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Urban Morphology and Microclimate: Street Design and Layout Effects on Air and Solar Access in Urban Canyons

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Abstract: There is broad consensus among scientists that urban climate has effective impacts on the indigenous and world climate which is subjected to several parameters such as urban morphology, mass density, urban transportation, and the properties of plants and urban geometry; of which inappropriate application can cause significant changes to create a special microclimate of urban zones. Therefore, to create this, as a main gold of sustainability, concentrating on streets as a main part of urban geometry is essential as the orientation and street design have a significant roles in term of solar irradiation absorption by surface. This study deliberates the recent works and suggestions for the special effects of street geometry and design on the urban microclimate with emphasizing the effects of streets geometry and orientation on airflow and solar access in an urban canyon. These investigations have shown that Specific design of street's geometry and orientation are very necessary to achieve a desirable urban microclimate in an urban canyon with a view to sustainability.

Keywords: Urban morphology, Urban microclimate, airflow and solar momentum, street's orientation and geometry.

1. Introduction

Urban climatology is a science shared between urban designers and climatologists [1]. In the last two decades, substantial advances have been made in the understanding of the scientific basis of urban climates. In addition, urban microclimate analyses are being used more and more to address the planning decision process to create livable and healthy public spaces [2]. Thus, the urban designers were more attracted to the impacts of the environmental forces on buildings, indoor climate of buildings, design strategies, energy requirements of supporting indoor comfort, and passive solar gains, since 1973`s oil crisis [3]- [4]. The urban designers have also gradually switched to urban geometry issues associated with rapid urban development.

It is important to note that urban morphology and city formation have special effects on their own climates. Urban climate is an essential parameter which has direct effects locally and globally in term of climate and thus urban livability [5]- [7], urban geometry, urban density, urban transportation, water levels and the properties of surfaces and plants. The unseemly usage of aforementioned parameters enhances to the rough treatment of nature and in this manner, making the temperature in the urban regions higher than in suburbia. This phenomenon called the urban heat island (UHI) [8]. This effect can increase energy resource consumption, change humidity levels, and worsen air pollution [9]- [10]. In the same line, the microclimate environmental issue of urban street has become major issue for both urban designers and climatologists [11]- [12]. Previous studies indicate that several factors affect the microclimate of the urban streets, such as urban geometry, properties of surfaces, surface and forms characteristics, and the vegetation [13]- [15]. The improper functions of these factors have increased the environment's harshness and global warming [16]. Prior researchers express that street geometry is the most effective factor impacts on street microclimate changes [17]- [20], and residents' health [21]. Therefore, the main reasons of forming UHI including heat trapping by urban geometry, properties of urban surfaces, replacement of vegetation by expansively built surfaces cover and the anthropogenic heat sources [22]- [24]. As a matter of fact, the term "heat island" describes built up areas that are hotter than nearby rural areas. The annual mean air temperature of a city with 1 million people or more can be 1.8–5.4°F (1–3°C) warmer than its surroundings. In the evening, the difference can be as high as 22°F (12°C) [25]. Furthermore, as more than a quarter of the urban regions are normally covered by streets, reasonable designing of urban streets is essential as a vital part to make an appropriate urban design and it has a significant role to create the urban climate. The urban streets vary in geometry as defined by height/width ratio (H/W) and length/width (L/W) and also the orientation that is defined by its long axis. These parameters directly influence the absorption and emission of solar radiation and also urban ventilation which have an important effect on the temperature variations within the street as well as the surrounding environment (UHI) [26]. This study analyses the recent works and make suggestion for the effects of street design on the urban microclimate concentrating on the effects of streets geometry (H/W ratio) and orientation of airflow and solar momentum in an urban street canyon with a view to sustainability.

2. Urban Morphology and Urban Design

Urban morphology as "knowledge of urban form", describes the city as "the most complex of human invention" in intersection between nature and artifact [27]. Urban morphologists have a same opinion that they analyze a city changes from its initial formation to subsequent developments with identification and description of its various components. City is results of Accumulation and integration of many collective activities which are unique and small that they are guided by cultural traditions and have been shaped by social and economic forces over the years. Urban morphologists concentrate on tangible results of economic and social forces: they study results of ideas and decisions, because they (ideas and decisions) create forms on the earth and give mold (objectivity) to our cities. Buildings, gardens, streets, parks and mountains are the main elements of morphological analysis. These elements are considered as organisms that are used constantly and afterwards change over time. They also have a dynamic and strong relationship with each other: structures formed by open spaces that around them are being formed and give them the shape, the public streets are serving private land owners, who are along them, and by them are used. Dynamic status of the city and inclusive relationship between its elements, has led many urban morphologists to prefer "urban morphogenesis" name for their field of study description [28]. Furthermore, urban design involves the arrangement and design of buildings, public spaces, transport systems, services, and amenities. Urban design is the process of giving form, shape, and character to groups of buildings, to whole neighborhoods, and the city. It is a framework that orders the elements into a network of streets (open spaces), squares, and blocks. Urban design blends architecture, landscape architecture, and city planning together to make urban areas functional and attractive [29]. In addition, keeping in mind the aforementioned points; there is a significant relation between urban morphology and urban design of which street design (open spaces) playing an essential role as a main part in these topics (Fig. 1) [30].

