Façade design and energy demand: fenestration indexes from an urban approach

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Abstract: Façade design has significant effects on inner conditions of spaces and also on the energy needs to achieve user's comfort. In this regard, the proportion of glazed surfaces to opaque ones plays a key role. Although the link between the fenestration ratio and energy demand for a space has been widely addressed in literature, a considerable number of these studies were based on isolated models, disregarding the effect of the urban surroundings. The aim of this paper is to provide insights on the impact of the window-to-wall ratio (WWR) on thermal energy demands taking into consideration a specific urban context. The *Eixample* district of Barcelona, with Mediterranean temperate climate, has been selected as the case study. Heating and cooling energy needs have been evaluated for a single residential space by means of computer simulations in Design Builder for different positions within the tissue. Results show that, from a thermal point of view, the design of façade openings within an urban context should vary depending on the orientation and the degree of obstruction, as a reflection of the differences in energy balance within the building envelope.

Keywords: Window-to-wall ratio, Mediterranean climate, Energy demand

Introduction

Building envelope, as the filter between outside and inside spaces, poses an environmental challenge for architects. Among all surfaces composing this enclosure, façades have been found to be decisive for environmental conditions inside buildings and, consequently, for energy requirements to maintain user's comfort levels.

Regarding the façade design, one of the first early-stage decisions made by designers is the proportion between glazed surfaces and opaque ones. For a particular space, this geometrical relationship may be expressed through two parameters: window-to-wall ratio (WWR) and window-to-floor ratio (WFR). Both indexes have been recurrently employed in literature to describe the link between fenestration design and inner environmental conditions regarding lighting (Bodart & De Herde, 2002; Ghisi & Tinker, 2005) and heat (Persson et al., 2006; Inanici & Demirbilek, 2000) either as individual aspects or from global perspective (Ochoa et al., 2012; Skarking et al., 2016).

One common approach for studies on the correlation between WWR and energy needs is to conduct their analyses based on a spatial model – usually a shoebox – conceived as an isolated entity. This definition of the study problem constitutes a logical starting point on the matter and allows us to provide valuable and straightforward insights for a simple, yet feasible, scenario. However, the final energy impact of windows on indoor environment not only depends on the element features itself but also on geometrical and material characteristics of the urban surroundings.

Investigations taking into consideration the effect of urban context are, though, much more limited. Some studies have been carried out defining a simplified urban context by using the endless canyon scheme. For example, Hegazy et al (2013) studied the combined effect of window size and shading device on daylight autonomy and energy consumption in Cairo. In this work, the complex balance between reducing air conditioning demands and lighting needs in the case of cooling-dominant climates was highlighted.

Despite the usefulness of the urban canyon approach, this model overlooks the 3D complexity of urban environments regarding local energy changes due to street intersections (Garcia-Nevado et al., 2016) and other non-canyon-shaped configurations (e.g. squares). In this sense, analysis based on urban tissue samples could contribute to a better understanding of the implications of urban façade design under more realistic conditions.

Based on a complex 3D environment, Fernández et al (2016) demonstrated that, results of window layout optimisation may differ depending on whether urban surroundings are taken into account or not. In the same vein, Vermeulen et al (2013) carried out an optimization analysis of the form and the façade layout for a block located in neighborhood of Paris. Results of this work suggested that, for heating-dominant climates, the optimum size of openings mainly depends on orientation and urban obstruction.

As shown, the role of façade design from an urban perspective is still in need of further research. This paper aims to provide additional insights on the impact of glazing ratio on thermal energy demands taking into consideration a specific urban context. This work focuses on a temperate climate, where heating and cooling needs have to be considered during the design process with regard to urban solar obstructions.

Method

In order to discuss the impact of WWR on thermal performance of spaces located in a specific built environment, a four-step method has been developed. First, the basic simulation model to be tested within a certain urban context is to be designed. The basic model is conceived as a single-space box with just one exterior façade where a variable-sized window will be located.

