EFFECTS OF STREET DESIGN ON OUTDOOR THERMAL COMFORT

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Abstract: The paper deals with the dependence of outdoor thermal comfort on street design with emphasis on summer conditions in hot and dry climate. The effects of the height-to-width ratio (H/W) and street orientation, the asymmetry of the vertical profile, the use of galleries, overhanging facades, as well as the use of rows of trees were investigated. The study was conducted by means of the three dimensional model ENVI-met, which simulates the microclimatic changes within urban environments in a high spatial and temporal resolution. Thermal comfort is assessed by means of the physiologically equivalent temperature PET. The results reveal that the vertical profile and orientation of the urban canyon have a decisive impact on the human thermal sensation at street level, as well as all other design details studied. This is mostly because affecting the sun exposure and so the heat gained by a human body. Shading appeared as the most important condition of comfort in the summertime, which can be reached by an appropriate combination of all those urban design describers.

INTRODUCTION

The integration of the climate dimension in the design process is lacking because of poor interdisciplinary work between urban climatology, urban design and architecture. The disconnection observed so far between the sophisticated but theoretical results of the urban climatology on one hand and the more empirical but design-oriented findings of urban design on the other hand should be overcome in order to provide climate-related design guidelines readily understandable by the practitioners, as this has been widely emphasized (e.g. ***Oke, T.*** 1988, ***Arnfield, J.*** 1990, ***Golany, G.*** 1982, ***Givoni, B.*** 1997, ***Mills, G.*** 1999).

In the last years, the "climatic" quality of urban open spaces has become a central issue for both disciplines, as can be observed in many recent scientific meetings (e.g. *PLEA: Conference on Passive and Low Energy Architecture, or ICUC: International Conference on Urban Climate*) and in the practice-oriented literature (e.g. ***Herzog, T.*** 1996, ***Rogers, R.*** 1997, ***Asimakopoulos, D. N. et al.*** 2001, ***Littlefair, P. J. et al.*** 2001, ***Hawkes, D. – Foster, W.*** 2002, ***Thomas, R.*** 2003). Indeed, urban open spaces in general and the urban street in particular consist on "shared" active facets between the building envelope and the open urban canopy. Their design affects both outdoor and indoor environments.

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The present study deals with the contribution of street design, i.e. street geometry, solar orientation and further design details, towards the development of a comfortable microclimate for pedestrians focussing on the applicability of the results. A special emphasis is put on summertime conditions in hot and dry climate (***Ali-Toudert, F.*** 2005, ***Ali-Toudert, F. – Mayer, H.*** 2006a).

LITERATURE REVIEW

The urban canyon, which is a simplified rectangular vertical profile of infinite length, has been widely adopted in urban climatology as the basic structural unit for describing a typical urban open space, i.e. filtered from irrelevant non-climatic aspects. From these studies, basic knowledge on street microclimate was gathered (e.g. ***Nunez, M. – Oke, T.*** 1977, ***Hussain, M. – Lee, B. E.*** 1980, ***Oke, T.*** 1981, ***Nakamura, Y. – Oke, T.*** 1988, ***Oke, T.*** 1988, ***Todhunter, P. E.*** 1990, ***Yoshida, A. et al.*** 1990-1991, ***Santamouris, M. et al.*** 1999, ***Asimakopoulos, D. N. et al.*** 2001, ***Arnfield, J.*** 2003, ***Bourbia, F. – Awbi, H. B.*** 2004).

Basically, the height-to-width ratio (H/W) and street orientation were found to be the most decisive features affecting the microclimate of the urban street canyon. This includes

- the energy balance of the urban canyon,
- the potential of irradiation of canyon facets (i.e. floor and walls),
- the surface temperature,
- the amount of energy transported into the urban canopy layer by the sensible heat flux, which increases for sunlit surfaces and leads to a higher air temperature close to them,
- the potential of wind flow at street level, which sharply decreases in the urban street canyon.

The building materials of the canyon surfaces were also found to affect the diurnal heat storage rate of a street canyon as well as the nocturnal cooling rate. The potential of solar access inside the buildings and, by implication, the site layout and urban density are also directly related to the vertical street profile and orientation (e.g. ***Knowles, R. L.*** 1981, ***Capeluto, I. G. – Shaviv, E.*** 2001, ***Kristl, Z. – Krainer, A.*** 2001, ***Pereira, F. O. R. et al.*** 2001).

