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Urban Facade Geometry on Outdoor Comfort Conditions: A Review

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Abstract

Designing urban facades is considered as a major factor influencing issues such as natural ventilation of buildings and urban areas, radiations in the urban canyon for designing low-energy buildings, cooling demand for buildings in urban area, and thermal comfort in urban streets. However, so far, most studies on urban topics have been focused on flat facades without details of urban layouts. Hence, the effect of urban facades with details such as the balcony and corbelling on thermal comfort conditions and air flow behavior are discussed in this literature review. This study was carried out to investigate the effective factors of urban facades, including the effects of building configuration, geometry and urban canyon's orientation. According to the results, the air flow behavior is affected by a wide range of factors such as wind conditions, urban geometry and wind direction. Urban façade geometry can change outdoor air flow pattern, thermal comfort and solar access. In particular, the geometry of the facade, such as indentation and protrusion, have a significant effect on the air flow and thermal behavior in urban facades and can enhance outdoor comfort conditions. Also, Alternation in façade geometry can affect pedestrians' comfort and buildings energy demands.

Keywords: Thermal comfort, Solar access, UHI, SVF, Fluid mechanics, Pollution, Facades.

Introduction

Research in urban climatology includes topics such as radiant temperature, air flow, air vapor pressure and urban structure (Mayer and Höppe 1987). For this reason, weather conditions in urban areas are different from rural areas (Yoshida et al. 1990). Urban canyon or streets are considered as the simplest geometry which describes the structure of urban environments (Dobre et al. 2005). Designing streets and urban facades is a key issue in urban design, because streets can be considered as interference of architectural and urban scale, and also include interface between buildings and its surrounding environments (Ali-Toudert and Mayer 2006). Hence, designing urban facades has a significant effect on energy consumption (Ge et al. 2013) and human health (Moonen et al. 2012). A number of studies have focused on mitigation technologies to enhance outdoor comfort condition (Santamouris et al. 2007; Santamouris et al. 2012). Facades are considered as critical areas in buildings that create thermal bridges (Goulouti et al. 2014). On the other hand, energy consumption is somewhat prioritized rather than others (Asdrubali et al. 2008; Asdrubali et al. 2013). Additionally, urban structure such as orientation can play a key role in reflection of solar radiation (Aida and Gotoh 1982). A study concluded that urban canyon or streets were generally considered as the main structural unit of a city (Arnfield 1982), then many studies were conducted about urban canyon including the characteristics of energy and heat, air flow, air pollution and analysis of the effect of surface heating on heat transfer and air flow areas (Ali-Toudert and Mayer 2007b; Offerle et al. 2007; Li et al. 2010; Li et al. 2012b; Allegrini et al. 2013; Qu et al. 2012; Cai 2012; Pearlmutter et al. 1999; Mayer 1993). Oke et al. investigated the geometry of street-building with the building height to street width ratio *(Oke 1988)*. These studies also showed that, there is a strong relationship between urban design factors and outdoor comfort conditions (Golany 1996), wind flow, ventilation and mitigation of UHI (Urban Heating Island) (Oke 1982; Kim and Baik 2005). Also surface energy balance is influenced by the surface features (Taha 1997). Energy consumption in urban settings has been investigated through three main categories, including operational energy (heating or cooling), embodied energy (material or construction) and transportation (Ji et al. 2007) which based on this study and some others (Kerr 1998; Kostof 1995; Hui 2001), operational energy has the largest percentage (Codoban and Kennedy 2008). This category is related to façade characteristics and can increase energy consumption around 20% (Sanaieian et al. 2014). Thermal comfort is accompanied by different environmental factors namely air temperature and wind speed (Matzarakis and Amelung 2008; Taleghani et al. 2013; Höppe 1999; Winslow and Gagge 1941; Kleerekoper et al. 2017). Studies conducted in this field often include urban canyon with flat facades and green walls. Also, as a research gap, the effect of urban façade geometry, such as corbelling or indentation on air flow behavior, thermal comfort conditions and solar access were not considered. Therefore, this study was aimed to investigate the effects of urban facade geometry, on air flow, outdoor thermal comfort, radiation and solar access.

