DAYLIGHTING AND INSOLATION IN HIGH DENSITY URBAN ZONES: HOW SIMULATION SUPPORTED A NEW LAW IN CURITIBA

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ABSTRACT

Building Performance Simulation can record a significant victory. In the city of Curitiba, Brazil, situations of poor access to both diffuse daylight and direct solar radiation in high density zones led the City Hall to consider the adoption of a simplified solar envelope concept. In order to evaluate the effectiveness of such change over a broad range of possible situations, a computer simulation code based on the raytracing technique was developed. Results were presented to the City Council in December, 1999 and supported the issue of new zoning regulations in January, 2000, despite the resistance offered by the building industry.

INTRODUCTION

In June, 1999 IPPUC, the Urban Planning Agency of Curitiba, Brazil asked the Universidade Federal do Paraná (UFPR) for support in an unusual task: to evaluate the effects a new zoning regulation on the indoor environment of residential buildings.

UFPR team agreed and a raytracing algorithm was adopted in order to quantify both illuminance levels at standard positions within the apartments and solar direct radiation availability on the building façades. Given the specificity of the situation and the multitude of situations arising, a considerable amount of input data was needed.

The need to optimize computation time encouraged the development of a new raytracing code, rather than adopting an available one. An automatic data generator was developed, creating geometrical models for a series of parameters like façade orientation and buildings' height. The code was validated by the analysis of both rendering and numeric solutions for regular geometries and well-known radiant fields. Details of the validation scheme can be obtained from the author.

Before the official presentation of the new zoning regulation draft to the City Council, the present research project remained confidential. The zoning act was approved in January, 2000. The analysis results are presented here for the first time in a scientific conference.

HISTORICAL BACKGROUND

Besides climate, the physical surroundings of a building play an important role in the creation of an indoor environment. That becomes evident when radiation phenomena are considered, comprehending both the direct solar gains and diffuse daylighting from the sky. Differently from sound and wind, which can bypass obstacles, radiation travels in straight lines and its propagation is therefore very sensitive to geometrical relations. The radiation field at a given site is particularly sensitive to the surrounding buildings.

Daylighting means to some extent the visual access to the sky hemisphere. It is a well documented fact that availability of diffuse sunlight can be warranted through adoption of the solar envelope concept. A solar envelope means that not only building height, but its proportion to horizontal distances between buildings has to be the object of regulations.

Solar direct radiation is on the basis of a bioclimatic approach to architecture. Access to solar radiation is also an important health issue, from a hygienic, as well as from a psychological point of view.

Cultural ties in Brazil which are not completely understood cause the building practice not to properly consider the diversity of climate. In the city of Curitiba such issue acquire a particular meaning. The city is known as the country's capital with the lowest average temperature. Further, according to recent satellite measurements by INPE (National Space Research Institute) it harvests the country's smallest amount of yearly solar radiation. Further, solar irradiation is needed because. Despite the relatively low latitude of 25°, low to moderate daily average temperatures in winter encourage the adoption of bioclimatic architectural practices. Nevertheless, poor access to direct solar radiation limits that possibility in several districts.

Setor Estrutural was a zone introduced in the early 1970es as an attempt to couple a high residential density and an efficient transportation system. It consisted of an North – South axis and a West – Northeast axis, both two-block wide. The building industry experienced a fast development in the following three decades. Nowadays, those zones form impressive canyons in the city geometry. It is worth mentioning that in the *Setor Estrutural* the building height is free, provided the observance of a maximum *occupation rate* of 50% (building footprint area / building lot area) and a *building coefficient* (total floor area / building footprint area) of 6.

The organization pattern based on high density axes was called a downtown linear expansion. However, a real estate reform like what happened in Manhattan before the high rise buildings were erected, has never happened in Curitiba. Consequently, it was not possible to make the private actors contribute to an idel implementation of the organization pattern. Building lots were kept rather narrow and deep, an inherited shape from in colonial times. As building heights often reach 30 floors, any sense of harmony is lost in the urban context.

