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ScienceDirect

Energy Procedia 122 (2017) 397–402

Energy Procedia

www.elsevier.com/locate/procedia

CISBAT 2017 International Conference – Future Buildings & Districts – Energy Efficiency from Nano to Urban Scale, CISBAT 2017 6-8 September 2017, Lausanne, Switzerland

Characterization of façade fenestration for energy studies within the "Eixample" urban tissue of Barcelona

Elena Garcia-Nevado[a] *, Benoit Beckers[b], Helena Coch[a]

[a] *Architecture and Energy Research Group - School of Architecture of Barcelona, Av Diagonal 649, Barcelona 08028, Spain*
[b] *Department of Building And Public Works (ISA BTP), Université de Pau et des Pays de l'Adour, Allée du Parc Montaury, 64600 Anglet, France*

Abstract

This paper explores the possibility of characterising the degree of fenestration of a certain city by studying a limited building sample. For the case study of the *Eixample* district of Barcelona, window-to-wall ratio (WWR) guiding values are provided and the role of the date of construction and the façade orientation is assessed regarding the opening size. Results indicate that not only average WWR values but also dispersion indicators should be provided to adequately describe façade fenestration. The age of construction has found to be a helpful parameter to approximate representative WWR values of a tissue reducing the uncertainty.

Peer-review under responsibility of the scientific committee of the CISBAT 2017 International Conference – Future Buildings & Districts – Energy Efficiency from Nano to Urban Scale

Keywords: Window to wall ratio; Urban Envelope; Barcelona.

1. Introduction

As the main human habitat, cities constitute one of the crucial scenarios with regard to the achievement of global sustainability. To this end, a solid knowledge basis on how urban structures work is required. Currently, an intense

* Corresponding author. Tel.: +34-93- 4010868.
E-mail address: elena.garcia.nevado@upc.edu

1876-6102
Peer-review under responsibility of the scientific committee of the CISBAT 2017 International Conference – Future Buildings & Districts – Energy Efficiency from Nano to Urban Scale
10.1016/j.egypro.2017.07.430

research activity on urban contexts is being encouraged, even with the emergence of new research fields such as Urban Physics [1]. Due to the complexity of urban environments, though, these studies are in need of simplified urban models, where the compromise between simplicity and accuracy poses some of the main questions [2].

Despite the astonishing progresses in computer-modeling tools and data acquisition techniques during the past decades, some aspects of urban modelling are still challenging. One of them would be the availability of extensive urban models at the suitable level of detail [3] for the purpose of the study. Other would be the representativeness of models reproducing existing environments, not only from a geometrical point of view, but also from a semantic one. In this sense, the modelling of building envelopes on an urban scale would be a significant example of these current limitations.

Building envelope acts as a filter between indoor and outdoor environments, where windows constitute especially sensitive spots to the energy exchanges taking place through the building skin. The importance of fenestration in buildings from an energy approach has been intensively addressed in literature based on the proportion of window surface to the opaque one (either façade or floor areas) [4]–[6]. However, these works consider fenestration ratios either as a prefixed input data or as a variable for theoretical studies, with scarce references to representative existing values in real built-up contexts [7].

The amount of glazed surface in an urban context is the result of multiple factors such as climate, solar orientation, aesthetics, historical tradition, technical aspects, urban regulations, economical restrictions, use of the building, etc. Consequently, as fenestration indexes differ to a wide range in the same urban tissue, the modelling of façades in urban studies tends to become a time-consuming task.

The aim of this paper is to explore the possibility of characterizing the degree of fenestration of a certain city through the study of a limited sample of buildings. To this end, two objectives are defined in the present work. Firstly, providing guiding values of window-to-wall ratio (WWR) for the sample discussing its representativeness regarding the whole tissue. Second, assessing the role of two variables with regard to openings size: the date of construction and the façade orientation.