Materials and Methods

This paper reviews the recent research on the effects of urban facades geometry on the outdoor air flow, thermal comfort and solar access pattern. The interrelationship between urban canyon factors (aspect ratio, geometry and orientation) and urban micro-climate has been the subject of many papers. According to these studies outdoor comfort condition is influenced by wind velocity and direction, solar radiation and heat transfer over urban canyons which depend on urban facades geometry such as overhanging, shading or adding elements. Therefore, this review reports the results of research on the geometrical factors influencing outdoor wind, thermal comfort and solar access. Studies conducted on the basis of subjective material and green features are excluded in this review. Furthermore, a few studies examined the influence of urban façade geometry directly and indirectly. Thus, this review tends to extract related matters from different research merely in this field.

The first part of the paper reports the studies on the effects of urban façade geometry on the air flow behavior. This heading is categorized into wind flow fields, air flow pattern in urban canyon and urban façade effect on buoyancy. The second part presents the results of urban façade geometry effect on outdoor thermal activity. The effect of urban façade geometry on solar access is explained in the third part. Finally, the most important geometrical factor of urban façade is presented in the fourth part of the paper.

Results and Discussion

The effect of urban facades on air flow behavior

It is necessary to discuss the flow around an isolated building in the boundary layers in order to understand the behavior of airflow in urban canyons (Hunt et al. 1978). These wind flow patterns around the buildings affect shapes, orientations and types of flows around the building blocks (Ahmad et al., 2005). An urban canyon is a place where the street is flanked by buildings on both sides creating a canyon-like environment (Li et al., 2012a; Nicholson, 1975). The dimensions of urban canyons are expressed by the height of the urban facades (H) to the street width (W) ratio. The shallow and deep canyons have a ratio of less than 0.5 and 2, respectively. If the length of a canyon is defined as the distance between the two main intersections (L) and the height of the building (H), then the short canyon is expressed as (L / H = 3), moderate (L / H = 5) and high (L/H = 7). Also, if the buildings on both sides of canyon have the same height, the canyon is symmetric (Vardoulakis et al. 2003). Asymmetric canyon with high-rise buildings in the direction of the wind are called as step up canyon, otherwise is called as step-down canyon (Ahmad et al., 2005).

Air flow hits the urban facades in three ways: perpendicular, parallel and oblique towards it (Ahmad et al. 2005). The researchers describe three types of air flow for the vertical direction respecting to building geometry (length to depth ratio) and canyon geometry (depth to width ratio) (Fig. 1) (Hussain and Lee, 1980; Nicholson, 1975). Their flow fields will not interact, if the distance between the two buildings is too high and the height is relatively low, so that (Fig. 1a), will result in "isolated roughness flow" (Ahmad et al., 2005). If the height and distance of the building blocks are such small, vortexes interfere and consequently, the flow pattern will change (Fig. 1b) and in larger H / W, there is vortex inside the urban canyon, which may lead to the movement across the shear layers at the height of the roof, and most of the flow does not enter into the urban canyon. Therefore, vertexes are formed only within the canyon (Stathopoulos and Baskaran, 1996) (Fig. 1c).

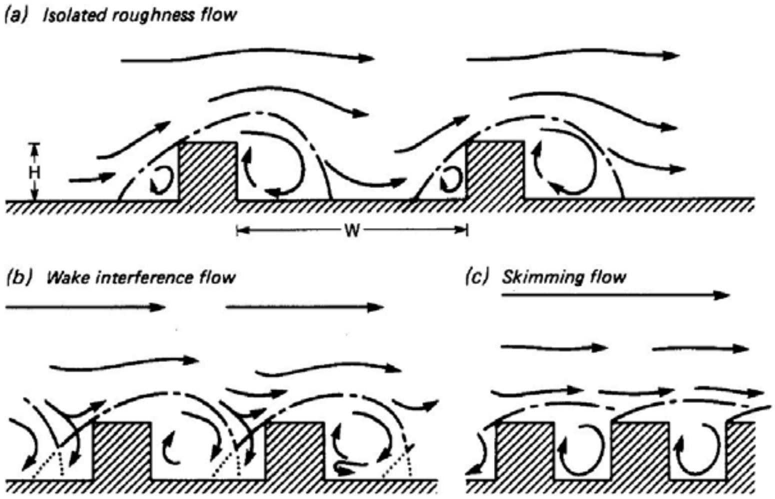

Figure 1. Types of air flow perpendicular to urban canyons for different ratios *(Oke 1988)*.

