4.1 The vertical solar potential trend

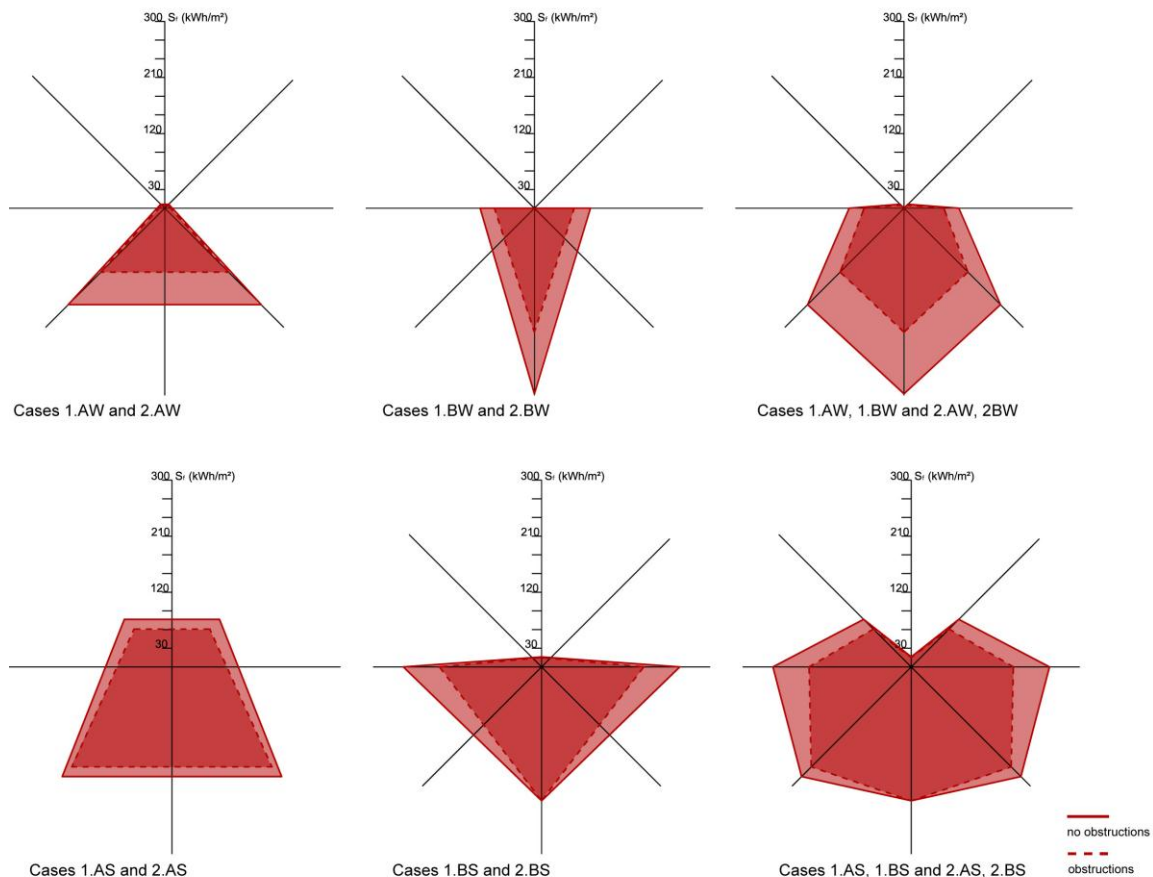
As expected, during the winter season, the vertical solar potential has a non-linear cyclical variation. Within the quadrants q.1, q.2, q.3 and q.4, the value of S<sub>f</sub> progressively grows from 0

to its maximum value on the south direction (297 kWh/m<sup>2</sup>), and then it symmetrically decreases back to 0 when rotating clockwise from the south to the north (Figure 4, above).

By comparing the partial increases of  $S_f$  (%), we can note that the growth rate becomes progressively higher from q.1 to q.3, but drops again between south-east and south. On the opposite half of the polar diagram, the trend is symmetrical: moving counter-clockwise from the north, the decreasing rate is heightened from q.8 to q.6 and drops again between south-west and south. This means that the rotation of a vertical surface from the south to the south-east or south-west orientation produces solar potential losses which are less important compared to those detected between south-east and east or between south-west and west.