However, the relationship between urban geometry and thermal comfort is by far less well understood and the number of studies are very few (e.g. ***Swaid, H. et al.*** 1993, ***Pearlmutter, D. et al.*** 1999). On the other hand, urban design concepts for climate regulation do exist, which were gathered from a long history of building practice (e.g. ***Ali-Toudert, F.*** 2000, ***Knowles, R. L.*** 1981, ***Ravérau, A.*** 1981, ***Golany, G.*** 1982, ***Lechner, N.*** 1991, ***Krishan, A.*** 1996) and further implemented in new projects. Yet, the quantitative assessment of these solutions is lacking or performed with weak methods.

Assessing thermal comfort itself is another issue. Methods applied outdoors have been adjusted from those originally conceived for indoors by including the additional solar radiation fluxes. The state-of-the-art is to use thermal indices, which are derived from the human energy balance (e.g. ***Fanger, P. O.*** 1970, ***Givoni, B.*** 1976, ***Mayer, H. – Höppe, P.*** 1987, ***Jendritzky, G. et al.*** 1990, ***Höppe, P.*** 1993, ***Mayer, H.*** 1993, ***Pickup, J. – de Dear, R.*** 1999, ***ASHRAE*** 2001). It considers all meteorological factors significant to the human perception of heat (i.e. air temperature, air humidity, wind speed as well as the short- and long-wave radiation fluxes from the three-dimensional surroundings) and human data (e.g. metabolic rate, heat transfer resistance of clothing) Complementarily, social surveys may provide more information on the adaptive behaviour of people for keeping comfortable (e.g. ***Nikolopoulou, M. et al.*** 2001, ***Spagnolo, J. – de Dear, R.*** 2003).

METHODS

The present study analyses the dependence of outdoor thermal comfort upon street design under typical summer conditions (1st August) in Ghardaia, Algeria (32.40º N, 3.80º E), a subtropical region characterised by a hot and dry climate. The investigation is based on the three-dimensional model ENVI-met (***Bruse, M.*** 1999), which simulates the microclimatic conditions within urban environments in a high spatial and temporal resolution. Numerical modelling was chosen as suitable method for its fastness and low-cost (***Arnfield, J.*** 2003), which allows an easy comparison between manifold urban configurations together with their influence on urban climate.

Microclimatic conditions were simulated for selected urban canyons (*Figure 1*), which differ in the aspect ratio H/W, street orientation and a number of design details. Symmetrical urban canyons with H/W equal to 0.5, 1, 2 and 4 and for different solar orientations (i.e. E-W, N-S, NE-SW and NW-SE) were studied. In addition, asymmetrical profiles with different openness to the sky were investigated together with the role of galleries and overhanging facades. Urban street canyons including rows of trees were also studied as a further possible way to improve the outdoor thermal comfort in the summertime. The analysis focused on the local spatial differences across the street, i.e. street centre versus street edges (sidewalks), and was performed on a daily basis in order to deal with the subjective dimension of people's use and time of frequentation of the space.

Moreover, a special emphasis was placed on a human-biometeorological assessment of these microclimates by using the physiologically equivalent temperature PET (***Mayer, H. – Höppe, P.*** 1987, ***Höppe, P.*** 1993, 1999) as well suited thermal index.