Fig.1.street design (open spaces) playing an essential role as a main part in urban morphology and urban design [30]

3. Urban Microclimate and Urban Canyon

A street canyon (also known as an urban canyon) is a place where the street is flanked by buildings on both sides creating a canyon-like environment [31]. It refers to the space which is formed by two typically parallel rows of buildings separated by a street and it creates the basic unit of modern cities [32]. Ideally a street canyon is a relatively narrow street with tall, continuous buildings on both sides of the road. But now the term street canyon is used more broadly and the geometrical details of the street canyon are used to categorize them. The most important geometrical detail about a street canyon is the ratio of the canyon height (H) to canyon width (W), H/W, which is defined as the aspect ratio. The value of the aspect ratio can be used to classify street canyons as follows [33]. If the canyon has an aspect ratio of around equal to 1 with no major openings on the walls it is called a regular canyon (*uniform street canyon)*. A canyon with an aspect ratio below 0.5 is a *shallow street canyon (avenue canyon)*; and the aspect ratio of 2, represents a *deep street canyon* (Fig. 2).

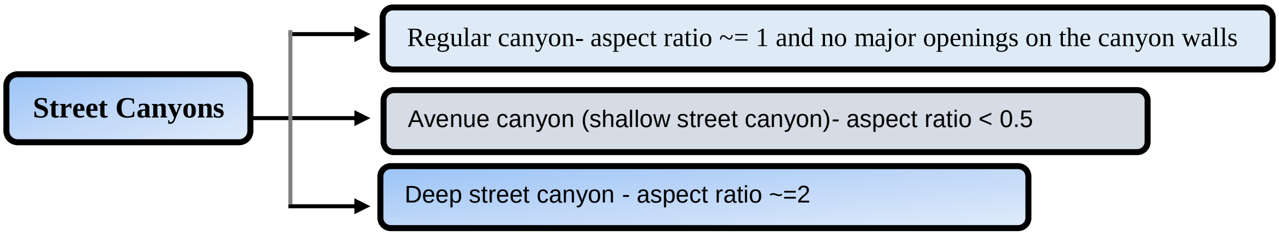


Fig.2.Category of Street Canyons [31].

The length of canyon (L) illustrates the road distance between two main intersections subdividing the street canyon into *short* (L/H= 3), *medium* (L/H = 5) and *long* (L/H = 7) (Fig.3). [34].

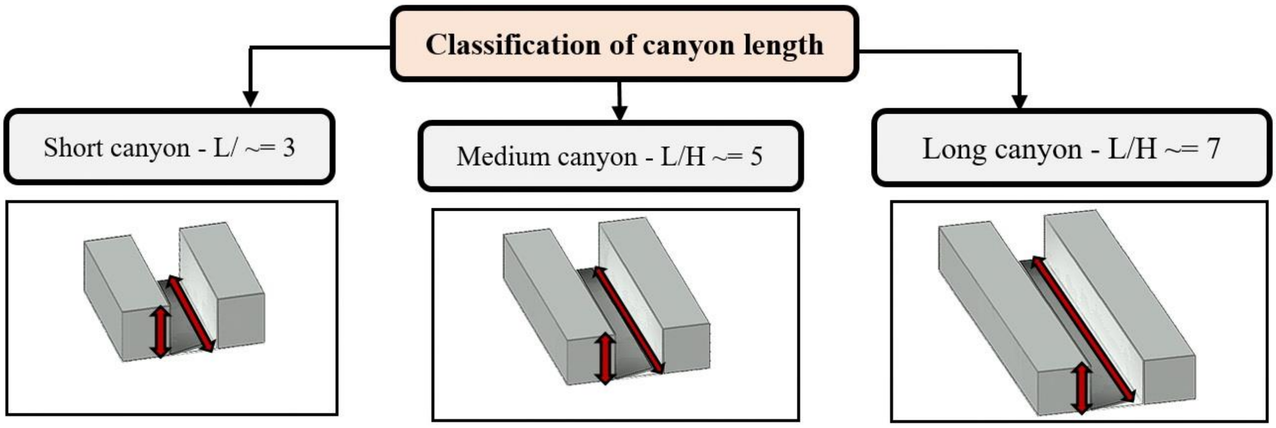


Fig.3. A classification above can be done depending on the distance between two major intersections along the street; defined as the length (L) of the street canyon [31].

Urban canyons contribute to the urban heat island effect. The temperature inside the canyon can be elevated 2-4 degrees [35]. The length of it has been proved that the geometry and orientation of the street canyon affect outdoor and indoor environments, solar access inside and outside the buildings, the permeability to airflow for urban ventilation, as well as the potential for cooling of the whole urban system. Moreover, the street design influences the thermal comfort at pedestrian level as well as the global energy consumption of urban buildings.

From a climatic point of view, in designing a street, the main complexity faced by the designer is the difference in the seasonal internal and external desires. For instance, in summer protection from the sun and in winter solar access are required. In theory, these imply compactness and openness to the sky, respectively [36].