Second, the urban context where to study effects of WWR changes is to be modelled. The urban model consists of a central block - where the basic model will be integrated - surrounded by the minimum number of additional blocks which reproduce a representative sample of the chosen tissue.

Third, a parametric study of the thermal behaviour of the base model is performed in terms of WWR for the previously-defined urban model. To this end, heating, cooling and total air conditioning demands are selected as assessment parameters. These parameters will be calculated by means of computer-based energy simulations on an annual basis.

Finally, an optimisation analysis of WWR is carried out for the selected urban context. The optimisation problem consists in minimising a single objective function, in our case, global air-conditioning demands. Two optimisation scenarios are analysed on the basis of the constraints imposed to the glazing ratio solutions. On one hand, the optimisation problem is solved with no constraints about either the minimum or maximum WWR. On the other, the optimisation assessment is performed fixing a minimum WWR and applying a tolerance range on the minimum demand of a 10%.

Case study

Base model description

The base model of the present case study consists of a shoebox (width·depth·height = 6m·6m·3m) representing a sample of a single residential unit. The model is completely enclosed by adiabatic surfaces except for one, the exterior façade, where a single window is placed. The WWR of the space is parametrically defined between 0% and 100%, in 10% steps. No shading devices have been taken into consideration. Thermal features of the base model are detailed in Table 1.

Table 1. Base model features.

Façade materials	Exterior wall	Brick wall (12cm) + air cavity (5cm) + Brick wall (6cm) [U=1,92 W/m^2]
	Window	Single glass (6mm) + aluminium frame without thermal bridge break [U=5,7 W/m^2; g = 0,8]
Partitions	Horizontal	Concrete joists & ceramic blocks (20cm) + floor slab (5cm)
	Vertical	Brick wall (12cm)

Urban context definition

The *Eixample* district of Barcelona has been selected as case study. The original urban plan was conceived by Idelfons Cerdà (Cerdà 1867) in response to the unhealthy conditions of the overcrowded industrial city. It consists of an orthogonal grid of streets with 45º North orientation whose basic repetition unit was a slightly chamfered square (113x113m).

As a result of speculative processes, the *Eixample* resulted to be a much more densely built urban structure than the one initially planned. For this work, the profile of the block where the base model will be tested is defined according to regulations into force between 1932 and 1976 (CCCB 2009). During this period, highest densities and land occupations were reached posing a critical scenario in terms of solar access.

The present case study comprises a sample of 9 blocks (3x3). The base model is evaluated for several representative locations within the centre block of the tissue in order to analyse thermal behaviour differences in height. These positions correspond to the middle point of each block facet at two different levels (L1, L5) (Figure 1).

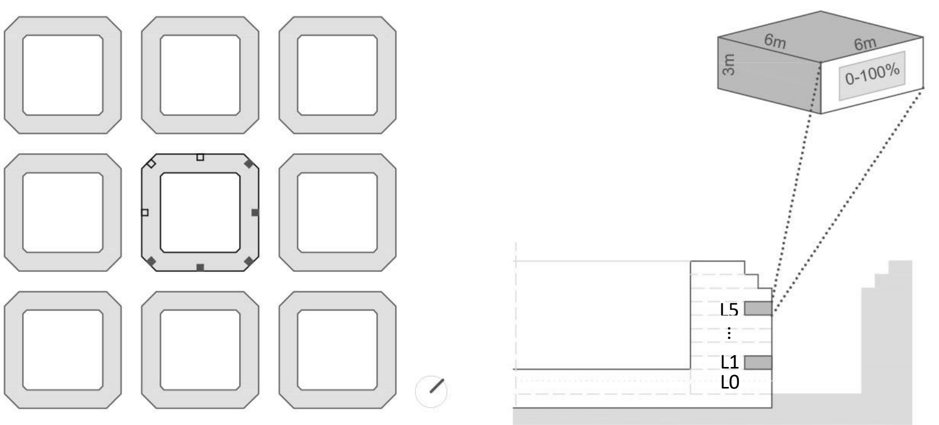

Figure 1. Plan (left) and section (right) of the *Eixample* tissue and selected locations for the test model.