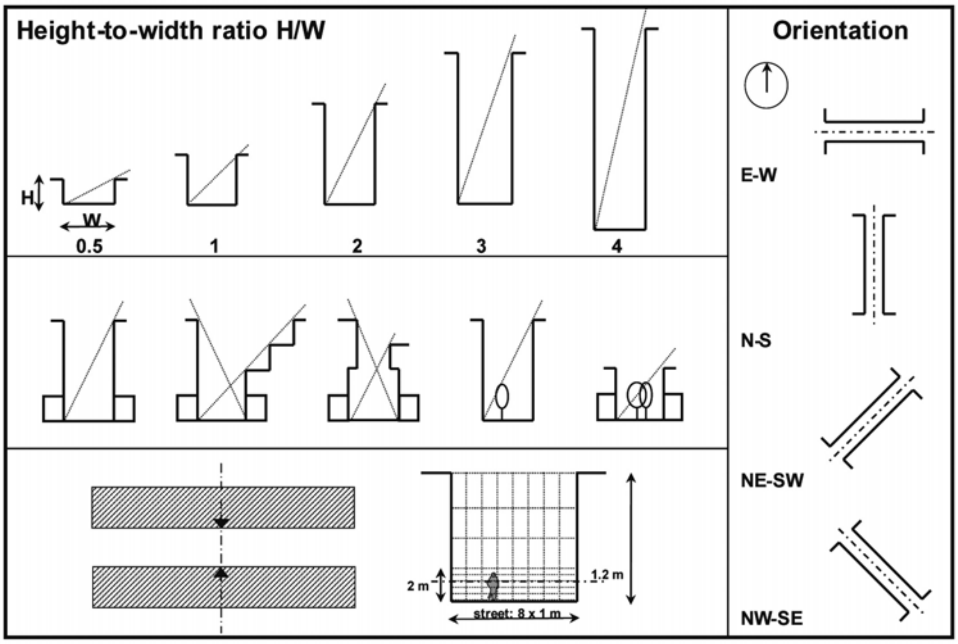

Figure 1 Scheme of the urban canyon geometries simulated by use of the ENVI-met model

RESULTS AND DISCUSSION

Air temperature T_a

The daytime evolution of T_a on a typical summer day was simulated for H/W varying from 0.5 to 4 as well as E-W and N-S orientations. T_a decreases moderately with the increase of the aspect ratio H/W (*Figure 2*) showing a peak difference of 3 K between the canyons with H/W = 4 and 0.5 around 15:00 LST.

The heating rate of the canyon air reflects the irradiances patterns of the canyon facets since sensible heat transferred to air increases with increased solar exposure. Hence, air temperature maxima ($T_{a,max}$) in deep canyons were reached at different times of day according to the orientation, in particular as the aspect ratio increases. Explicitly, $T_{a,max}$ occurs in the early afternoon for N-S canyons and in the late afternoon for E-W canyons, which corresponds to the time of the largest solar exposure of canyon facets for each orientation, respectively.

The whole simulations also revealed that the use of geometrical irregularities in the vertical profile has a weak impact on T_a in comparison to a simple geometry. Yet, a larger openness to sky of the canyon (i.e. higher sky view factor) showed an evidence to heat more in the daytime and cool faster in the evening (***Ali-Toudert, F.*** 2005). In contrast, T_a was found to decrease up to 1.5 K if rows of trees were available, mostly because of less warming of the ground in shade (***Ali-Toudert, F. – Mayer, H.*** 2005).

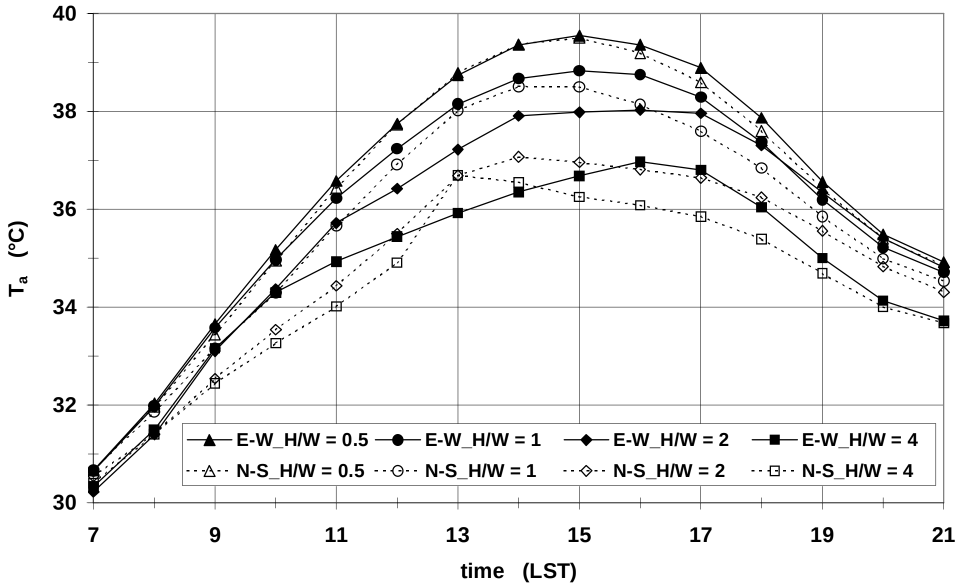

Figure 2 Diurnal variation of the simulated air temperature T_a at street level in urban canyons with aspect ratios H/W from 0.5 to 4 and for E-W and N-S orientations, typical summer day (1st August) in Ghardaia, Algeria (32.40º N, 3.80º E)