The wind flow inside the street canyon is usually driven by the main wind flow from the outside of the canyon. If the outside wind velocity is too slow, the relationship between the upper and the inside flow is lost (Nakamura and Oke, 1988). The direction of the vortexes near the ground and the direction of the wind outside the urban canyon are opposite to each other (DePaul and Sheih, 1985). Two vortexes are formed in deep canyons: the peripheral wind flow directs the vortex upwards, while the upper vortex flow goes downward and the direction of the lower vortexes is opposite of the upper vortexes (Jeong and Andrews, 2002). If the length-to-width ratio of the urban canyon is 20, the effects of the canyon will dominate across the vortex (Yamartino and Wiegand 1986). In short canyons, middle vortexes in the corners of the building, which are responsible for convection from the corners of the building to the middle of the block, create a convergence area in the middle of the canyon (Hoydysh and Dabberdt, 1988). The canyons generate an unstable vortex in an open area, increasing constantly in the upward direction, while the canyons generate stable vortex that suppress street ventilation (Meroney et al., 1996).

The parallel wind flow is along the axis of the urban canyon, which increases the height of the wind while the friction of the urban facades delays the wind flow (Nunez and Oke, 1976). Urban blocks are considered as rough elements for the high atmospheric flow (Cheng and Castro, 2002) and the number of rotary vortexes in the deep and shallow canyons is generally dependent on the canyon ratio (H / W) (Hall et al., 2010). As the wind flow enters the canyon, the longitudinal velocity increases along the canyon, while this value in the next rows of buildings decreases (Dobre et al. 2005). The pressure drops slightly and drives the air above the urban canyon, leading to the air momentum exchanges (Hall et al., 2010).

The formation of spiral vortex along the canyon and the spiral flow pattern in the unban canyon shows the wind direction (Wedding et al. 1977). When there is an angle between the urban canyon and wind flow, the flow is a combination of rotational and longitudinal flows, considered to be the most realistic and both flows change linearly proportional along parallel and perpendicular axis to the canyon (Ahmad et al., 2005). A clear relationship between wind velocity of the canyon and undistributed wind is observed for the upper parts of the canyon and wind velocities higher than 2 m/s (Santamouris et al., 2008). Distribution of temperature and air circulation affects the heat transfer between buildings and urban canyon air and consequently pedestrian's comfort and buildings energy demands (de Lieto Vollaro et al., 2014). When the surface temperature is high and wind speed is low, the flow fields in the urban canyon are significantly affected by buoyancy (Allegrini et al., 2012a). When a windward façade of the building is heated by the sun, the buoyancy force forms a hot cortex near the warmest façade. The effect of natural convective vortex in these conditions increases for the leeward facade (de Lieto Vollaro et al., 2014). With the heating of the buildings envelopes, a strong buoyancy force is created near them which are influenced by the ratio of the height (H) to width (W) (Xie et al., 2007). From different studies protrusive or reentrant geometrical elements on facades affect wind-velocity related comfort in urban canyons. Indentation on urban facades can increase wind velocity (Yang et al., 2013) and mitigate nocturnal heat island (Yuan and Chen, 2011).

The impact of urban facades on thermal comfort

As mentioned earlier, UC (Urban Canyon) is described by the ratio of the canyon height (H) to canyon width (W) (H / W) and is arranged in each urban area according to the correct solar orientation (Arnfield, 1990; Cheng and Castro, 2002; Givoni et al., 2003; Ahmed, 2003; Costa and Araujo, 2003; Masmoudi and Mazouz, 2004; Picot, 2004; Chatzidimitriou and Yannas, 2017; Aleksandrowicz et al., 2017; Omonijo, 2017). Many streets are designed with special texture in order to overcome the stressful climatic conditions, such as corridors and other common solar shading facilities in the traditional warm climate architecture. Also, it is possible that some eastern streets in cities and asymmetric vertical sections may be used to build climate-responsive urban buildings and they may have an effective solar gain in the winter (Capeluto and Shaviv, 2001; McPherson et al., 1994; Kristl and Krainer, 2001).