According to the most related studies, street canyon geometry's parameters (height-to-width ratio (H/W)) and the street orientation are the most relevant urban parameters responsible for the microclimatic changes in a street canyon [37]- [38]. These parameters directly affect the potential of airflow at street level, solar access and therefore urban microclimate [39]- [40].

Even though, traditional and contemporary architectures make a lot efforts to design urban streets according to climate with a view of sustainability, quantitative information about the best possible street design, based on scientific methods, in order to regulate the climate comfort is still required [41]- [42].

4. Effects of Urban Street Canyons On Airflow

Studies of wind in urban canyons include both modeling and observation [43]. Wind in urban street canyons is essential for dispersing heat and pollutants. Furthermore, understanding wind in these canyons relies on basic principles of fluid dynamics [44]. Urban airflow patterns are determined by the interaction between an approaching wind with the built environment. The formation of airflow within a street canyon is necessary for human health, outdoor and indoor thermal comfort, air quality, the energy efficiency of buildings and as a result, providing a pleasant urban microclimate [45]- [46]. For example, the cooling effect of airflow, mainly at night, could mitigate effects of urban heat island phenomenon. Several studies indicate that the pattern of an existing regional wind is changed when it flows through a built environment [47]. Thus, designing built environment and especially street canyon is an essential point in formation of urban airflow patterns. Below are three examples of how canyon geometry can affect airflow [48].

Channelization effect: An ideal situation for flushing out pollutants, but one that can lead to pedestrian discomfort, the channelization effect occurs when the wind is moving parallel to the canyon's orientation. The severity of this effect is primarily a function of the wind's speed and the total length, the average width, and the average height of the canyon. Venturi effect: The speed of wind increases when it funnels through small openings. This is again uncomfortable for pedestrians, but an excellent way to disperse pollutants. The severity of the Venturi effect is a function of width, length, height, and size of openings in the canyon. Bar effect: The Bar effect occurs when air flows over a street canyon at a 45-degree angle. On the opposite side (leeward) the wind speeds up. This effect depends on the width, length, and average height of the sides and size of the openings in the canyon (Fig.4).

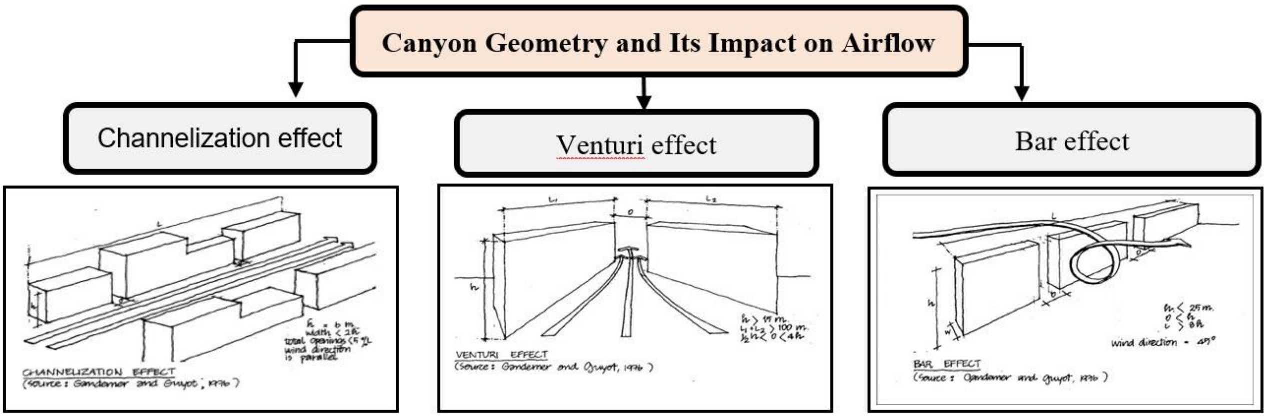


Fig.4. three examples of how canyon geometry can affect airflow [48].

The air over urban areas could be divided into main layers: urban canopy layer and urban boundary layer. The urban canopy layer is the layer blow roof tops in the spaces between buildings and influenced by solar energy falling on building facades and ground. The urban boundary layer is above the average height of buildings. Heat transfer, pollutant emission, evaporation and transpiration and generally contemporary urban development are the main factors affect air temperature in urban boundary layer [49]. Due to barriers such as buildings and trees, airflow in the urban canopy layer is more blocked in comparison with airflow in the urban boundary layer. Therefore, there is slower airflow in the urban canopy layer than in surrounding rural areas [50]. A secondary circulation feature driven by urban boundary layer provides airflow in a street canyon which is strongly affected by the street orientation and geometry (H/W and L/W) [51]. A combination of those effects can lead to different flow patterns depending on the aspect ratio of the canyon when the airflow in the urban boundary layer is approximately normal to street axis. For instance, the aspect ratio can determine the difference between isolated roughness flow, wake interference flow, and skimming flow as illustrated below [52]- [54] (Fig. 5).