Nomenclature

WWR	window-to-wall ratio
SD	standard deviation
VC	variation coefficient

2. Method

Once the study sample has been selected, a three-step process is carried out in order to draw conclusions regarding the size of façade openings. First, a multi-approach data collection procedure is conducted over the selected urban sample. On one hand, the outward appearance of buildings is graphically documented combining ground (Google Street view, on-site images) and airborne imagery (Google Earth Pro). On the other, spatial (size, shape, orientation) and non-spatial information (date of construction of the building) is gathered through cadastral surveys.

Second, a data processing is undertaken over the information collected in the previous step. This process is built upon the manual drawing of building elevations. These elevation drawings, besides providing a qualitative view of openings layout, are the working basis to quantify the area of openings and opaque surfaces. The data processing is then completed with the development of a specific database that includes the area of opaque/glazed surfaces, orientation and date of construction for each façade facet of the buildings within the sample.

Third, based on the database information, fenestration indexes for each façade facet are calculated and assessed in terms of average and dispersion indicators. For this study, the window-to-wall ratio (WWR) has been selected as the evaluation parameter. WWR is a dimensionless indicator calculated as the quotient of opening area and the total wall area where those openings are placed. WWR calculations in this work have no taken into account the ground level in order to avoid the possible deviation introduced by commercial window shops and pedestrian/car access.

Finally, conclusions on the WWR dataset are drawn from twofold perspective. On one hand, the degree of fenestration for a certain urban tissue is characterized by providing WWR guiding values and heterogeneity indicators. On the other, we assess possible patterns of correspondence between WWR values and the two variables under analysis: date of construction and orientation.

3. Case study

The *Eixample* tissue of Barcelona (Spain) is considered a representative case study to be analyzed. The original project was conceived by the engineer Idelfons Cerdà in response to the unhealthy conditions of Barcelona during the first half of the 19th century. However, its urban consolidation was stretched out in time as a progressive filling process of a basic mesh in contrast to the typical oil slick growth. First, the basic grid was built upon urbanization works and sanitation system (blocks of 113x113m and 20-meter-width streets). After, the plot distribution was carried out over the basic urban units. Finally, buildings were built up spread over time, until the pre-existing urban skeleton was completely filled. As a result of this layered consolidation, buildings from different architectonic periods coexist in relative small urban areas. This fact, together with the characteristic geometry of the tissue, makes this area a suggestive case study to address the link between façade design, orientation and age of construction.

3.1. Description of the study area

The study area selected for the present work, bounded by Marina, Napols, Provença and Industria streets, belongs to the *Eixample Dreta* district. Among the nine urban blocks comprised within this area, five of them have been selected for further analysis (Figure 1). On the whole, the study sample consisted of 125 buildings, built between 1900 and 2013. For this work, only the exterior façades of the blocks have been analyzed, bringing the overall total of 48.044 m^2 of façade surface distributed in eight orientations (NE, NW, SE, SW, N, S, E, W).