Explicitly, the south-facing buildings are placed at a lower altitude to allow the northern facades to be exposed to more radiation from the sun in the winter. By solar shading of the façade on itself or the protection of the street at pedestrian level, sometimes the facades are balanced on the street (Krishan, 1996). The concept of these designs is inspired in many urban areas to contemporary architecture, which increasingly use detailed layouts as climate control strategies in open spaces (Capeluto, 2003). For example, by this irresponsible way of urban designing surfaces, temperature and consequently air temperature in cities increase, resulting in UHI phenomenon (Farrell et al., 2015). Urban canyons with ratios of 0.5< H/W <4, were simulated in different orientations (Ali-Toudert and Mayer, 2006). The results show that with passive methods, the average air temperature decreases by increasing the H / W ratio and Solar shading (the most decisive strategy to reduce the intensity of heat) (Ali-Toudert and Mayer, 2007b). So, urban canyons with different characteristics were investigated in several studies in this field (Fig. 2).

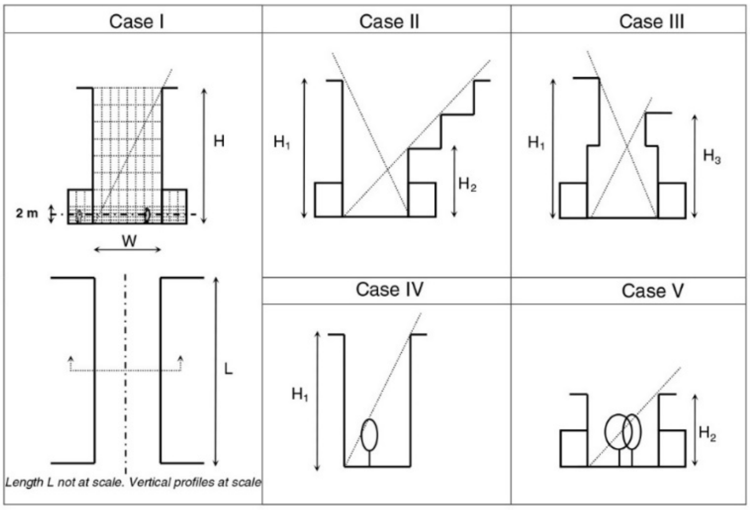

Figure 2. Urban facade geometry effect on outdoor thermal comfort (Ali-Toudert and Mayer 2007a).

According to studies, geometry is considered as a significant factor in the air flow and distribution of temperature in urban canyons (Offerle et al., 2007). However, air temperature (Ta) is relatively stagnant and responds only on average to geometric variations. This is consistent with field studies that report small differences in the air temperature of the canyon (Yoshida et al., 1990). Many slight differences are observed in the measured flux depends on the warming of the windward or leeward facades, due to buoyancy interference with the rotation of ordinary vortexes and cooler air on windward-facades heating compared to the much more heat transferring near the leeward-facades heating (Offerle et al., 2007). Although geometry and trees are not efficient for every urban canyon, with the help of designing asymmetrical facades, shading, suitable orientation and urban canyon ratio, comfort hours in streets can be increased (Bourbia and Awbi, 2004). Trees can decrease temperature with the aid of the heat absorbed by the surface under the plants and therefore, the cooling effect felt under the crown of the trees, but this function depends on the sun position and trees orientation relative to each other (Shashua-Bar and Hoffman, 2000). Also, trees can affect outdoor thermal comfort through shading and evaporative cooling (Mochida and Lun, 2008). Several studies have investigated the relationship between urban design factors and outdoor comfort conditions (Golany, 1996). The results show that one of the influential factors in this field is urban façade geometry (Jamei et al., 2016). Because by the aid of designing façade geometry, heat losses through facades can decrease or increase (Ratti et al., 2005) or applying passive strategies on facades, can impact thermal comfort (Okeil, 2010). For example, sometimes shading on urban facades and providing cooler urban surfaces is more efficient than direct solar access in order to enhance outdoor thermal comfort (Lin et al., 2010).