MODEL DESCRIPTION

Within the current zoning practice in Curitiba, two predominantly residential sectors were considered. One is the *Setor Estrutural* (SE), as described above. Another is a mid-to-high-density zone called ZR4. Three different situations were compared.

First situation reflected the zoning regulations prior to 2000, which had set minimum requirements on the distance from the side and back façades to the building lot limits. It also used the criteria of a maximum *occupation rate* and a maximum *building coefficient*. Although such criteria could limit to some extent the real-estate exploitation and consequent disadvantages to the built environment, also impacting on energy efficiency, they revealed that former the regulations had a limited comprehension of the physical environment. Unhealthy situations were tolerated, like whole façades of residential buildings receiving no sunshine throughout the year.

Second situation corresponded to what the City Office was proposing as a guiding criterion for the new zoning regulation. It introduced a solar envelope concept, in that side and back façades of a new building were required to keep a distance to the building lots limits of at least one sixth of the height (H/6). Such criterion apparently does not take façade orientation into account. However, it was preferred because of its simplicity.

Third situation, rather theoretical, was a variation of the second, requiring least distances of H/5. It had the sole purpose of clarifying the problem sensitivity regarding the displacement / height proportion.

Each of the three situations was tested in a set of 6 buildings, arranged in two parallel rows. Every building kept to the others minimum allowable distances as described in each situation. The building in the middle was the analysis object of indoor comfort conditions. The other ones were taken as standard barriers to solar direct and sky diffuse radiation.

Further, each of the zones (*Setor Estrutural* and ZR4) gave rise to two variations, according to the adopted building height. Thus, 4 zone situations arose. All of the building lots considered were rectangular. The buildings were rectangular too, reflecting the practice of achieving the maximal allowable density.

First variation considers the ZR4 sector with building height of 6 floors and within a 15m x 30 m lot (ZR4-6).

Second variation consideres the ZR4 sector in 10 floors height, which is a legally accepted exception as compensation for extra investment, by the building company, in the preservation of green areas or historical buildings in the city (the so-called „solo criado“ mechanism). Same 15m x 30 m lot was considered. (ZR4-10).

Third variation considers the *Setor Estrutural* with 12 floors height within a 30m x30m lot (SE-12).

Fourth variation considers the *Setor Estrutural* with 21 floors height within a 30m x 30m lot (SE-21).

The daylighting simulation results generated large output files. Here only the floors 1 to 6 are displayed. Such floors were found critical in daylighting issues as sky factor decreases to a minimum.

Within each floor, an apartment with all of its windows opening to one of the side façades was simulated. Minimum allowed displacements from side façades to the lot limits were considered: 2.0 m for ZR4-6, 3.2m for ZR4-10, and 2.0m for both ZR4-12 and ZR4-21. Within each apartment, two points were selected for illuminance levels simulation: calling the building depth *D* the distance from front façade to back façade, one was at *D*/2, another was at 3*D*/4). Both points were 3.6m apart from the side façades, and on a 0.85m level above the floor. Such placement reproduces a classical criterion of the British Daylight Code as mentioned by Hopkinson et al.

The building side façades were considered as having window panes on each floor starting at 1.0 m height and reaching the ceiling, 2.0m above. Windows were considered as continuous stripes from the front façade to the back façade. Inner partition walls were omitted. Interiors were taken with a white coating with a reflectivity of .9, and the buildings external coatings, as well as soil albedo, were taken as having a reflectivity of 0.5. A uniform sky of 3000 bl was adopted, resembling a cloudy weather.

Direct radiation results were obtained for five different orientations of the front façade: N, NE, E, SE, and S. Results for NW, W and SW were obtained by a consideration of symmetry.

The solar path considered was as for July 1st and latitude of -25.5° as corresponding to Curitiba, under a clear sky condition. Atmosphere absorption was simplified by adoption of an irradiation density of 1000 W/m² on a perpendicular surface. Direct solar radiation hitting each of the building façades was accounted in kWh/m² day. Division of that amount by 1000 yields a duration of perpendicular irradiation in hours with same energetic significance (*equivalent hours of perpendicular solar irraidation*). Such parameter expresses the physical possibility to the architect in the use of solar gains in a bioclimatic design.

