Recommendations of Height Restrictions for Urban Canyons in Curitiba, Brazil

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Abstract
Urbanization is commonly associated to densification, which may lead to upward growth or urban consolidation. High-rise buildings with a given height (H) relative to a certain street width (W) create what may be termed urban canyons. The present study evaluates the potential of having optimal daylighting conditions as a function of urban morphology for the city of Curitiba (25º25'50" S, 46º16'15" W), where street axes designated to allow densification (in the so called Structural Sector of the city) may lead to the formation of urban canyons by not imposing height restrictions to existing buildings. Daylight analysis was based on software simulations with Luz do Sol, DLN, ECOTECT and RADIANCE. It was verified that diagonal axial orientations relative to the North (rotated in 45º) provide higher daylighting potentials to buildings located in urban canyons. From the obtained results, height restrictions are suggested for such buildings and for different axial orientations in the Structural Sector of Curitiba.

Keywords: urban canyons; daylighting; computer simulation; urban planning; solar access

1. Introduction
The environmental impacts of urban growth belong to an important field of investigation faced in diverse cities around the globe. Such impact may be accompanied by both densification and urban sprawl, in complex and interrelated ways. In Brazil, urban growth is commonly associated to densification, which may lead to verticalization (upward growth or urban consolidation), which allows a control of urban sprawl, diminishing the need of spreading infra-structural services, such as electricity and water supply, sewer and telephone lines, also reducing the necessity of enlarging urban transportation lines and urban equipments, and finally, minimizing the effects of urban growth towards adjacent native forests.

The development of new technologies based on steel frame construction and concrete and continuous improvements on elevators allowed the construction of the first skyscrapers by the turn of the twentieth century1. Due to diverse technological developments throughout the twentieth century, the height of skyscrapers gradually increased, together with their widespread utilization in several cities around the world, mainly in developed countries. Consequently, urban canyons were formed in highly densified areas.

Although both verticalization and densification processes in cities can provide several advantages, such modifications in the urban landscape were implemented extremely fast, especially after the Second World War. The resulting impacts of these processes cannot be easily measured and the estimation of the size of urban effects often proves difficult2.

This urban growth pattern has been spread all around the world and local land use regulations usually do not take into account peculiarities such as the sun path diagram for the location in order to reasonably establish solar (daylight) access within a city. Proper knowledge of the solar path for a given latitude may be a first step towards deciding for a compact or a spread-out array and defining setback lines between buildings in order to permit solar access. Regarding upward growth, one of the most immediate effects is the reduction of available daylight in floors close to the ground floor in buildings forming an urban canyon.

With the energy crisis of the 1970s and the creation of the concept of Sustainable Development, the need of utilizing electric energy more efficiently led to several initiatives in the building sector. Energy efficiency standards have improved and diverse energy rating systems were proposed. However, although such initiatives can be applied to an individual building, clusters of adjacent buildings may have a substantial impact on its performance. The difficulty in many cases
is how to adequately deal with site-specific constraints such as surrounding and sun-obstructing buildings. Usually the building designer considers the building as a self-defined entity, ignoring the effect of urban geometry on energy consumption within the building.

In this context, this paper investigates the effects of the several Master Plans designed for Curitiba, South Brazil, focusing on the impact of the verticalization process in the so called "Structural Sector", where no restrictions are made regarding building height. The main purpose of this study is to analyze potential daylighting conditions with increasing densification. For such, simulations were performed with different aspect ratios (relation between building height (H) and street width (W), H/W) and for different solar orientations of actual urban canyons in Curitiba focusing on winter.

2. Local Site

In the last decades, a great concentration of people has taken place in urban areas worldwide. In Brazil this trend has been observed since the 1940's, with the rural population increasingly shifting towards urban centers. Within the last two centuries the country became mainly urban, as the percentage of urbanites grew from 5.9% in 1872 to 85.2% in 2001.