The effect of urban facades on solar access

There are various effective factors on solar access in urban canyons, including urban density, canyons orientation, building outlines and aspect ratio of urban canyons (Hachem et al., 2011, 2012). Also, a number of studies have been carried out on the importance of radiation on outdoor comfort (Höppe, 1999; Höppe, 1993; Taleghani et al., 2014; Thorsson et al., 2014; Taleghani et al., 2015). Two factors are arisen in this field: reflection of the surface and access to solar radiation which depends on the combined materials and their geometric arrangement (Mochida and Lun, 2008). In many studies, the importance of geometry is shown using numerical models in the radiation exchange of a deep and shallow canyon (Nunez and Oke, 1977; Terjung and LOUIE, 1973; Aida, 1982). All methods show that for buildings with equal height, the reflection of a curved surface is less than a flat plate composed of similar materials, also seems that this effect rises with increasing latitude and the ratio of H / W, and becomes more visible in the seasons with low sun and also, it is greater in the EW canyons than the S-N canyons (Terjung and Louie, 1973). Different reflections in the deep and shallow canyons are a function of the W_1 / W_2 ratio in which W1 is the width of the block elements and W_2 is the distance between the blocks or the width of the street (Oke, 1988). Other researchers also have highlighted that orientation of facades, distance from the facades and obstruction sky view can affect significantly on solar access and energy consumption (Santamouris, 2013a). Moreover, the amount of solar radiation increases by minimizing total reflection of absorption, because the absorption of geometric compounds can be less than a flat plate, not by the canopy (Terjung and Louie, 1973). Fig. 3 shows different surface's solar access for different urban E-W canyons ratios.

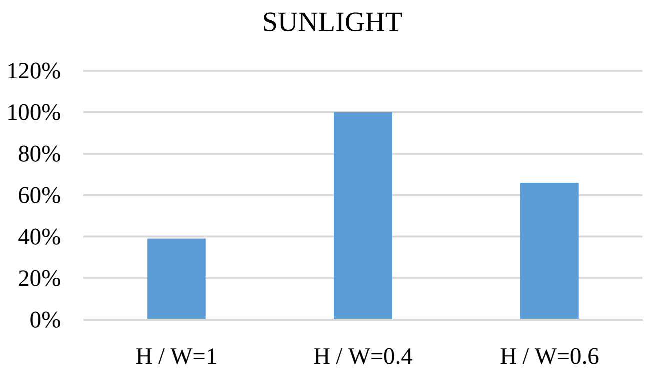

Figure 3. The access of sunlight for urban surfaces in E-W canyons with different ratios (Oke 1988).

The asymmetry of daylight distribution in the canyons is significantly different between surfaces with high light intensity and low light intensity (Fig. 4a). While, the light distribution at the bottom surface is relatively similar to the cloudy sky, it is slightly asymmetrical due to direct light at low angles during the day (Fig. 4b) (Strømann-Andersen and Sattrup, 2011). Also, by the help of designing facades properly, the reflected light reaches a reasonable daylight level of 50%, even at the width of 10 m, H / W = 1.5 (Fig. 4c) (Ahmad et al., 2005). Facades experience more direct, diffused and reflected radiation than the middle of the street. Also, the distribution of radiation curves is affected by the sun's angle, direct radiation composition and reflection of facades. As shown in Fig. 8 in the lower part of the canyon and inside the depths, the light is distributed equally while in the canyon with low reflectivity, 80% daylight curve by different buildings is almost identical and solar access is almost exclusively dependent on the sky view (Strømann-Andersen and Sattrup, 2011). The best combination of distance and height of buildings in urban canyons should be used for achieving proper access to sunlight. This also depends on the space between the buildings and the longitudinal orientation of the street (Capeluto and Shaviv, 2001). In this vein, solar access plays a vital role in creating outdoor human comfort conditions. Because building facades are the most obstacles to limit achieved rays and sky view (Correa et al., 2012), defined by "the ratio of the amount of the sky which can be seen from a given point on a surface" or SVF (Oke, 2002) which is determinant factor to absorb and emit solar radiation and change buoyancy rate and air flow (Yang et al., 2013). For instance, thermal comfort level in urban canyons with high SVF is the lowest in summer while the worst thermal performance in winter belongs to the urban canyons with low SVF (Lin et al., 2010), one tenth increase in SVF would rise 8% in wind velocity at pedestrian level (Yang et al., 2013).