One must observe that in a strictly regulated real-estate environment, the shadow thrown on the façades by surrounding, either existing or allowable buildings, are to be regarded as design constraints as well as climate or building. Such constraints are even more important because of being permanent.

NUMERICAL METHOD

Both daylighting and solar irradiation were numerically simulated by geometric, three-dimensional models. Drawing and rendering algorithms were developed. Such methods were not intended to display final results, but rather to allow a visual monitoring of the numerical modelling process in order to check for possible discrepancies. A direct reflection algorithm allowed the role of every modelled surface to be accounted for. Further, a discretizing algorithm allowed 3D space to be represented by a number of vectors.

Daylighting was modeled by a ray-tracing algorithm. However, rather than the generation of high-quality rendering, the purpose of adopting that method here was to generate discrete numerical results, as a virtual luximeter. Thus the simulation's main task was to resemble a luximeter, integrating the illuminance equation

$$dE = L \cos\theta \, d\theta \, d\alpha / d^2$$

over the visible hemispheric domain covering the horizontal plan at each of the measurement points. Here E represents illuminance (lm/m² or lux), L represents luminance of a distributed light source element (cd / m² or bl), θ is the inclination angle between the vertical line through the measurement point and the light source element, α is the azimuth angle and d is the distance from the measurement point to the light source element.

As stated in the model description above, such luximeter was placed in two different locations in each of the building's six lowest floors. Each "measurement" location was supposed to be a horizontal plan (a table) and had its visible hemisphere divided into 80 different inclinations and 36 differents azimuths, yielding 2888 directions. Every light ray was traced back up to 7 reflections. Every time the sky being hit within such reflections, a contribution value to the total illuminance on the table was accounted for. Results could thus be computed in lux and were later converted into the classic daylight factor through a multiplication by $100 / 3000\pi$.

Direct solar radiation adopted a hourly simulation model in order to express the continuous variation of solar angles. Irradiation vectors were generated in the propagation direction of sun rays on a clear day. In order to simplify the physical equations, there was no regard of atmosphere refraction. Solar radiation was discretized by one vector for every 4 m², meaning 4 kWh energy for every hit on a façade. Such value was adopted as a compromise between precision and computation time.

For each of the daylighting and solar radiation problems a specific computer application was written, which comprehended about 4,000 programming lines in C++, object oriented. All library tools were developed by the author.

RESULTS: DAYLIGHTING

Adoption of the new zoning criterion of H/6 as least distance from side façades to the building lot limits, as proposed by the city ofice, proved effective in the amelioration of illuminance levels at the considered points. More than 30% were achieved in all of the four situations. Particularly the SE-21 situation was noticeable with 387% improvement. Such results are summarized in Table 1.

As absolute values, the illuminance results in lux achieved under old regulations can be regarded as critical. The four situations analyzed at the 12 measurement points showed average illuminance levels of 101 lux (ZR4-6), 99 lux (ZR4-10), 176 lux (SE-12) and 88 lux (SE-21). Although such values correspond to a daylight factor of about 1% under 3000 bl as recommended for living rooms and most residential spaces by former BRS (Building Research Station) in the UK, they were obtained under unrealistic considerations of wide windows, white paints, no furniture and no curtains. Under practical conditions, such rooms are not suited even for leisure reading.Estimated improvement by adoption of H/6 was quantified as 31%, 99%, 84% and 387% respectively. Thus, illuminance levels turned satisfactory. The option for H/5 proved to be a further step into improvement of the indoor environment. However, it was discarded by the city office as a too extreme solution.

Looking deeper into the results, a strong dependency of illuminance levels on floor height was demonstrated. That confirms significant differences between the lowest and top floors and gives rise to a questioning on the need to adopt same floor partition scheme and window areas regardless of floor height.

The results sensitivity to the external coatings reflectivity became evident. In the practice, the city offers no constraints in the choice of the coating colors of side façades. Moreover, there is no regulation regarding maintenance of such façades – old buildings thus become light sinks for the surrounding buildings.