Physiologically equivalent temperature PET

The results for the simulations of PET (*Figure 3*) reveal that the thermal comfort is difficult to reach passively in a region with subtropical hot and dry climate. PET maxima amount to 68 ºC and PET minima are in all cases by few degrees higher than T_a (up to 4 K). Nevertheless, improvements are possible by means of appropriate geometrical choices. Basically, contrasting patterns in the comfort situation were found between shallow and deep urban street canyons as well as between the various orientations studied. The duration and time of day of extreme heat stress as well as the spatial distribution of PET across the canyon depend strongly on the aspect ratio H/W and street orientation. Wide streets (H/W ≤ 1) are highly uncomfortable for both orientations. Yet, N-S streets have some advantage compared to E-W streets as the thermal conditions at their edges along the walls are thermally less stressful for people. This advantage is also reflected by a shorter period of heat stress and lower PET maxima. Increasing the aspect ratio ameliorates the thermal comfort for both E-W and N-S orientations, but the N-S orientation still offers better thermal situation for people. For shallow canyons, implementing shading strategies at street level (galleries, trees, etc.) is the only way to improve substantially the human thermal comfort.

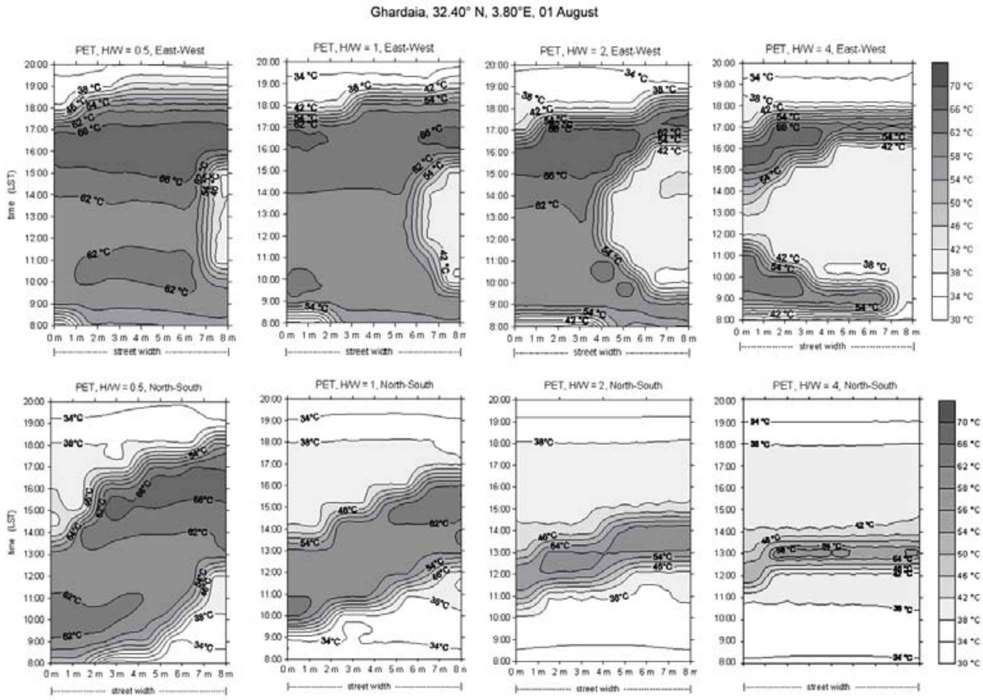

Figure 3 Spatial and temporal distribution of the thermal index PET at street level in urban canyons with aspect ratios H/W from 0.5 to 4 and for E-W and N-S orientations, typical summer day (1st August) in Ghardaia, Algeria (32.40º N, 3.80º E)

The differentiated thermal situation observed across the street (centre and edges) is also worthy of note since this will directly influence the design choices in relation to street usage, e.g. streets exclusively planned for pedestrian use or including motor traffic, and also the time of frequentation of urban spaces. These results also confirm the dominant role of the sun exposure, more precisely the radiation fluxes expressed by the mean radiant temperature T_{mrt} under summer conditions. A pedestrian absorbs energy from the irradiated surrounding surfaces and from a direct exposure of his body. This fact points out the necessity of shading as a main strategy for keeping the street area in a thermal comfort range (***Ali-Toudert, F. et al.*** 2005, ***Ali-Toudert, F. – Mayer, H.*** 2006b). Air temperature was found to be a secondary factor in influencing the human thermal comfort, since it is only moderately affected by urban geometry changes (***Ali-Toudert, F. – Mayer, H.*** 2006a).