Within the *Eixample* block, two kinds of façades can be identified: chamfer and long façade (Figure 2). The former, belonging to a square-shaped space, presents a lower degree of sky obstruction than the latter, pertaining to a canyon-shaped space. In sight of solar obstruction diagrams, it can be stated that more significant differences in height are found in longer façades (SW/SE, NW/NE) than in chamfer ones (E/W, N, S) regarding solar radiation availability.

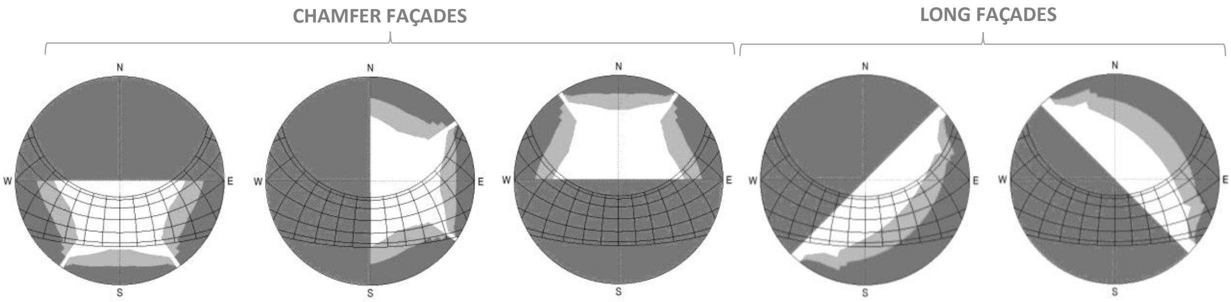

Figure 2. Solar obstructions in stereographic projection for L1 (dark grey) and L5 (light grey) for S, E, N, SE and NE façades, calculated in Heliodon (Beckers & Masset 2006).

Simulation settings

Energy simulations have been conducted using the software Design Builder v.5. This tool computes heating and cooling loads of spaces through dynamic thermal simulations based on climate data. Energy calculations in this software take into account shortwave radiation interactions with the urban surroundings (obstruction of diffuse and direct radiation + source of reflected radiation). As for longwave exchanges, the urban environment is considered to be a sky view obstacle, which is at the same temperature as the air. An overview of the simulation settings used for the present case study is included in Table 2.

Table 2. Simulation settings.

User's profile	Residential use Occupation rate 0,04 p/m^2 Schedule 100% 23-7h / 25% 7-15h / 50% 15-23h
Location	Barcelona 41^{o}N - IWEC Weather file
Set-point Temperature	Heating 21 ^{o}C Cooling 26 ^{o}C
Free cooling	21 – 24h from June to September
Infiltrations	0,5 ren·h^{-1}
Reflectivity	R_{GROUND} = 0.4 $R_{BUILDINGS}$ = 0.4

Results and discussion

Cooling, heating and global demands

Results of air-conditioning demands depending on WWR are shown in Figure 3 for rooms belonging to an isolated block and also for an urban one. Differences in energy requirements between E, SE, NE and W, SW, NW orientations respectively are barely noticeable on an annual basis; therefore, only the former have been depicted.