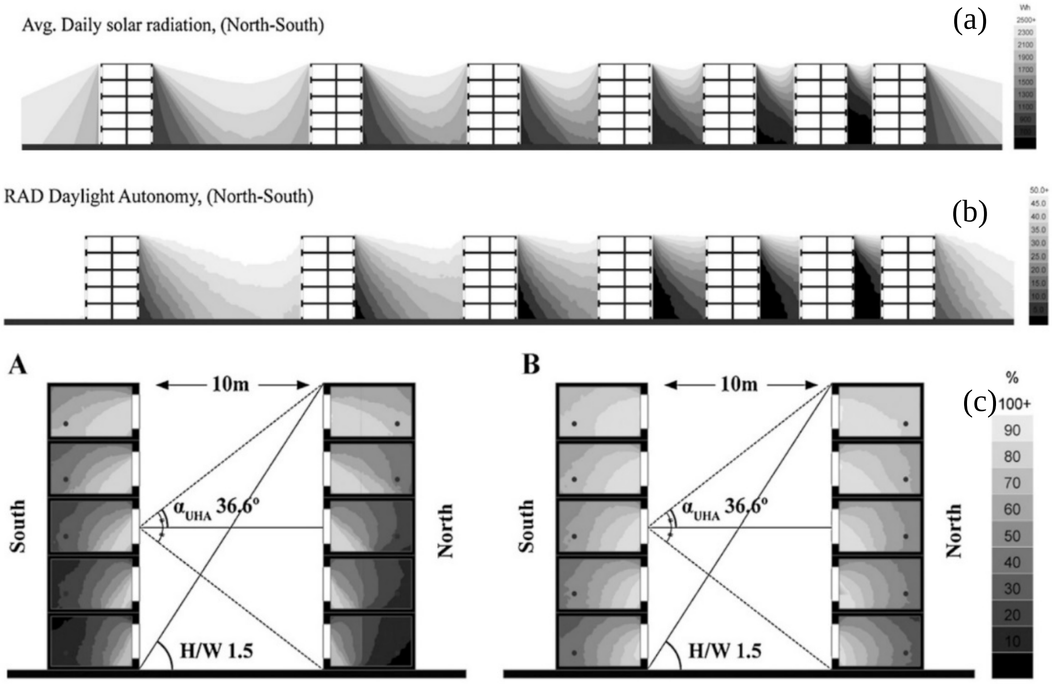

Figure 4. a) Average daily sunlight in the urban canyon, b) Annual light intensity > 10,000 LX in the urban canyon, c) Annual light intensity> 200 LX in the urban canyon with surface reflection variables (Strømann-Andersen and Sattrup, 2011).

Increasing SVF reduces air temperature and comfort (Bourbia and Awbi, 2004) or decreasing SVF and dense green coverage can reduce outdoor air temperature almost 8.7 (Charalampopoulos et al., 2013). Some studies have included that lower SVF-canyons accompanied by higher green features are more effective to improve comfort conditions (Giridharan et al., 2005; Bottyán and Unger, 2003; Hamdi and Schayes, 2008; Giridharan et al., 2007; Dimoudi and Nikolopoulou, 2003).

Urban façade geometry is the most important in this field, due to facades are the most suitable for solar panels or other technologies to generate solar energy (Capeluto and Shaviv, 2001; Morello and Ratti, 2009; Knowles, 1981; Knowles and Berry, 1980; Knowles, 2003; Ghosh and Val,. 2006; Compagnon, 2004; Mardaljevic and Rylatt, 2003; Kämpf et al., 2010). Urban facades include most of the vertical urban surfaces and have considerable solar potential in order to design and develop urban areas (Kanters and Wall, 2016; Redweik et al., 2013). For this reason, some studies which focused on mitigation technologies to enhance outdoor comfort conditions (Santamouris et al., 2007; Akbari and Levinson, 2008), presented facades as the most influential to solar energy access (Kanters and Wall, 2016). Added technical elements with double function and free-standing structure are two parts of urban facades which should be studied (Munari Probst et al., 2013). Fig. 5 is an outline about the role of urban façade geometry, its effects on outdoor air flow, thermal comfort and solar access and also the outcomes.