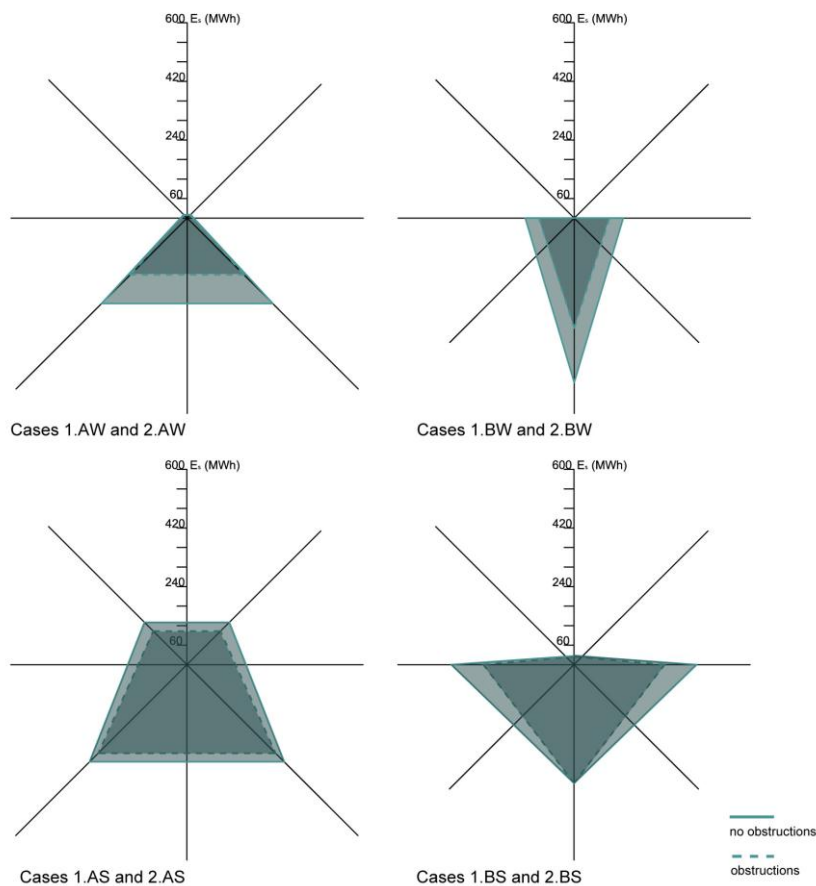
With regard to the total gains, configuration B allows an amount of solar energy to be collected which is greater than A (+4.2% in the absence of the obstructions). This means that, from a quantitative point of view, it is more productive to concentrate the potential gains on the south-oriented surface than to expose two “collector” façades to the S-E and S-W. Instead, if the qualitative performance is considered, situation A ensures a more homogeneous and equitable distribution of the solar gains along the lateral envelope of the block (Figure 5, above).

Figure 4. The  $S_f$  trend in winter (above) and summer (below)



Source: Authors' own.

Figure 5. The  $E_s$  trend in winter (above) and summer (below)



Source: Authors' own.

The façades' solar performance in the summer season is pretty different from their performance in the winter. In the summer case, the highest values of vertical solar potential are found on the south-east and south-west orientations (Figure 4, below); starting at 16 kWh/m<sup>2</sup> on the north side, the  $S_f$  quickly grows in the q.1 and q.2 sectors, reaches its maximum (249 kWh/m<sup>2</sup> in the absence of obstructions) in the south-east direction and reverses this trend in the q.4 sector. Just as before, this trend is symmetrical to the vertical axis of the polar diagram (North-South).

When the surrounding blocks are taken into account, in both seasons, the  $S_f$  function displays a tendency that is analogous to the one that considers no obstructions, even if the values are lower. It is interesting to note that in the summer, the solar potential of the south façade is exactly the same in cases 1.BS and 2.BS (215 kWh/m<sup>2</sup>): this point will be discussed in the next section.

Concerning the energy cumulated by the exterior façades in the summer, layout A ensures an overall amount which is greater than what is provided by solution B: the decrease in  $E_s$  from A to B amounts to 5.6% in the absence of obstructions. In fact, in the first case, there are two

main surfaces (F.2 and F.3) perpendicularly oriented to the directions of maximal solar potential (S-E and S-W); instead, in the latter the south façade (F.2) has a lower solar potential, due to the small angle of incidence of sunrays on it (about 18° at 12:00 p.m. on 21 June).

Situation B once again proves to be more favourable than A, since it provides less solar exposure to the façades; in fact, in a climate like that of Barcelona, protection from direct solar radiation is normally required during the hot months. Therefore, is layout B definitively the most appropriate to meet the changing solar demands of Barcelona throughout the whole year?