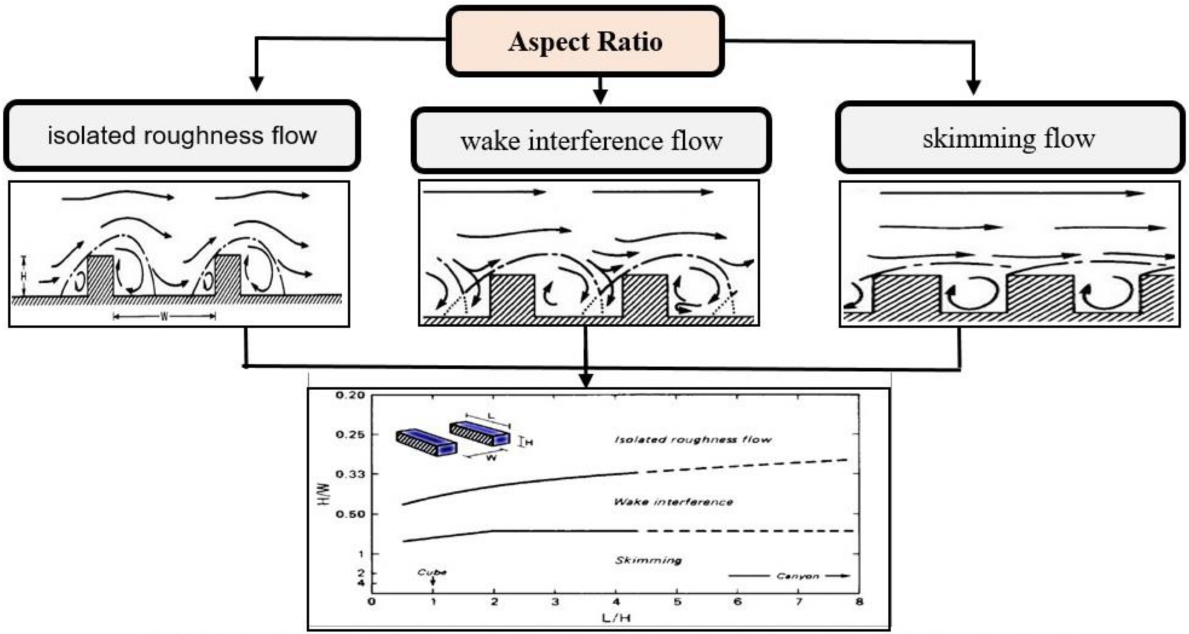


Fig. 5. Different flow patterns depending on the aspect ratio of the canyon [51-54].

The isolated roughness regime takes place between well-spaced buildings, when there is no interaction between windward and leeward flows, similarly to a wind movement around an isolated barrier. By increasing the H/W ratio, the wakes are disturbed leading to a wake interference regime. Further increase of H/W ratio makes the street canyon isolated from the circulating air in the urban boundary layer and therefore, a steady circulatory vortex is created in the canyon. This stable circulatory vortex brings about a skimming regime which is the most frequent in urban areas [17]. Moreover, it could be concluded that there is slower airflow in deep street canyons in comparison with uniform or shallow ones. The effects of street design on airflow have been investigated in many studies. For instance, Johansson [27] studied the influence of street geometry on airflow has been studied in Morocco as case studies with real site measurements for a period over 1.5 years. Both deep and shallow street canyons with aspect ratio of 9.7 and 0.6 respectively were studies in detail. The results illustrated an obvious relationship between street canyon geometry and the microclimate within an urban canyon (1.7 m). This study shows that the wind speeds are slower and more stable in the deep canyon (0.4 m/s) in both winter and summer seasons. while the shallow street canyon had an average wind speed of 0.7 m/s in summer and 0.8 m/s in winter. In another study by Al-Sallal and Al-Rais [47] in Dubai, it has been proved that narrow street canyons (4 m and less) could increase wind speed passing through it, resulting in a better passive cooling performance yet creating eddies at bending angles. When the wind speed was higher (5 m/s), wind reached deeper inside the traditional narrow streets providing better potential for thermal comfort. Most locations (49-57% of the studied area) with street canyons aspect ratio of 2-0.67 had wind speeds that ranged from light to gentle breeze.

In addition, some studied assessed the impacts of building's heights on the airflow within a street canyon. In this term, Priyadarsini and Wong [56] found that strategically placing a few blocks of high-rise towers will improve the velocity within the street canyon when the airflow in parallel or perpendicular to the canyon. In addition, the temperature was lower when high-rise towers were placed in a street canyon. By placing some high rise towers, the velocity is increased by up to 90% for parallel flow and the temperature is decreased by up to 1°C. For perpendicular flow, the velocity is increased up to 10 times and the temperature is decreased by 1.1°C. Furthermore, Robins and Macdonald [52] discovered that additional wakes create additional air exchange and U-shaped vortices could occur by designing a few tall buildings among surrounding buildings restricted in the urban canopy layer (Fig.6A). Upstream tall buildings would bring about more vertical flow up from the street canyon to the urban boundary layer. Downstream buildings would create additional vertical flow down from the urban boundary layer into the urban canopy layer. Furthermore, providing adequate openings between streets and courts improves air exchange within the urban canopy layer. In addition, it has been proved by Chan et al. [57] who discovered that better ventilation could be provided by different building heights. Thus, tall buildings do not essentially promote obstacle. Furthermore, they found out that better mixing of air is brought about by a wider urban canyon and street geometry should be limited to threshold value for skimming flow and the maximum relative canyon length ratio L/H should not be more than five. In addition to streets geometry and orientation, the configuration of street could affect the air flow at canopy layer. Streets which are straight and parallel to each other would promote air movement into and within the urban areas. Lack of vegetation and appropriate covers in straight streets causes severe heat (in hot-dry climate) or cold (in cold- dry climate) wind blow into the streets due to straight air movement [51] (Fig.6B). Narrow and winding streets reduce cold or hot winds and decrease the influence of stormy winds (Fig.6C). This pattern is proper for tow stressful climates (hot-dry and cold-dry) [51].