For the same aspect ratio, intermediate orientations NE-SW and NW-SE (***Ali-Toudert, F. – Mayer, H.*** 2006a) show some similarity in the temporal and spatial evolution of the thermal situation with a N-S oriented urban street canyon. By contrast, these orientations experience a noticeably shorter period of time of discomfort than E-W streets, with the street being always partly in shade.

Effects of design details

Using galleries (*Figure 4*) reveals to be beneficial for mitigating thermal stress (for details see ***Ali-Toudert, F.*** 2005). This is due to the reduced direct solar radiation received by a human body and to less long-wave irradiation emitted by the surrounding surfaces, in particular the ground.

However, discomfort can shortly extend under galleries when the sidewalks in the "open" street area already experience extreme thermal stress (see e.g. *Figure 5*) as a consequence of direct irradiation of the pedestrian and the ground surface. This is more marked for wide urban street canyons and depends on street orientation as well as gallery's height and width (here each gallery was 3 m wide and 4 m high). The galleries of an E-W street are best protected as well as a SE gallery in a NE-SW oriented street. The asymmetry, as expected, increases the sun exposure of the street and hence the

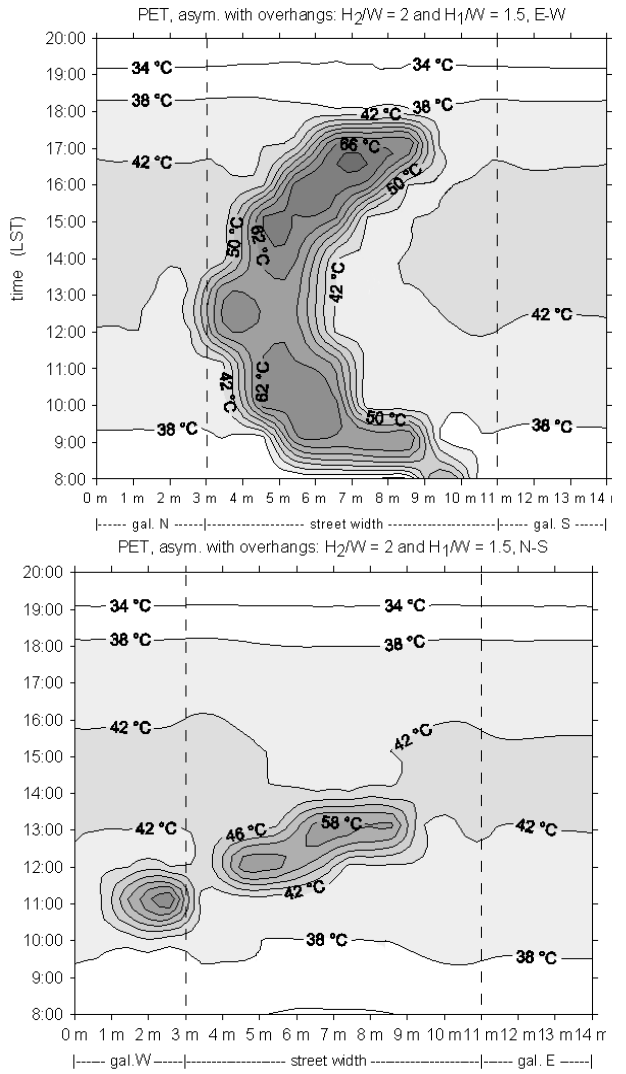

Figure 4 Spatial and temporal distribution of the thermal index PET at street level in an asymmetrical urban canyon with galleries and overhanging facades for E-W and N-S orientations, typical summer day (1st August) in Ghardaia, Algeria (32.40° N, 3.80° E)

thermal stress. Yet, the asymmetrical profile investigated ($H_1/W = 2$, $H_2/W = 1$) shows a better thermal situation than a symmetrical street with H/W = 1 in the morning and late afternoon as well as a trend to cool faster than a canyon with H/W = 2.

Overhanging facades as horizontal shading devices (can also be balconies) help to increase substantially the area and duration of shade at street level and reduce further the heat stress as shown in *Figure 4* (***Ali-Toudert, F.*** 2005). Maximal values of PET also slightly decrease. This design solution is advisable if combined with an asymmetrical profile: On one hand, there is more shading at street level in summer and on the other hand more internal solar access is ensured in winter. Moreover, these "self-shading" facades reduce the overheating of indoor spaces by less warming of their surfaces and hence less heat conduction towards indoors.