In order to give a exhaustive and effective answer, we must analyse the problem at a more complex level, that means introducing and examining the impact of the urban canyon geometry. The *aspect ratio*, in fact, is an important parameter which allows the influence of the shadows cast by surrounding blocks to be controlled and therefore the solar access on the façades to be regulated and improved.

#### 4.2 The influence of the aspect ratio on different orientations

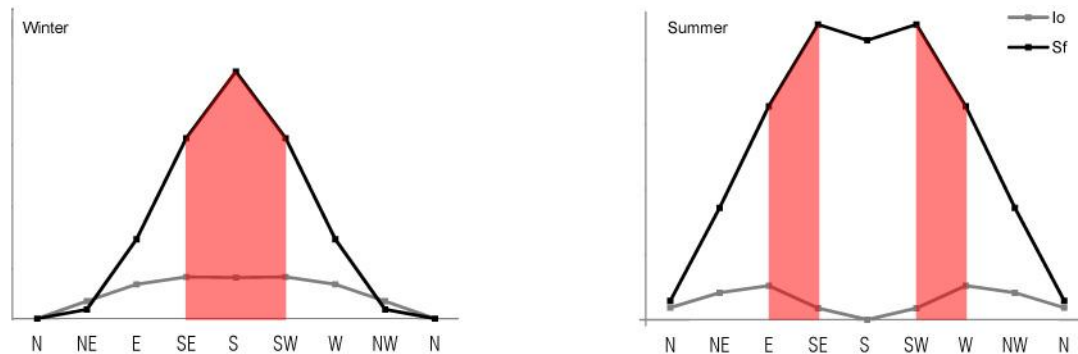
In the urban fabric sample taken as a case study, the H/W ratio has a constant value: it is, therefore, pretty obvious to study how the  $I_o$  changes according to the different façade orientations. The attention is mainly focused on the façades exposed from the east to the west (from q.3 to q.6 in the polar diagram) where the most solar collection is concentrated.

In the winter, the percentage of solar energy loss due to obstructions is almost uniform in the S-E, S and S-W directions, with values ranging from 33 to 34% (Table 3, left).  $I_o$  is slightly lower on the east and on the west sides of the block (28%), and it is half as much on North-East and North-West façades (14%) where the solar potential is lowest.

In the summer, the impact of obstructions is equal on the S-E and S-W façades (9%), but, unlike above, it declines to zero on the south side; in other words, the shadows cast by the surrounding blocks have no influence on this side throughout the whole season.  $I_o$  rises considerably to 26% on the east and west fronts and then maintains a steady value in the N-E and N-W directions (Table 3, right).

The influence of obstructions and the solar potential show a similar tendency curve. Nevertheless, the two trends are opposite between south-east and south-west in the winter, and between east and south-east and south-west and west in summer (see the graphs in the Figure 6).

Figure 6. Comparison between the Sun factor and the influence of obstructions



Source: Authors' own.

In the first situation,  $S_f$  rises while  $I_o$  retains an almost constant value; in the latter, an increase in  $S_f$  is associated with a drop in  $I_o$ . These findings provide interesting and crucial information. In fact, on the one hand, they suggest that an enhancement of winter solar gains might be more easily obtained between S-E and S-W directions (q.4 and q.5 in the polar diagram), while on the other, we can deduce that façades oriented within the sectors q.3 and q.6 should be avoided or, at least, they should be equipped with solar protection devices.

## 5. Discussion: the right combination of H/W ratio and orientation

The overall quantitative analysis of the results shows that the selected urban pattern oriented to the cardinal points provides greater solar protection for the exterior façades during the summer, while at the same time enhancing their potential winter gains, in both the presence and absence of obstructions.

However, from the qualitative point of view, it is necessary to add some important considerations regarding the distribution of radiation and therefore the effective opportunities for a passive use of the sun on the façades. Firstly, in case B two *extreme* local conditions were detected, which are: 1) the total absence of direct radiation on the north-facing side of the block throughout the entire cold season ( $E_s = 0$ ); and 2) the complete exposure of the south façade during the summer months ( $I_o = 0$ ).

Concerning the first point, the most critical consequence for the indoor spaces which only overlook the north side of the block is that they have no chance to enjoy the benefits of direct sunlight just when the thermal and lighting demands are the highest. Actually, this condition is found in several blocks of the *Eixample* district, where the sites' great depth (25-30 m) requires reconsideration of single aspect dwellings. The east and west wings of the block would also have a less favourable orientation compared to the south side.