The Brazilian State of Paraná has a population of 10,387,378 inhabitants distributed over an area of 199,800 km². Two climate types can be identified in this region, according to Köppen's system: a) subtropical climate type (Cfa), characterized by a monthly temperature average under 18°C in winter and above 22°C in summer, with a concentration of rain storms in summer but without a definition of a dry season and b) temperate climate type (Cfb), characterized by a monthly temperature average under 18°C in winter and under 22°C in summer, mild summer periods and no defined dry season. The latitude range of the Paraná lies between 23°S and 26°S, rather small, so that conclusions regarding daylighting potentials can be extended for all the region.

Curitiba (25°25'50"S, 49°16'15"W, 917 m elevation) is the capital of Paraná. The city has a population of approximately 2 million inhabitants and has a long history of urban planning. This longitudinal experience in urban planning, which has attracted worldwide attention as a model of sustainable urban development, provides an interesting background of succeeded urban experiments in the twentieth century, which strongly affected its current urban morphology.

In its beginning, in the 1940s, Alfred Agache designed an urban lay-out characterized by concentric rings, which main roads would had a street width of 30 meters. Although such rings were not fully implemented, some of the main roads kept the original width when a new Master Plan was conceived in the mid-sixties, known as the Serete Plan. This plan proposed the creation of a system composed of linear and radial circulation roads to foster urban growth. With an ever-increasing urban growth, the city plan underwent a series of revisions which led to an innovative mass transportation system capable of supplying current and future demands, as well as measures for preserving the city's heritage and green areas.

As a result of this rationale, street canyons were created, termed "structural axes", which have a street width of 30 meters and no height restrictions. Through such canyons, the most intense vehicular traffic flows towards the city center. The Structural Sector congregates three distinct and inseparable functions: to serve as important traffic routes, to support the existent mass transportation system and to function as a means of controlling land use. However, since land use regulations for such sector allow densification (restricted to the street axes themselves), a stronger demand for mass transportation is created. It should also be emphasized that the first two floors in the Structural Sector are destined to commercial activities and the occupation rate is 100% of the lot. No height restrictions are made to the buildings forming the urban canyon, but a maximum built area equivalent to 400% of the size of the lot is allowed to the floors above the commercial levels (thus, total built area can reach a maximum of 600% of the lot's size). Another restriction refers to a mandatory recess equivalent to H/6 (H=total height of the building), meaning that apart from a minimum distance of 2.5m to both sides of the building (neighboring lots), for a given height, a minimum distance equivalent to the height of the building divided by a factor of 6 should be respected.

However, it is a paradox that a city which is worldwide acknowledged for its urban planning does not recommend building height restrictions in a sector destined to densification. The highly densified Hong Kong, with a population of 6.7 million inhabitants living in 1100 km², yields a population density of approximately 60 inhabitants/hectare, since 1956 recommends minimum spacing between buildings to ensure a sustainable vertical angle, with minimum horizontal widths and maximum heights. Furthermore, it is interesting to point out that ancient civilizations already had knowledge about the solar path throughout the year and, according to that principle, town planning occurred, taking advantage of appropriate solar orientation. In E-W axes street width between buildings would be determined with variations according to local latitude, on the basis of solar access in winter solstice, as in the vernacular example of Pueblo Acoma. Even in Brazil, cities such as Florianópolis (27°35'48"S, 48° 32'57"W, sea level) establish height restrictions. In this city, taking the middle of the street as a reference, an angle of 70° is set as a height limit for buildings.

If on one hand the structural axes may serve as tools for stimulating urban growth, together with a mass transportation system, on the other hand no
Considerations are made regarding shading effects generated in different axial orientations and resulting solar paths. Fig. 1 shows the location of the structural axes in Curitiba.

The main three axes analyzed were the following:
• Canyon 1 – Rua P. Anchieta, axial orientation almost east-west with canyon buildings facing N and S;
• Canyon 2 – Av. J. Gualberto, northeast-southwest axial orientation with canyon buildings facing NW and SE;
• Canyon 3 – Av. Rep. Argentina, axial orientation almost north-south with canyon buildings facing W and E.