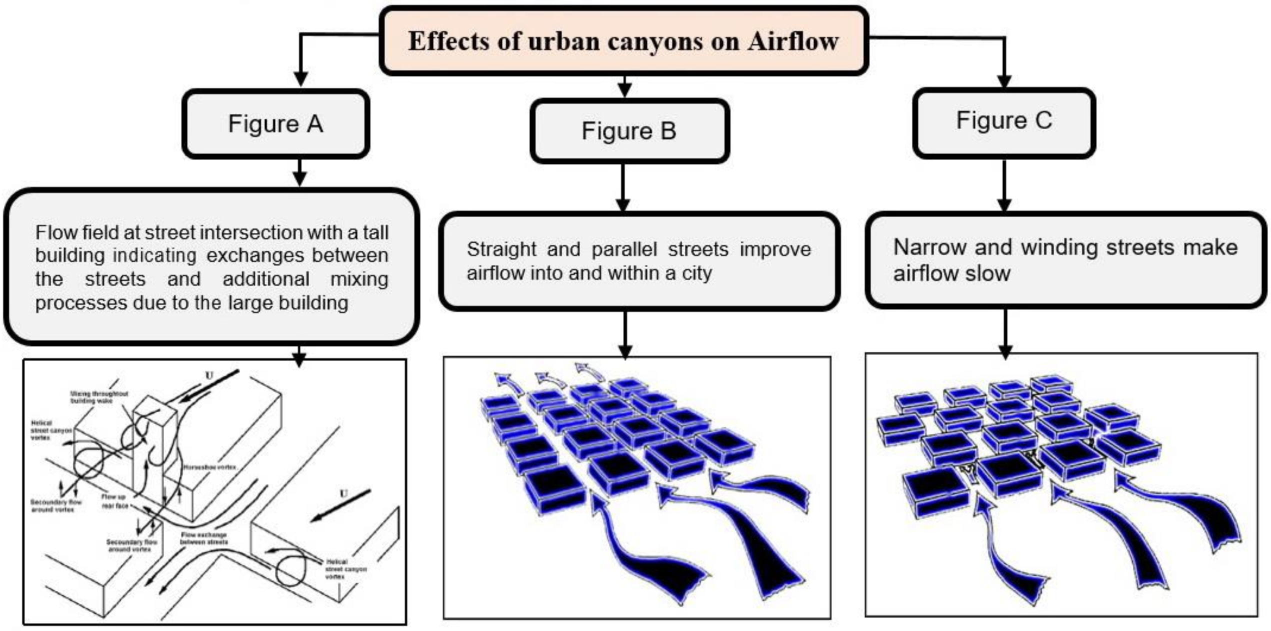


Fig.6(A-b-c). Different flow patterns depending on the aspect ratio of the canyon [51].

5. Effects of Street Design On Solar Access

The effect of the sun on the climate is prominent. Solar energy falling on an urban area is received either by buildings facades and roofs or by the ground between buildings. From the urban street canyon point of view, the amount of solar radiation could directly influence the solar access and hence, thermal comfort at pedestrian level. Thus, designing urban streets in a way which utilize solar access in urban canyon is vital to improve urban microclimate.There are several studies which have evaluated the impacts of street's geometry and orientation on solar access within an urban canyon. Arnfield [24] investigated the amount solar access in different urban canyons by using a numerical method. The purpose of this paper was to discover the dependence on aspect ratio and orientation of the irradiances on canyon facets (walls and floor) and on a pedestrian model. The research was conducted for E-W and N-S street's orientations for all latitudes and seasons. Furthermore, aspect ratios ranging was considered from 0.25 to 4. Evaluating the monthly average irradiations illustrated that the H/W ratio first influences the quantity of solar energy received by buildings and ground between buildings in a street canyon. By reducing the H/W ratio the amount of solar energy received by the street surfaces increases (Fig. 7). Nonetheless, this solar energy is not distributed equally on the various surfaces of the urban street. Fundamentally, the ground receives more solar radiation in comparison with vertical surfaces (walls). For a same street canyon, the H/W ratio impacts the ground more than the walls.