Effects of vegetation

The use of a row of trees improves the thermal comfort situation within the urban street canyon, mostly because the direct solar radiation under the tree canopy is strongly decreased (*Figure 5*).

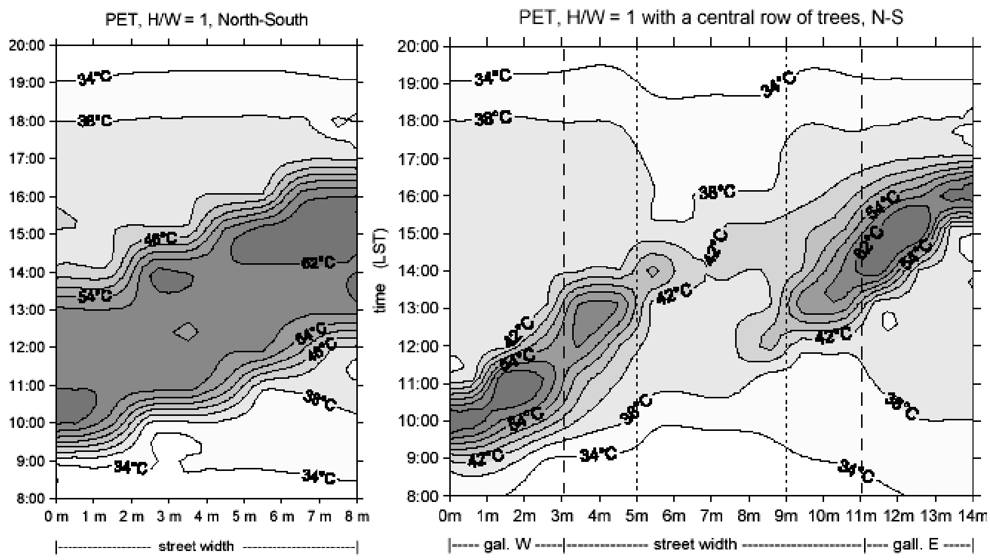

Figure 5 PET at street level in an urban canyon oriented N-S (H/W = 1) with and without trees and galleries (---- footprint of the central planted area; – – – footprint of the galleries), typical summer day (1st August) in Ghardaia, Algeria (32.40º N, 3.80º E)

So, shading is the main property of the vegetation that leads to heat stress mitigation. However, almost no extent of these advantages could be observed in the surrounding space, as also noted experimentally by ***Shashua-Bar, L. – Hoffmann, M. E.*** (2000).

Depending on the use of the street, a row of trees (central or on the sidewalks) may be planned on the areas of pedestrian. For deeper urban street canyons, vegetation seems to be more relevant for E-W than for N-S orientation due to the much longer period of discomfort. For N-S oriented streets with H/W > 1, the time of discomfort is limited to a short period around noon and may not necessitate planting. The optimal location of trees within the street canyon also depends on street orientation and on aspect ratio. For E-W orientation, the highest discomfort period occurs on the north side during a large part of the day suggesting the use of trees at this location.

CONCLUSIONS

This study showed that all features of urban street canyons influence the human thermal comfort with a differentiated situation across the street between centre and edges. Hence, manifold possibilities by means of design are available to control the thermal environment of people. In summer, shading is the key strategy for promoting thermal comfort in hot and dry climate. This can be reached by (1) a judicious choice of aspect ratios and orientation and (2) arranging complementary solutions, e.g. galleries, planting trees, or shading devices on the facades. A climatic-conscious street design must also take into account:

- street utility, i.e. structural role of the street in the whole urban plan, implying scale, activity and use (pedestrian streets or including motor traffic). This has a direct impact on the absolute dimensions of the street (i.e. width and height), the period of time at which thermal comfort is essential (frequentation time by people) and the area of the street where thermal comfort is at most required (whole area, edges etc.).
- building use: domestic (housing) or non-domestic (e.g. office or educational buildings). Domestic buildings are concerned with thermal comfort the day round and require passive solar gains. South, south-east or east exposures of the facades are the most suitable. In non-domestic buildings, comfort is mostly crucial during the daytime where day-lighting is the main concern. The potential of natural light is almost equal for all solar orientations and is much more sensitive to the sky view, i.e. aspect ratio.

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