RESULTS: SOLAR IRRADIATION

Table 2 summarizes the simulation results. Adoption of H/6 allows in average but a modest improvement of the façades solar gains. The most significant improvement is for ZR4-10 (figure 1) and for SE-21 (figure 2), about 20% over the situation given by pre-2000 regulations.

Single orientations of front façade like S and SW show a considerable improvement. Even in those cases, in the same building, the different performance on each of the façades should encourage the pursuit of corresponding solutions for the apartments lay-out. It most significantly prevents one from adopting one- or two-axes symmetry when distributing apartments into each floor, as it is current practice in Brazil.

On the other hand, it explains the current practice of adopting different prices for apartments of same area, depending on orientation.

As the buildings front façades proved to be the only surface with potential to plenty of sunshine availability, there is the need to consider street width and orientation as a further limitation factor to buildings height.

CONCLUSION

The noticeable improvement of daylighting conditions was a strong argument for adoption of the least displacement criterion of H/6 in Curitiba, as it should be adopted in other cities as well. Discussions on the ideal population density can be assessed in order to cope with urban issues like transportation, water and sanitation. For the guarantee of a healthy indoor environment, H/6 proves that *proportion, more than absolute dimension of objects, plays an important role in defining what urban landscape is desired.* As a general criterion it proved better than the criteria applied under the former zoning regulation. However, a further refinement is possible.

Even under the constraints set by the zoning regulation, an acceptable environmental quality cannot be achieved without a careful consideration of climate, use and built landscape in the architectural design. A continuous effort to the capacity building of potential apartment buyers and renters can contribute to the establishment of a higher quality of buildings.

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NOMENCLATURE

d: distance from the measurement point to the light source (m)

E: illuminance on a work plan (lm/m² or lux)

L: luminance of a distributed light source (bl)

α: the azimuth angle of a light source regarding the measurement point

θ: inclination angle comprised between the vertical line through the measurement point and a light source

Tabela 1 Simulation results: daylighting. Influence of the side façades distances to the fences on the illuminance level (lux) in residential buildings in Curitiba, Brazil

	ZR4-6			ZR4-10		SE-12			SE-21	
Regulation	former	new		former	new	former	new		former	new
Building lot dimensions (m²)	30x15	30x15	30x15	30x15	30x15	30x30	30x30	30x30	30x30	30x30
Displacement of side façades regarding fences	2.5m	H/6	H/5	4.0m	H/6	2.0m	H/6	H/5	2.0m	H/6
Height (floors)	6	6	6	10	10	12	12	12	21	21
Height (m)	18	18	18	30	30	36	36	36	63	63
Simulation results as an average of two points, at ½ depth and ¾ depth, at 3.6m from the side window (lux)										
6th floor	900	978	927	719	949	564	893	1025	323	1026
5th floor	334	513	672	367	708	366	735	882	176	968
4th floor	184	305	464	217	579	305	619	759	154	918
3rd floor	174	252	386	183	512	295	577	694	154	872
2nd floor	174	250	386	178	476	292	537	660	154	839
1st floor	101	147	232	99	287	176	319	378	88	489
Average (1 to 6)	311.2	407.5	511.2	293.8	585.2	333.0	613.3	733.0	174.8	852.0
Improvement over Pre-2000		31.0%	64.3%		99.1%		84.2%	120.1%		387.3%

Table 2 Simulation results: Solar irradiation. Influence of the side façades distances to the fences on the total equivalent solar irradiation hours in residential buildings in Curitiba, Brazil