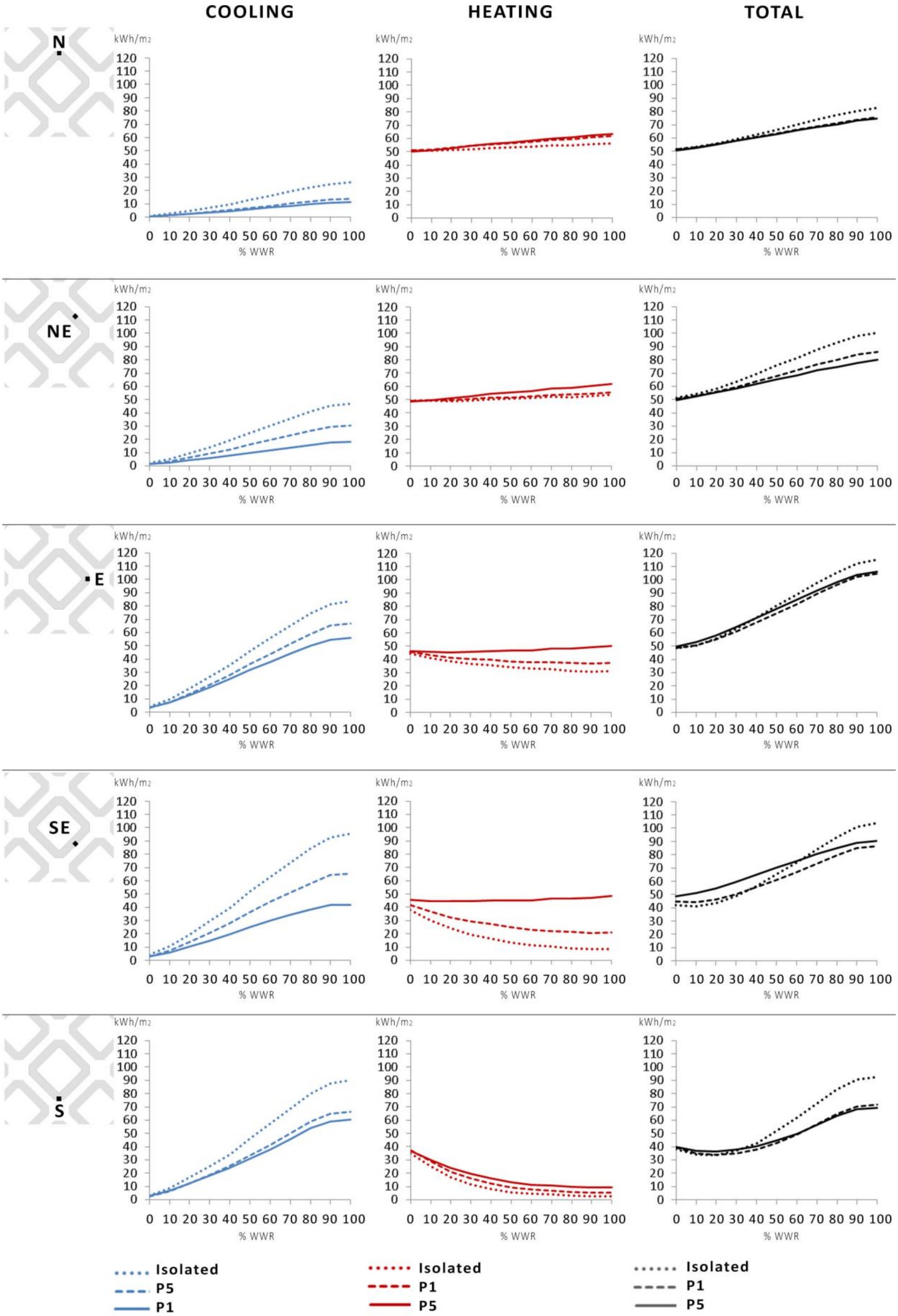

Figure 3. Air conditioning demands for an isolated and an urban block at levels P1 and P5.

Figure 3 shows that the increase in the opening size results in an almost linear rise in cooling requirements for all the analysed cases. Since cooling needs are mainly driven by radiation loads, the significance of this increase demand will depend not only on orientation but also on the degree of obstruction. Consequently, for the same orientation, the higher the floor level is, the more noticeable the increases in cooling demands are computed as openings enlarge. Changes in cooling demand due to higher WWR may be significant in both relative and absolute terms, increasing energy needs between 11 to 64 kWh/m^{2}year (in N-L1 and E/W-L5 cases, respectively).