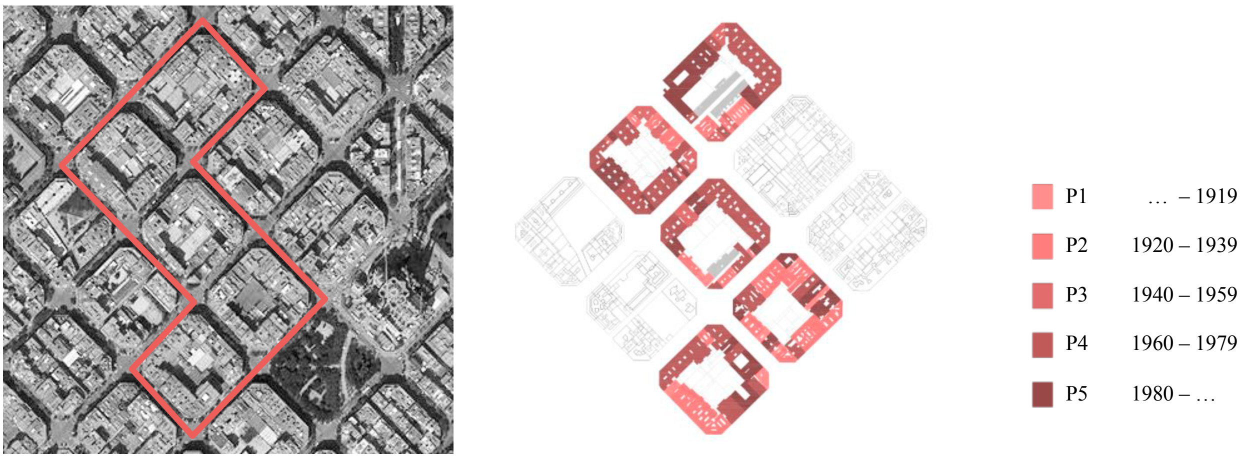

Figure 1. Location of the study area (left) and selected urban blocks by period of construction (right)

3.2. Criteria for the architectonic period

History of architecture has provided a reading of the glazed surface evolution mainly in qualitative terms, limiting the quantitative approach to rough comparisons between epochs. In order to assess the historical implications on transparency degree of façades, five 20-year periods have been defined for the present work (Figure 1). Time boundaries between periods correspond to key milestones for history of architecture in Spain, such as armed conflicts and significant changes in technical or regulatory aspects.

4. Results

The elevations of the façades under study are depicted in Figure 2, including information about the date of construction and orientation. In the light of these drawings, the marked heterogeneity in building openings is corroborated. Notable differences are detectable among buildings, even with a neighboring position. Additionally, disparity is also present between the ground and the rest of floors, reflecting differences of use and accessibility from the pedestrian level.

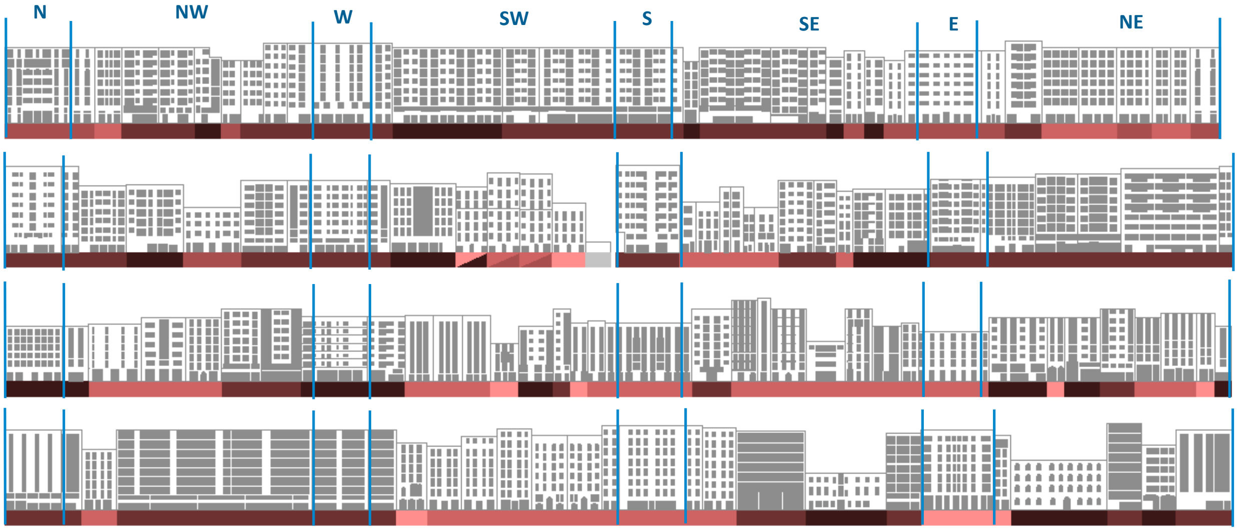

Figure 2. Elevation drawings for the selected blocks (Color legend, the same as in Figure 2).