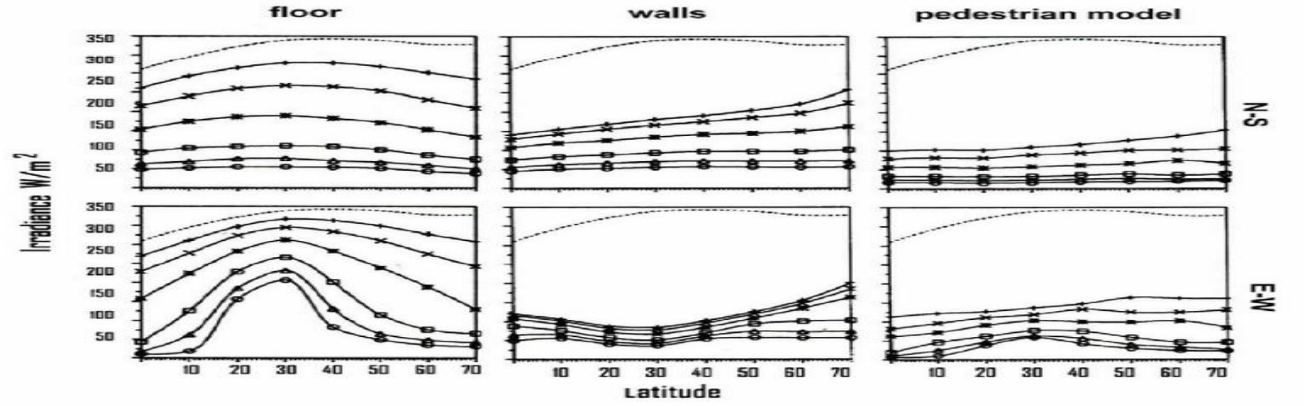


Fig. 7. Monthly mean canyon irradiances simulated for June for E-W and N-S canyons and different aspect ratios. The symbols +, x, *, □, Δ, ○ correspond to H/W = 0.25, 0.5, 1, 2, 3, and 4 respectively [24].

This study Arnfield [24] found out that the orientation of the street is more affective on the amount of solar energy obtained by walls and H/W ratio influences the availability of solar energy on the ground. In addition, the impact of orientation is more significant in summer than in winter. There is an easier seasonal solar control for the buildings walls oriented N-S (i.e. E-W streets) as the walls are protected in the summer and exposed in the winter. For the pedestrian, the orientation hardly affects the irradiations. For higher latitudes, the sun position is lower in the winter and creates strong obstacles. Thus, the irradiances reduce for high latitudes and this is especially obvious for the E-W orientation. The effects of H/W ratio and orientation of streets on receiving solar energy by ground and other street surfaces are more significant in latitudes 20°- 40° in different seasons. This illustrates that in the subtropics climates, street geometry is more important for the solar control.

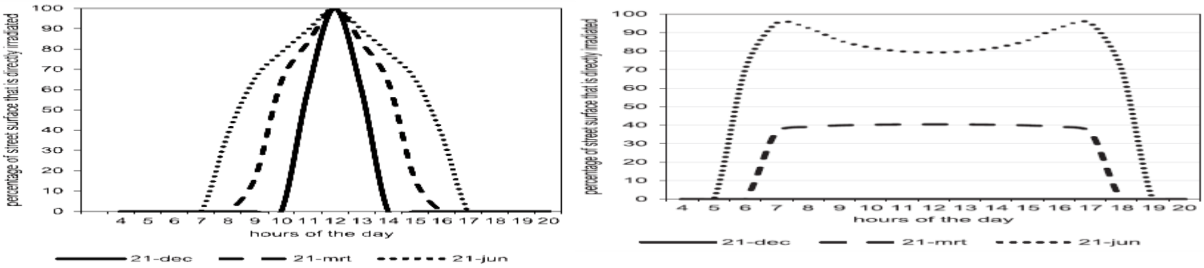
Former study has been proved by Van Esch et al [52] who analyzed the effects of street design parameters (width and orientation) on solar access to the urban canopy. They studied four street widths: 10, 15, 20 and 25 m, with two orientations; E-W and N-S. All calculations and simulations are conducted with actual weather data for De Bilt, The Netherlands (52◦06_N and 5◦11_E) of the year 1995.

Street width (m)	December 21st	March 21st	June 21st
E-W street orientation			
10	13.6	57.8	**124**
15	16.0	68.0	**146**
20	18.5	78.6	**169**
25	21.0	89.2	**193**
N-S street orientation			
10	13.8	56.6	**124**
15	16.1	66.8	**147**
20	18.5	77.2	**170**
25	**20.9**	**87.6**	**193**

Table 1: Total Radiation Yield of the Canyon in Kwh/M for Different Street Directions, Typical Dates And Street Widths with Flat roofs [52].

Table1 indicates the impact of increasing the street width. As shown, street width significantly affects the total global radiation yield of the canyon. For all studied canyon, increasing street width from 15 m to 20 m increases the radiation yield with 17–20%. In different seasons the relative increase in radiation yield is more or less equal – about 19% per 5 m increase of the street width. However, the absolute increase differs quite strongly; as the radiation yield is rather low in winter; an extra 19% means only a few kWh/m, while in summer it is an extra 20–25 kWh/m [52].