As for heating demand, the enlarging of the glazed surface has uneven effects on energy requirements depending on the orientation and the degree of obstruction. On one hand, a decrease in heating needs is observed for south facing spaces and the less obstructed ones facing SE/SW and E/W orientations. This reduction in energy demand is explained by the fact that, for these locations, solar gains exceed conduction losses. Due to this effect, heating demand is reduced between 8 and 32 kWh/m^{2}year (in E-L5 and S-L5 cases respectively). On the other hand, the growth of the window size is associated to a slight increase in heating requirements for the rest of orientations regardless the height.

Regarding total air-conditioning demands, the parametric increase from 0 to 100% of WWR is linked in general terms to a rise in energy needs (ranging from a 1,5 to a 2,1 factor for N-L1 and E/W-L2 cases respectively). However, it is worthy to differentiate two particular situations in this regard. On one hand, for all N, NE, NW, E and W cases, the bigger the window is, the higher total demand is computed, reaching the minimum total demand for a 0% WWR. On the other, for S, SE and SW orientations the minimum air conditioning demand is reached between the 30% and 10% WWR.

Optimization of WWR to minimise total air-conditioning demand

In this subsection, the WWR optimization based on the minimisation of the total air-conditioning demand (T_{min}) is discussed. In this regard, two different scenarios have been assessed and graphically represented (Figure 4 and 5).

First, the “optimum WWR” for each case is determined as the glazing ratio linked to the minimum total air conditioning demand (T_{min}), without any further constraints on the window size. Though in this scenario lightning requirements may not always be fulfilled, it constitutes a conceptual approach on the thermal impact of the window size worthwhile to analyse. Results for this optimisation case are depicted in the elevation of Figure 4. Under this approach, windows would be present only in south façades and in the higher floors of southeast/southwest ones. These results indicate that, for the study case, the presence of glazing surfaces only has a positive thermal impact for S, SE and SW orientations and under highly-unobstructed conditions.

Second, the “optimum WWR” is defined as the maximum window size that does not lead to a “significant increase” in demand compared with T_{min}, being WWR≥ 10% in any case. For the present study, a “significant increase” has been defined as an increment of 10% of T_{min}. Block elevations based on these criteria are depicted in Figure 5. Urban façade design resulting from this thermal optimisation is characterised by a non-uniform layout. Differences in WWR glazing ratios are detectable between orientations. Additionally, for the more obstructed façades (SE, SW, NE, NW), they are also present in height, reflection of the link between obstruction and the window net energy performance.

It is worth-mentioned that the maximum glazing ratio obtained for this scenario (30%) is similar to the WWR average found by the authors in their ongoing research about fenestration in the *Eixample*. A possible explanation for this parallelism could be the existence of a non-explicit knowledge on the part of designers about certain façade configurations which pose a good compromise between thermal and lighting performance for this climate and urban context.

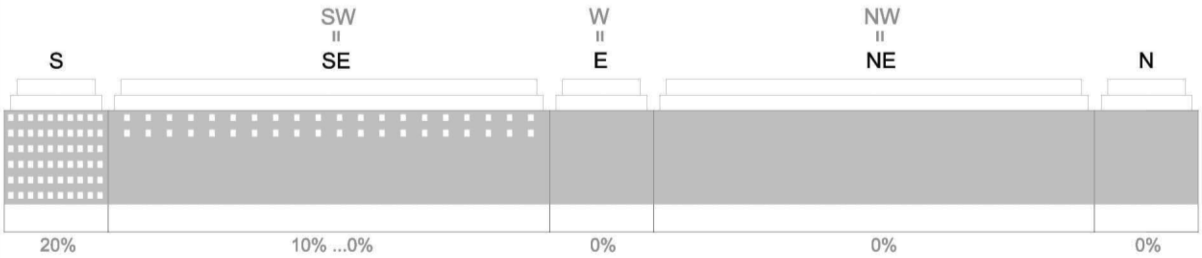

Figure 4. Elevation with WWR associated to the minimum air-conditioning demand.