	ZR4-6			ZR4-10		SE-12			SE-21		
Regulation	former	new		former	new	former	new		former	new	
Building lot dimensions (m²)	30x15	30x15	30x15	30x15	30x15	30x30	30x30	30x30	30x30	30x30	30x30
Displacement of side façades regarding fences	2.5m	H/6	H/5	4.0m	H/6	2.0m	H/6	H/5	2.0m	H/6	H/5
height (floors)	6	6	6	10	10	12	12	12	21	21	21
height (m)	18	18	18	30	30	36	36	36	63	63	63
Simulation results (average irradiation hours on each of the front façade orientations)											
N	2.8	2.7	2.9	2.5	2.6	3.0	3.2	3.2	2.9	3.3	3.3
NE	2.6	2.5	2.7	2.2	2.2	2.6	2.5	2.7	2.3	2.5	2.5
E	2.1	2.1	2.2	1.7	2.0	2.1	2.3	2.5	1.9	2.6	2.8
SE	1.5	1.6	1.7	1.1	1.5	1.5	1.6	1.7	1.3	1.8	2.0
S	1.5	1.7	1.8	0.9	1.6	1.4	1.4	1.6	1.3	1.8	2.2
Average	2.1	2.1	2.2	1.7	2.0	2.1	2.2	2.3	1.9	2.4	2.5
Improvement over Pre-2000		0.6	7.2		16.4		3.6	10.7		24.3	32.2

Figure 1 - Simulation results for ZR4-6: equivalent hours of solar perpendicular irradiation on the building façades according to the orientation of the front façade. Average of the lowest 6 floors.

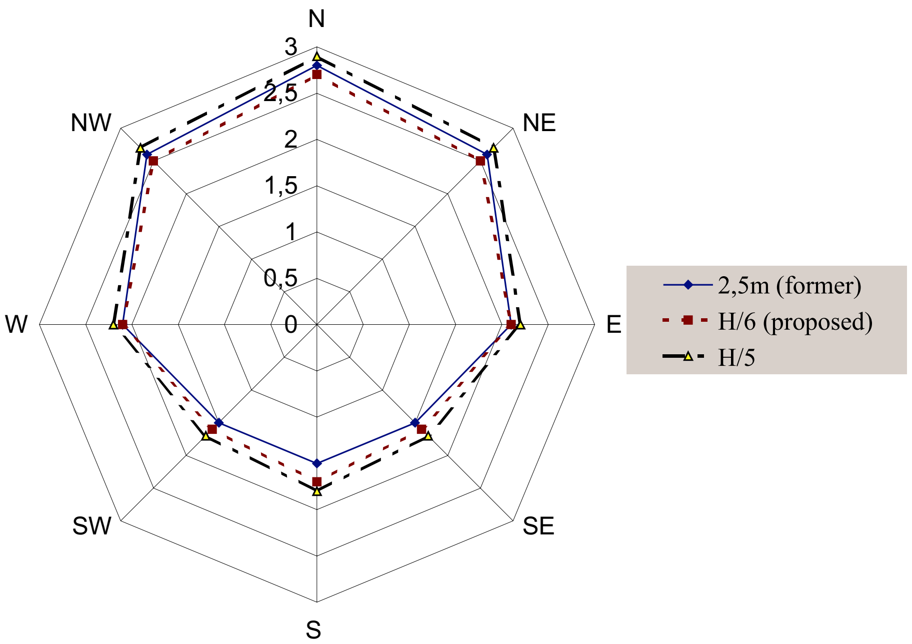
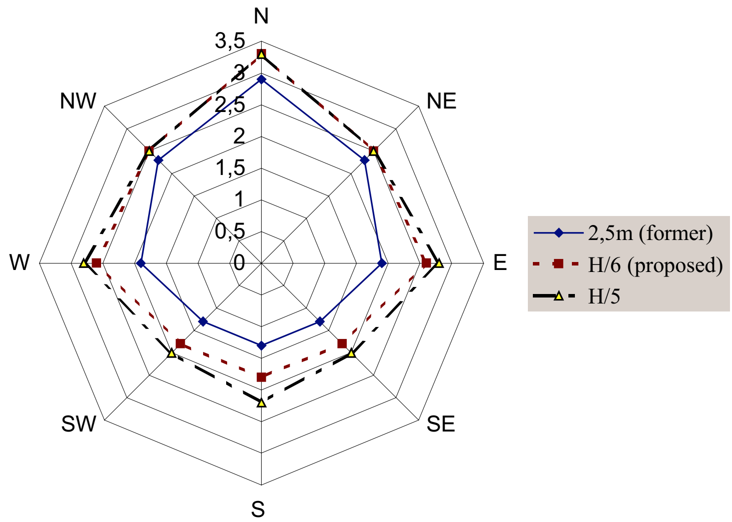


Figure 2 - Simulation results for SE21: equivalent hours of solar perpendicular irradiation on the building façades according to the orientation of the front façade. Average of the lowest 6 floors.