The second point entails the possibility of improving the solar performance of the façade in winter to some extent. If the south surface is never shaded by the opposite building from June to September, a hypothetical decrease in the aspect ratio in East-West oriented urban canyons

would not modify this performance, but would instead enhance the solar gains during the cold season. In other words, for  $H/W \leq 1$ , we can affirm that the winter and the summer performance of the south façade are *independent*. From the quantitative standpoint, this would clearly provide some improvements, but from the qualitative point of view, the distribution of the vertical solar potential would be even more overbalanced than before, with most of the energy gains concentrated again on the south front of the block.

An identical reduction of the aspect ratio in case A (applied equally to the N-E/S-W or to the W/S-E streets) would certainly improve the winter exposure of the South-East or South-West façades, but it would also affect the influence of obstructions and would increase the solar gains during the hot months.

The crucial goal is, therefore, to achieve independent performance in both seasons, that is to obtain  $I_0 = 0$  in the summer: to get to this condition in a diagonal street network orientation, a lower  $H/W$  ratio would be necessary. In general terms, the bigger the tilt angle of the grid to the north (between 0 and 45°), the broader the range of  $H/W$  values which would affect both seasonal behaviours. In other words, to equalise the solar potential of the S-E and S-W sides with the solar potential on the south side in the winter, a lower aspect ratio would be needed<sup>5</sup>; at the same time, a reduction in the height-to-width proportion would affect the summer gains to a larger extent than in a N-S orientation.

Cases A and B can be considered as the two *extreme* situations. An urban pattern oriented at 45° combined with the absolute regularity of the solar paths with respect to the cardinal points yields a *perfectly symmetrical situation*, which ensures totally balanced conditions for all the façades of the block but reduces the effective amount of energy collected and the leeway to improve *selective* solar performance by means of design tools.

On the other hand, the orthogonal orientation displays more distinctive solar behaviour between winter and summer that appears more suitable to the variable thermal needs of a Mediterranean climate. Nevertheless, it entails some limitations regarding the chance to enjoy homogeneous vertical solar potential.

Given the specific impossibility of making these two conditions coexist in a unique ideal urban layout, we must look for halfway solutions. The results of the research demonstrate that the most adequate street network orientation, under given conditions (e. g. courtyard block,  $H/W = 1$ , temperate climate), should be sought between the S-E and S-W directions (see the 4.2 section). More precisely, orientations within the q.4 sector should be preferred over orientations in the q.5 sector because the air temperature is normally lower during the morning hours so that the east façades need a greater amount of solar radiation compared to the west side (Olgyay, 1998).

With regard to the urban canyon geometry, lower  $H/W$  ratios are more appropriate on north-east/south-west oriented axis and might be achieved by widening the streets ( $W$ ) or by lowering the height ( $H$ ) of the north wing of the blocks. In general terms, the differentiation of the aspect ratio between longitudinal and transversal axes it is not completely effective for 45° oriented

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<sup>5</sup> This result confirms the contents of the previous literature (Gropius, 1955; Knowles, 1981).

grids, but it better fits non-symmetrical configurations, providing maximum benefits for tilt angles equal to zero (N-S orientation).

## 6. Conclusions and future developments

This comparative analysis proves that a more balanced solar performance in the *Eixample* typological configuration might be achieved by slightly rotating the current grid toward south and by simultaneously re-proportioning the N-E/S-W urban canyons.

The implementation of a systematic analysis would make it possible to find a series of *optimal pairs* of H/W values and street network tilt angles within the q.4 sector. This operation would obviously require a univocal system of reference, that is to say a *scientific* criterion to evaluate the *degree of balance* between the quantitative and the qualitative characteristics of the vertical solar potential associated with a certain urban layout. In this regard, it would be interesting to develop a comprehensive *indicator* which compares and synthesises a façade's real energy requirements and its ability to meet these requirements with the solar contribution.

Obviously, with the purpose of future development in this direction, specifications would be necessary. First of all, the diffuse and reflected components of solar radiation should be included, since the urban canyon's proportions and orientation also affect the *Sky view factor* and the urban *albedo*, two aspects which are not considered in the present study.

The structure of the urban block is an additional parameter that should be taken into account when defining a possible synthetic indicator to evaluate the vertical solar potential. In fact, the formal and functional potentialities provided by a specific block typology at urban and architectural scale might improve the effective passive use of the sun and therefore the quality of the solar potential. The *row* typology, for instance, would allow the north-south grid orientation to be taken better advantage of. In fact, with adequate dimensional proportions, it would make it possible to consider for the design double oriented and cross-ventilated dwellings and to avoid east and west façades, providing equal solar distribution to all indoor spaces.

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