3. Methodology

In order to analyze daylighting potentials in Curitiba's urban canyons, a test office room was defined and used for simulations. The dimensions of this test room are: room width 2.8 m, length 5.0 m and height 2.6 m. The height of the window sill is 1 m, window height is 1.2 m and its width 2.4 m. Internal finishes were considered in light colors. Simulations were carried out assuming the test room to be 10 meters above the street level, on the third floor. Configurations consisted of varying the height of the buildings forming the urban canyon, considering deep and shallow canyons (Fig. 2). Street width was kept constant for all simulations (W=30 m) and building height varied according to the following aspect ratios: H/W=0.33; H/W=0.66; H/W=1 and H/W=2. The vertical towers above the second floor must be 4 m off the border, which results in a total width of 38 m. Therefore, the corresponding building heights were of approximately 13 m, 25 m, 38 m and 76 m, respectively. The existent canyon orientations (of Canyon 1, 2 and 3) were then simulated for this varying geometry for the winter solstice condition (Fig. 3).

Following softwares were utilized: the Brazilian software Luz do Sol and DLN, ECOTECT and RADIANCE.

Luz do Sol was developed by Roriz in 1994 and provided the hours of possible direct solar incidence in the test room resulting from the different canyon configurations, thus allowing a first verification of the effects of urban density on daylighting potentials.

DLN presents hourly outdoor illuminance data for typical days of several Brazilian capitals, including Curitiba, which served as input to ECOTECT. By using this software, we built the 3D geometry adjusting the canyons to the real orientations and performed simulations for overcast sky. The interface with RADIANCE enabled a further approach on indoor comfort focusing on indoor lighting levels for sunny and clear sky conditions. Set-up conditions considered in RADIANCE were the following: high quality of detail and variability; nine inner reflections. The reflectance values considered were: 0.2 for the external obstacles in the urban canyon, 0.32 for glazing, and...
0.5 for inner walls in the model room. Time step was set to every two hours, and considered illuminances were read from the top view images, always taking into account the lowest illuminance value found as a reference for comparisons.

It should be stressed that by considering the most unfavorable condition (first floor above the commercial floors, the lowest daylighting level read usually close to the inner wall opposite to window) a greater variability in the results was achieved, i.e. such condition proved to be more sensitive to H/W variations. And, depending on the orientation, the room model can receive sunlight after two or more interreflections inside the canyon\(^{13}\), which can be problematic. Additionally, the critical condition of continuous (infinite) canyon walls was considered for all simulations, thus not taking into account the afore mentioned H/6 rule.

4. Simulation Results and Analysis

4.1 Luz do Sol

By means of using the Brazilian software Luz do Sol it was possible to assess the hours of possible direct solar incidence in the test room resulting from different canyon configurations, allowing a first verification of the effects of urban density on daylighting potentials. We assumed that once daylight is available, diverse shading elements can be employed in order to control excess lighting.

In the graphs, a semicircle shows in radiuses the different aspect ratios considered, ranging from 0.33 (spread out urban array or shallow canyons) to 2 (densified urban array or deep canyons). Each radius follows one of three different orientations of the street axis and shows results, which are divided in two façade orientations (the half column towards the bottom of the diagram, in Canyon 1, for instance, represents a south-facing canyon facet). Finally, colors represent hours of incoming direct sunlight in the test room.

For almost N-S axial orientations, it was found that for both façade orientations of the urban canyon quite similar solar incidence occurs in winter. For an axial orientation tending to E-W, a façade orientation towards north presents enormous potential of daylighting use, especially for H/W=0.33. As expected, for Curitiba's latitude, a south façade does not provide direct solar incidence in the test room. The limitation of this first approach consists of inferring just the sunshine hours and not the resultant lighting levels for each configuration.