Even though street orientation hardly affects the total global radiation yield of the canyon, it brings about differences in the distribution of the total radiation yield over the different street surfaces – ground, facades and roof. Street orientation significantly influences the diurnal and seasonal pattern of irradiation of the street surfaces. Streets with an N-S orientation receive some solar radiation on the shortest day of the year (21st of December), even when the street is narrow (Fig. 8: A). Although this promotes thermal comfort in winter, spring and autumn, it could be unpleasant in summer, as there is no shade on the streets during the hottest day of the year. In contrast, streets with an E-W orientation are in shadow on the shortest day of the year, throughout the whole day, for all street widths studied (Fig.8: B). In comparison with N-S oriented streets, streets with E-W orientation provide some shade during the hottest hours of the day. However, E-W oriented streets receive high percentages of direct solar radiation in the morning and afternoon in summer compared to N-S oriented streets [52].



(A) (B)

Fig. 8. Impacts of street orientation on solar access. Percentage of street surface that is directly irradiated when the street's orientation is N-S direction (a) and E-W (b) for the reference canyon (street width of 15 m) [52].

From the other point of view, in another study which is conducted in Ghardaia, Algeria, Ali-Toudert and Mayer [58] found out that for arid regions it is quite difficult to keep an E-W oriented street canyon in the shade. In E-W orientation the walls provide very limited shading, even for very deep street canyons (H/W ≥ 2). In contrast, N-S oriented street canyons create more pleasant microclimate as they provide enough shadow and solar energy in summer and winter respectively. Therefore, the orientation of the street canyon should be choosing based on the area's latitude as in different latitude difernt orientation is appropriate.

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In addition, Ali-Toudert and Mayer [58] concluded that better comfort conditions could be created by rotating the street to a NE-SW or NW-SE orientation. As in this case the shading effects of walls is more effective in summer compared to E-W oriented streets. Furthermore, in winter more solar access is provided by NE-SW or NW-SE oriented streets in comparison with N-S orientation. Nevertheless, a NE-SW orientation allows a solar exposure in the morning whereas NW-SE orientation implies an exposure of the walls in the afternoon, which could make the interior spaces overheated. They also investigated the impacts of street orientation on solar access and found out that the availability of solar energy on the street's facades reduces rapidly with the increase of the aspect ratio of the canyon. These studies indicate that deep and narrow urban canyons (H/W ≥ 0.5) are more proper for hot regions as they reduce solar access generally. In contrast, uniform, shallow and generally wide street canyons (H/W ≤0.5) are appropriate for cold areas which require more solar access throughout the whole year [58]- [60].

6. Conclusion

The final outcomes of the study have shown that specific design of street’s geometry and orientation are very necessary to achieve a desirable microclimate in an urban canyon with a viewpoint of sustainability. There are environmentally-conscious factors affecting urban street microclimate of which inappropriate application can cause significant changes to create a special microclimate of urban zones. Therefore, designing street and concentrating on it as a significant factor of urban geometry which covers around a quarter of urban areas is essential in a global approach for an environmental urban design to create a special microclimate of urban zones. The geometry of streets as defined by height/width ratio (H/W) and length/width (L/W) also the orientation that is defined by its length axis directly influence the airflow and solar access in urban canyon and therefore thermal comfort at pedestrian level in urban area. Provision of fresh air and having a better airflow is possible in a wider street within street canyon and better ventilation can be happen in a street with different building heights. Furthermore, the amount of solar energy obtained by street surfaces influenced by the height/width ratio. Street orientation barely affects the quantity of solar radiation of the canyon; it will change the distribution of the overall radiation over the different street surfaces. Street orientation considerably affects the daytime and seasonal pattern of street surfaces irradiation with more impact on the vertical surfaces of the street.

As a final point, for having a desirable microclimate in urban areas, appropriate airflow and utilize solar access are main elements that should be taken in account in designing urban streets, which would influence climate and energy consumption of entire buildings.

As a future researches author recommend establishing a continuous dialogue between urban designers and researchers in order to achieve sustainable urban design. In addition, following the bellow framework could facilitate the procedure of built environment development (Fig. 9).