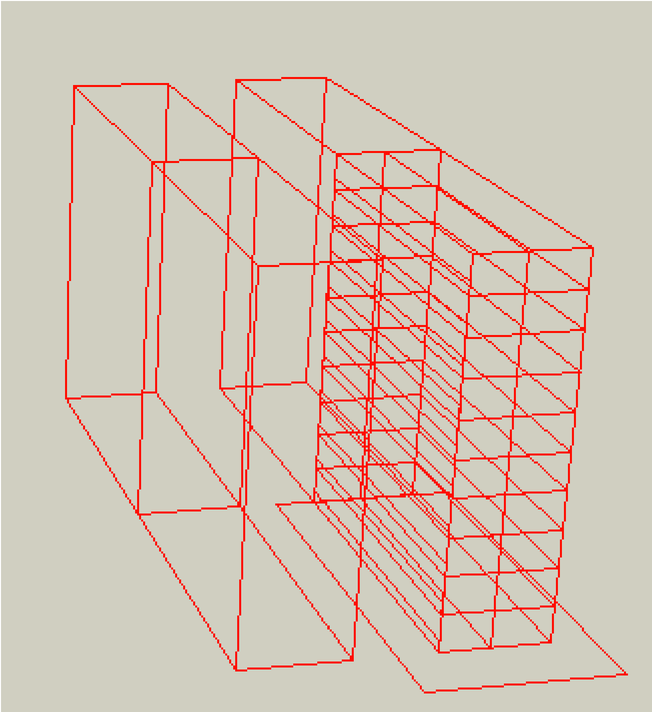


Figure 3 - A framework view of the ZR4-10 zone model (former zoning regulation) used for daylighting simulation. The right, front building was the simulation object. The remaining buildings were used to cause reduction of sky factor.

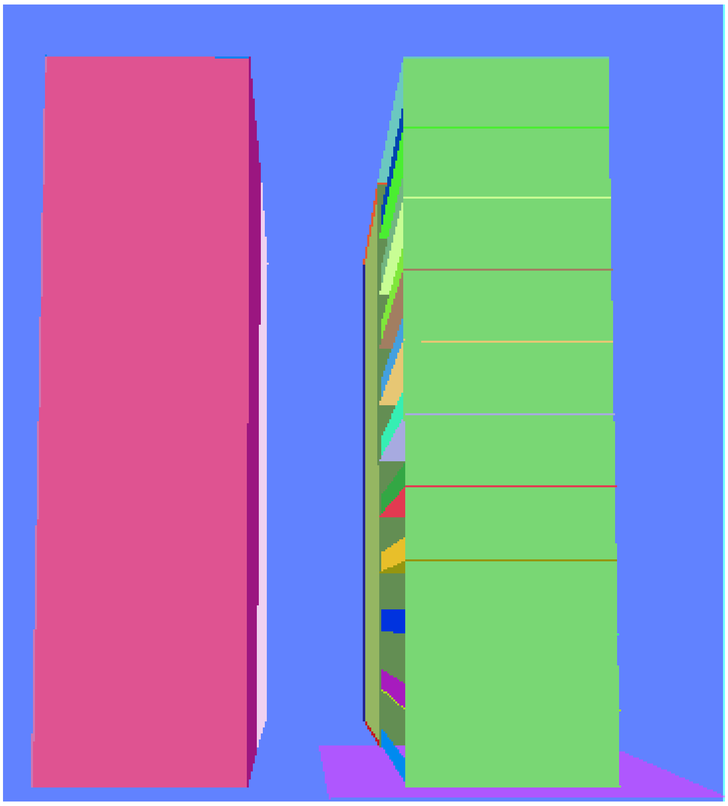


Figure 4 - A rendered view of the ZR4-10 zone model (former zoning regulation) used for daylighting simulation. The rectangle under the right building represents the building lot.