4.2 DLN and ECOTECT

The Brazilian DLN software was used as a support for ECOTECT. DLN provides sky horizontal illuminance data for specific days and seasons of the year. Such data were then used as input in ECOTECT, which computed average daylighting levels in the test room under overcast sky conditions.

In these conditions, the most important factors affecting daylighting potentials within a given room are: the geometry of surrounding obstacles, the dimension of the room's openings, glazing properties and overall reflectance of interior surfaces, irrespective of façade orientation. Average illuminances are generally low, especially for higher aspect ratios (Fig.5.). Aspect ratios between H/W=0.33 and 1 will need artificial lighting, though with a proper lighting project, spots near the window can remain inactive during most of the day. Aspect ratio H/W=2 presents extremely low average illuminances in the test room and, even in the peak, it would not exceed 142 lx.

4.3 ECOTECT and RADIANCE

Regarding the analysis of clear sky and sunny conditions, ECOTECT was used to model the canyons. The computational 3D model was then used in RADIANCE together with the solar altitudes in winter solstice, resulting in a graphic output. The analysis was made for the following hours of the day: 10 am, 12 noon and 2 pm. Results are presented here in terms of minimum illuminance obtained from RADIANCE's isolux contours, considering all axis orientations and H/W ratios in only one graph. Again, the semicircle graph was adopted, this time colors represent the minimum illuminance in lux, generally occurring in the rear wall of the test room, opposite to the wall with the opening.

At 10 am (Fig.6.), solar incidence is higher when the test room is facing E (Canyon 3), NW (Canyon 2) and S (Canyon 1). The results show that even with the peak illuminance occurring at the rear wall, the average illuminance remains very low, especially for aspect ratios greater than 1.
2) and N (Canyon 1). It can be observed that the lowest minimum illuminance levels occur in south- and west-facing façades. The effect of densification (increased H/W ratios) is not at all evident in the most impacted façades at this hour of the day (S and W), but is significant and diminishes proportionally with the aspect ratio in a north-facing room. An undefined pattern can be noticed in the diagonal axis, presumably due to inner reflections within the urban canyon.

At 12 noon (Fig.7.), a south-facing test room (Canyon 1) offers very little daylight (minimal illuminance will not exceed 150 lx). A north-facing test room will have a great daylighting potential, due to the low winter solar altitude with azimuth 0º. As a result of inner reflections and the greater solar altitude in the course of the day, daylighting levels remain high in this façade even for an aspect ratio of H/W=1. Regarding the NE-SW street axis, except for the highest aspect ratio, all other conditions will yield minimum illuminance above 150 lx. Although a NW-facing test room may offer a higher daylighting potential, both sides of the canyon present favorable conditions. For the E-W canyon (Canyon 3), an azimuth of 0º at 12 noon results in similar lighting levels in both façades. Most of the sunlight is indirect and due to inner reflections, so that minimum illuminance does not exceed 300 lx even for lower canyons.

At 2 pm (Fig.8.), solar position affects more substantially those canyons aligned to the main cardinal points. At this time, a south-facing room (Canyon 1) presents, regardless of the aspect ratio H/W, minimum values below 150 lx. Extremely low illuminances are obtained for all façade orientations in deep canyons with H/W=2, which show a daylighting performance similar to that of a south-facing test room, i.e. minimum illuminance not higher than 150 lx. Façade orientations towards N, NW and W will show minimum illuminance levels higher than at 12 noon, due to the lower solar altitude at that hour of the day. At such time, solar beams reach more deeply inside the room. Therefore, at this time, the minimum illuminance obtained for the NW orientation was close to 1400 lx with a H/W=0.33 ratio.

5. Final Considerations

Densification by means of high-rise buildings in the city center is an essential form of containing urban sprawl. Through such strategy the need of enlarging existing infra-structure is reduced and several issues related to urban mobility are addressed (need of creating new or expanding existing transportation lines; traffic jams; noise and pollution; energy consumption for transportation; among other aspects). In the case of Curitiba, densification may also inhibit the ongoing process of illegal occupation of areas destined to natural preservation, as a consequence of uncontrolled urban sprawl. In the city center, incentives and recommendations for an appropriate densification process may also help reduce vacant lots, which are currently used by land speculators as an investment source.