4.1. WWR values for the whole dataset

According to results, openings represent, on average, almost 31% of the façade for the study case (Figure 3). It should be noticed, though, that the WWR dataset is characterised by a scattered distribution (SD=11, VC=37%), with WWR values ranging from 73% to 10%. From an analysis in terms of frequency of WWR values (Figure 3), it can be stated that the bulk of façades (85%) has less than 45% of glazed surfaces and also that half of façades present a WWR between 16-30%.

WWR values	Whole dataset
Maximum	72.8
Average	30.8
Standard deviation	11.4
Variation coefficient	37%

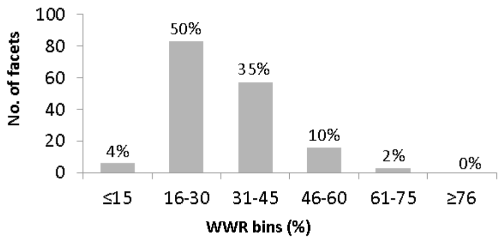

Figure 3. Numerical WWR overview (left) and frequency chart (right) for the whole WWR dataset.

4.2. WWR results by orientation

WWR values by orientation have been summarized in Table 1. The extreme WWRs are found in NE (WWR_{max}=34%) and W (WWR_{min}=26%) orientations, without an equivalent behavior in the symmetrical orientations (NW and E respectively). Additionally, taking into account orientation does not lead to a reduction of the uncertainty in WWR, as shown by the similarity in terms of SD and VC for the whole dataset and for the longer façades (NW/NE, SW/SE). According to these results, it can be stated that no straightforward correlation pattern exists between orientation and WWR, confirming the impressions from the elevation drawings at first glance.

Table 1. WWR values by orientation.

WWR values	Whole dataset	NW	SW	SE	NE	N	W	S	E
Maximum	72.8	53.6	72.0	72.8	62.6	46.6	52.5	34.6	33.6
Average	30.8	30.3	29.0	30.3	34.0	30.7	25.7	26.3	27.5
Standard deviation	11.4	10.5	10.5	11.5	11.8	13.5	18.8	6.2	5.6
Variation coefficient	37%	35%	36%	38%	35%	44%	73%	23%	20%

4.3. WWR results by date of construction

Window-to-wall ratios values by date of construction depicted in Figure 4 are summarized in Table 2. According to results, buildings dated before 1960 (periods P1, P2 and P3) present, on average, less glazed surface and less dispersed values than the more recent ones (P4 and P5). Additionally, it has been observed a decrease in WWR from the beginning of the century until the 60s (by almost 5% between P1 and P3), which is more pronounced between 1940 and 1959 (P3). This downward trend is interrupted during the following architectonical period (P4) with an almost 13% increase in the average WWR between 1960 and 1979, also characterized by a rise in the dispersion of the dataset. Over the last decades analyzed (P5), openings size has been reduced on average, reaching values closer to the ones accounted in the beginning of the century (P1).

Based on the correlation between average WWR values and architectonical periods, it can be inferred that technical innovations have substantially contributed to the fenestration changes. The marked increase in WWR during the 60s and 70s may be largely attributable to the spread of the pillars and beams concrete structure which allowed the façade to be relieved from its bearing function. Consequences of regulatory changes are also readable from the trends in WWR, as shown by the decline in the average opening size beyond 1979 linked to the entry into force of new thermal regulations (P5).