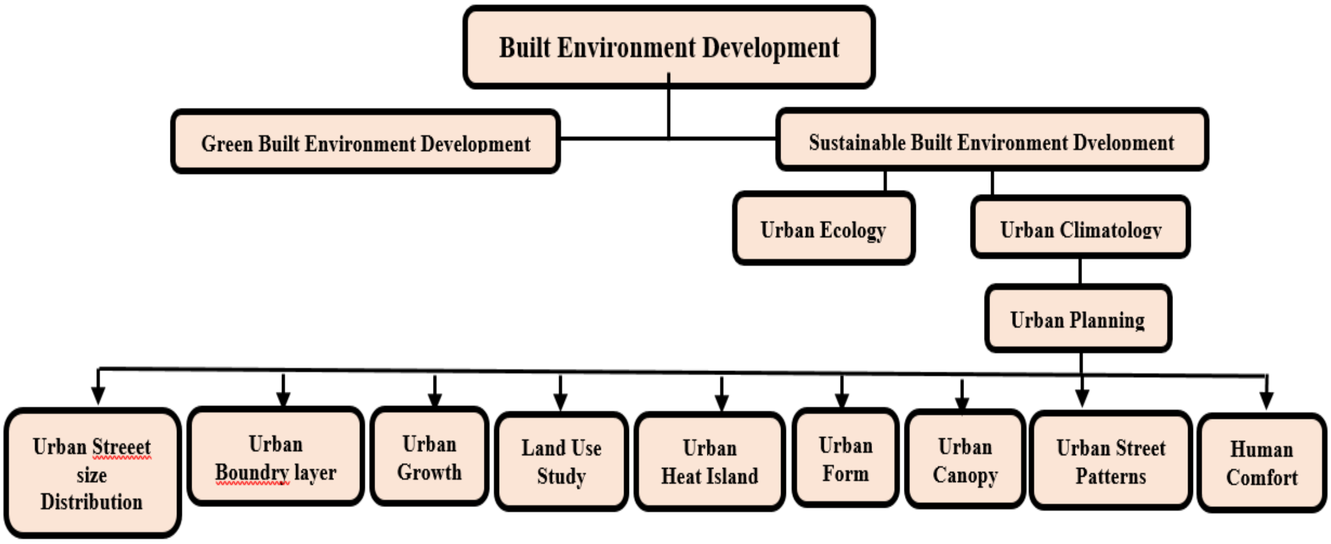

Fig. 9. Recommended procedure of built environment development for urban design.

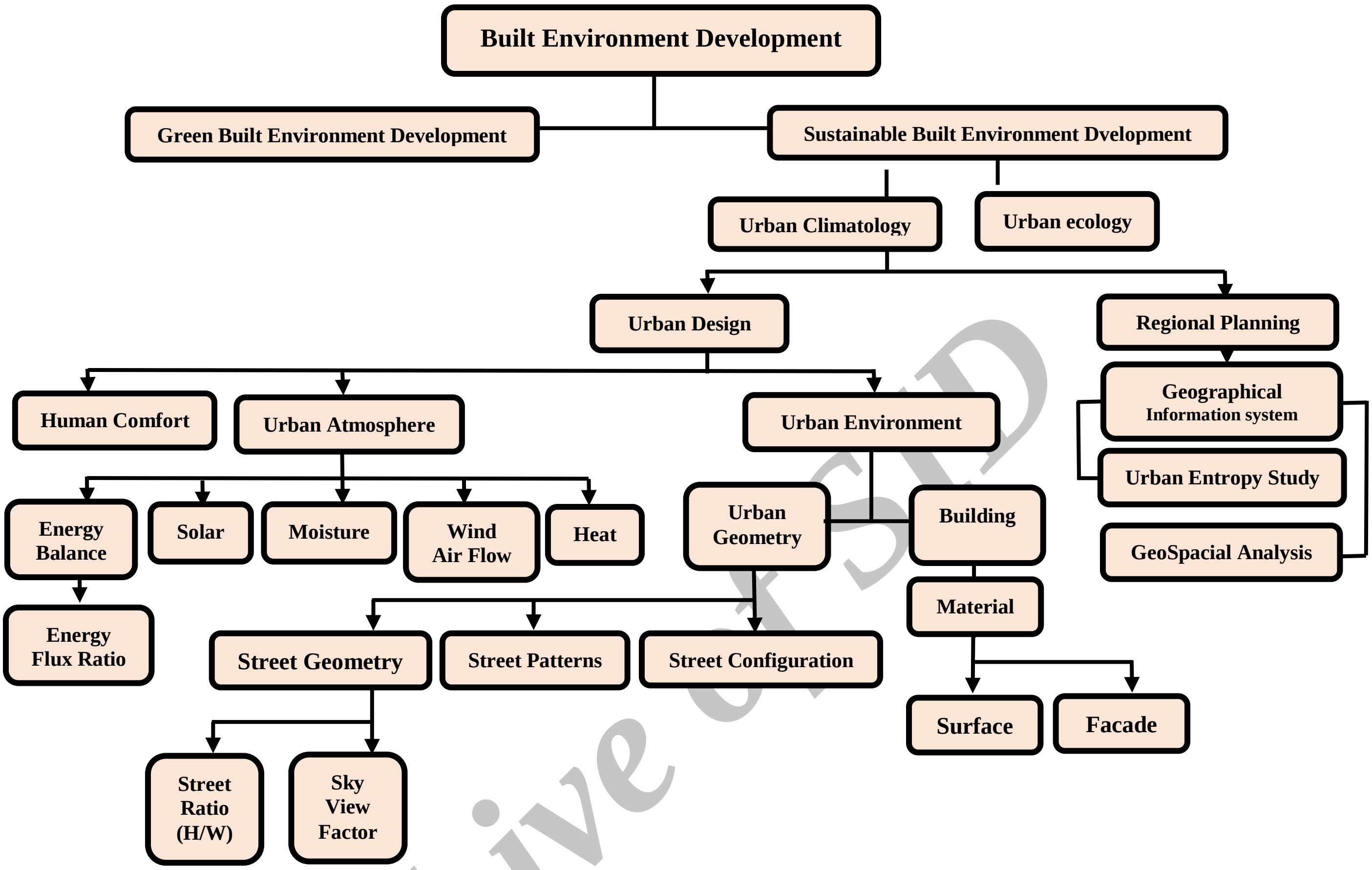

Fig. 9. Recommended procedure of built environment development for urban design.

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