It should be mentioned that the afore mentioned H/6 rule for the Structural Sector may help increase daylighting levels in urban canyons, provided new buildings are erected according to that rule. This factor was not taken into account in our analysis, since the obligatory recess, obtained as a function of building height, will depend on the lot's size and on how many lots shall be occupied by the development. Thus, the H/6 rule was considered applicable only to very particular analyses of daylighting conditions, where obstructions are well defined. Also, we consider that since that rule was created specifically for Curitiba, obtained results might be of interest for other cities of
The main issue to be mentioned is that canyons with higher aspect ratios (H/W=2), irrespective of their axial orientation, will lead to extremely low daylighting levels, indicating a low daylight potential and possibly a stronger dependence on artificial lighting. For the structural axes of Curitiba, this would mean an initial height restriction of 38 m, about 10 floors, corresponding to H/W=1. It should also be emphasized that the daylight performance in the test room for Canyon 2, with a street axis aligned with NE-SW, is favorable for both facets of the canyon. Thus, the obtained luminous performance will corroborate with Knowles' findings\(^4\), which suggest that diagonal streets, rotated in 45 degrees relative to the N-S axis, will provide greater solar loads than those aligned to an E-W axis. The oblique alignment of the street is likely to be more effective in enhancing inner reflections in the canyon and the opposite façades act as reflectors, yielding more balanced illuminance levels than configurations aligned to cardinal points.

From the obtained results, recommendations for height restrictions were drawn as a function of potential daylight use in offices located at the structural axes of Curitiba. For such, both the number of hours with direct sunlight in the winter solstice, under clear sky conditions, were considered.

Regarding mainly the illuminance aspect, some façade orientations will allow higher obstacles, such as the case of Canyon 1 (north façade) and Canyon 2 (northwest façade). Analogously, opposing façades in the same axes will require lower building heights. Considering a street axis practically aligned to N-S (Canyon 3), an aspect ratio of H/W=0.66 is suggested as a limit for both sides of the canyon. It should be observed that if one also considers the aspect of the number of hours with direct sunlight within the test room, N- and NW-facing offices may have taller obstacles, whereas S- and SE-facing offices should be less obstructed. For N-S canyons, H/W limits could be very similar. Schematically, such recommendations are presented in Fig.9.

In this paper daylighting performances were presented for Curitiba's urban canyons, as a means to facilitate the choice of optimal height restrictions in Curitiba and in locations of similar latitude. The main aspect considered was the daylight potential for office activities. Other aspects should and must be regarded for a comprehensive establishment of height restrictions, such as thermal considerations; aspects of air movement and ventilation within the canyon; noise and pollutant control strategies; among other aspects.

References

9) Ng E. Applying computational simulation results to the development of a design method for daylighting design and regulation in high-density cities. 18th IBPSA Conference Proceedings. Eindhoven, Holland 2003: 943-950.

Notes
1) Setor Especial Estrutural - SE.
2) Note that the H/6 rule is relatively new (implemented in 2000: Lei 9803 – Prefeitura Municipal de Curitiba), so that many of the existing buildings did not have to attend to such restriction by the time they were built, being responsible for the creation of continuous canyon walls.
3) Curitiba, by its turn, has a population of approximately 1.7 million and an area of 432.14 km\(^2\), which yields a population density of about 4,000 persons per km\(^2\).
4) Or an average population density of 58,000 persons per km\(^2\) of built-up land\(^1\).
5) It should also be mentioned that, at the present, the H/6 rule is bringing a disastrous consequence in the case of small and narrow lots, as it inhibits investors to built in such lots. Central and well located lots remain vacant, attracting drug dealers and other illegal activities to these central spots.