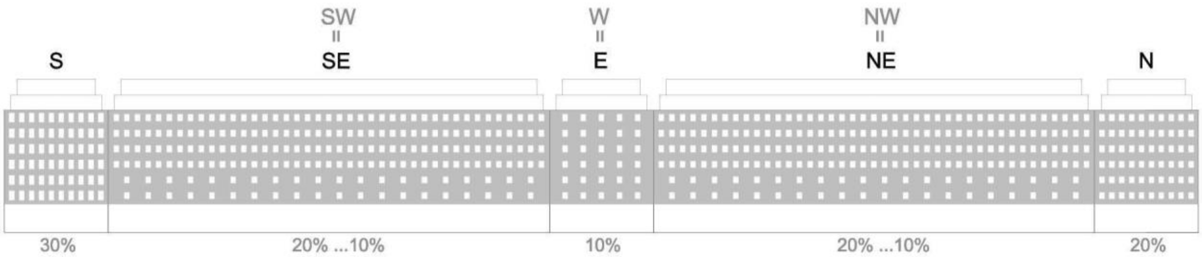

Figure 5. Elevation with WWR increasing by less than a 10% the minimum air-conditioning demand.

Conclusions

In this paper, the impact of WWR on air-conditioning demands has been discussed from an urban perspective. Results indicate that, for the climate of Barcelona, only the windows with a south component (S, SE, SW) on highly unobstructed contexts present a net positive effect from a thermal point of view. It has been shown that, for the urban tissue of the *Eixample*, WWR increases beyond a 30% always result in rises in total air-conditioning demands, regardless orientation and degree of obstruction.

In this work, a discussion on the possibilities of optimizing WWR to minimize air conditioning needs has been also carried out for the *Eixample* case. To illustrate conclusions on this point, a schematic view about a thermally optimised urban landscape of the *Eixample* has been included (Figure 6). The urban layout of the tissue is highlighted as one influencing factor regarding the obtained optimum glazing ratio. Consequently, façade design resulting from a thermal-based WWR optimisation differs among orientations. In addition to this, the optimum opening size from a thermal point of view grows in height (the higher the floor, the bigger the window) for the more obstructed façades.

The complexity of energy exchanges taking place through the building façade makes difficult for architects to understand the consequences of its design. Results of this work provide insights about thermal implications associated to changes in the WWR, an aspect which is present from an early stage of design. Findings on this paper may also contribute to a better understanding of the role of façade design regarding the thermal behavior of urban tissues.

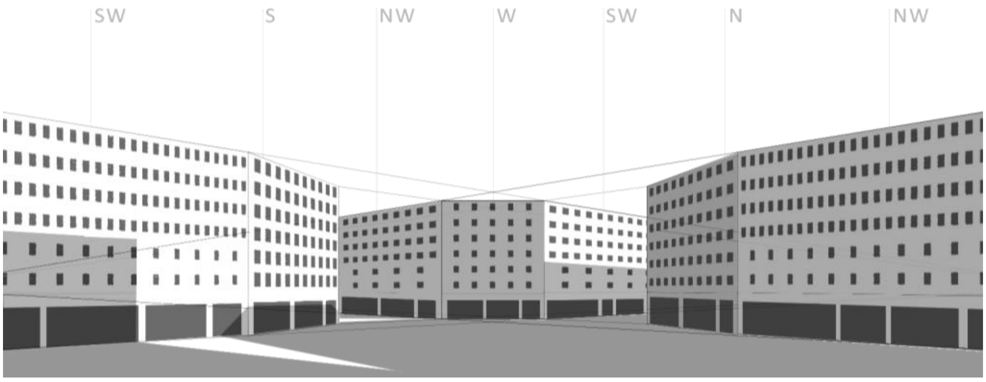

Figure 6. Urban landscape of *Eixample* with WWR which minimises air conditioning demands.

Acknowledgements

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