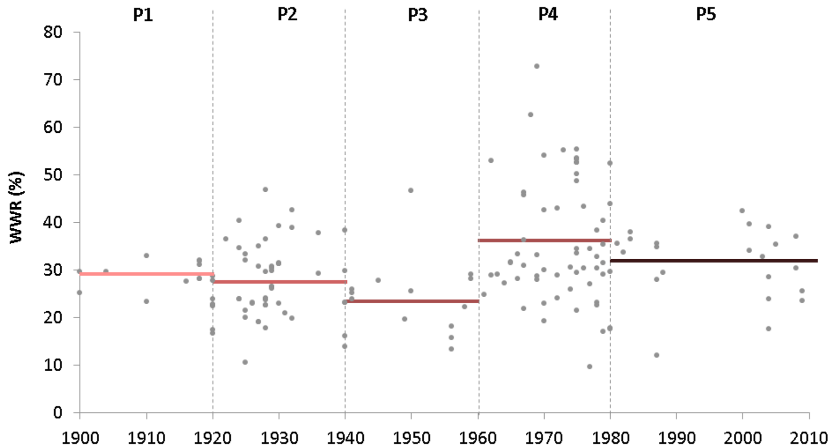

Fig. 4. WWR by date of construction: individual values (grey dots) and average values for the architectonic periods (color lines).

Table 2. WWR by architectonic period.

WWR values	Whole dataset	P1	P2	P3	P4	P5
Maximum	72.8	32.9	46.8	46.6	72.8	52.3
Average	30.7	29.1	27.5	23.3	36.1	31.8
Standard deviation	10.7	2.9	7.5	9.7	12.7	8.9
Variation coefficient	35%	10%	27%	42%	35%	28%

Conclusions

In this paper, façade openings of an urban tissue sample from the *Eixample* district of Barcelona have been analyzed in terms of window-to-wall ratio (WWR). According to results, glazed surfaces correspond, on average, to 31% of urban vertical surfaces. This value underlines the relevance of fenestration regarding energy exchanges through the built envelope.

The extreme heterogeneity of urban surfaces is highlighted by the remarkable dispersion in WWR values detected for the study case. In order to explore the variables governing this deviation, two parameters have been assessed: orientation and date of construction.

Results show that façade orientation, despite its substantial influence on indoor environmental conditions, is not a key parameter driving the size of openings of buildings. Cerdà's *Eixample* was conceived as an isotropic mesh where block orientation was fixed seeking "democratic" sunlight conditions. However, the solar concerns shown by the initial urban plan had no significant effects on the design of façades during the consolidation of the urban tissue.

As for the influence of the date of construction on the size of openings, it has been found that the quantitative assessment carried out over the sample agrees with the qualitative description of fenestration given by the history of architecture. According to results, building system developments seem to be the most influential factors with regard to the occurrence of changes in the amount of glazed surfaces in building façades. In this vein, the popularization of concrete structure with non-load-bearing façades is readable from the increase of average WWR detected within the sample during the 60s and 70s. For the case study, it has been shown that regulatory changes and other socio-economic aspects also affect windows size, though its impact is more limited.

Findings in this work suggest that it is possible to provide an additional reading of the urban history of a city based on the fenestration size. Though results obtained for Barcelona cannot be extrapolated to other locations, the existence of this kind of correlation is in itself interesting. In this sense, it could be revealing to repeat this study in other cities with a different climatic, socio-economic and technological background.

Currently, there is a growing interest in developing energy-based studies within the urban context in response to the deterioration of urban life quality and global environmental crisis. However, in these investigations, the lack of information on real characteristics of built environments may undermine the validity and reliability of the conclusions drawn. Results on this paper contribute to a better knowledge of urban façade layout, providing indicative window-to-wall ratio values helpful to enrich urban models used as a basis for energy studies.

Acknowledgements

This work has been supported by the Spanish Ministry of Economy under project code BIA2016-77675-R and a FPU fellowship from the Spanish Ministry of Education granted to Elena Garcia Nevado. Assistance provided by the students of the MBArch Master in Architecture, Energy and Environment (ETSAB-UPC), particularly by Marina Morey Rubert, was greatly appreciated with regard to data collection and elevation drawings process.

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