Urban facade geometry function:

- Producing wind pressure difference over urban facades (Bady et al. 2011; Zhang et al. 2005)
- Changing long wavelength radiation emission from facades to sky (Allegrini et al. 2012b)
- Changing byuoancy of facdaes (Allegrini et al. 2012a)
- Changing direct sunlight and shadow level in winter and summer (Ali-Toudert and Mayer 2007a)
- Using solar shading equipment on protrusive parts of facades (Kanters and Wall 2016)
- Effect on solar access and PV potential (Karteris et al. 2014)
- Changing SVF and sky exposure (Yan et al. 2014; Correa et al. 2012)

Effects:

- Changing Absorbed heat by facades (Taleghani 2017)
- Changing temperature of urban surfaces and air (Allegrini et al. 2012b)
- Changing trapped heat in the canyons (Ratti et al. 2005)
- Changing solar rays gain by facades (Okeil 2010)
- The passage from operational energy into low-energy buildings (Sanaieian et al. 2014)
- Changing long-wave radiation loss at night (Ratti et al. 2005)
- Changing the cooling rate of the urban surfaces (Givoni 1998)
- Changing radiative cooling and comfort during days and nights (Correa et al. 2012)

Outcome:

- Changing cooling demand and natural ventilation in building and urban canyon (Chow et al. 2013)
- Changing Urban Heating Island (UHI) intensity (Santamouris 2013b; Johnson 1985; Svensson 2004; Unger 2004; Yamashita et al. 1986; Yuan and Chen 2011)
- Improving or threatening ecosystem (Onmura et al. 2001)
- Effect on the level of outdoor comfort (Busch 1992; Kikegawa et al. 2006; Lynn et al. 2009; Radhi and Sharples 2013)
- Changing air quality and pollution dispersion (Akbari and Konopacki 2004; Sarrat et al. 2006)
- The best strategy to provide longer comfort condition during the year (Ali-Toudert and Mayer 2007a)
- Effect on thermal behavior and air flow pattern simultaneously (Sanaieian et al. 2014)
- Effect on wind velocity and providing thermal comfort around buildings (Yang et al. 2012; Yang et al. 2013)
- Changing day and night air temperature (Yan et al. 2014)
- Changing comfort level in summer and winter (Lin et al. 2010)

Figure 5. The effects of urban façade geometry on air flow, thermal comfort and solar access.

The most important and effective factor of urban facades: balconies

Few studies have been carried out based on details of urban facades. According to the results of these studies, different elements such as balconies or roughness of building envelopes have a significant effect on the wind pressure on buildings, and balconies are the most effective in reducing wall pressures (Stathopoulos and Zhu 1988). In addition, when only the single ventilation strategy is selected, the effect of ventilation performance is improved by the important elements of facades such as the balconies (Mohamed et al. 2011). On the other hand, design standards require information with high precision for cost-effective designs, and reducing wind damage and the costs of implementation of the building (Ginger and Letchford 1999; Chen and Zhou 2007). Building energy simulation (BES) programs require information on pressure coefficients such as analysis of input for ventilation and the penetration rate (Costola et al. 2009). Pressure coefficients are determined by site measurements, wind tunnel measurements or numerical simulation (Levitan et al. 1991; Levitan and Mehta 1992; Caracoglia and Jones 2009). Some estimates have been made for predicting the distribution of medium wind pressure over the windward surface and another surface for a conventional building with or without the balcony (Chand et al. 1998) and this element can change the spectrum of the longitudinal turbulence intensity (Blocken et al. 2008) and pressure coefficient on facades (Snyder 1981). These results have been achieved according to the measurement done along the guidelines (the lines placed in the middle of the balconies introduced) in the windward and leeward facades (Tominaga et al. 2008; Franke et al. 2011). The results clearly show the significant effect of balconies on the distribution of pressure coefficient by making flow, rotation, and separating (Fig. 6).

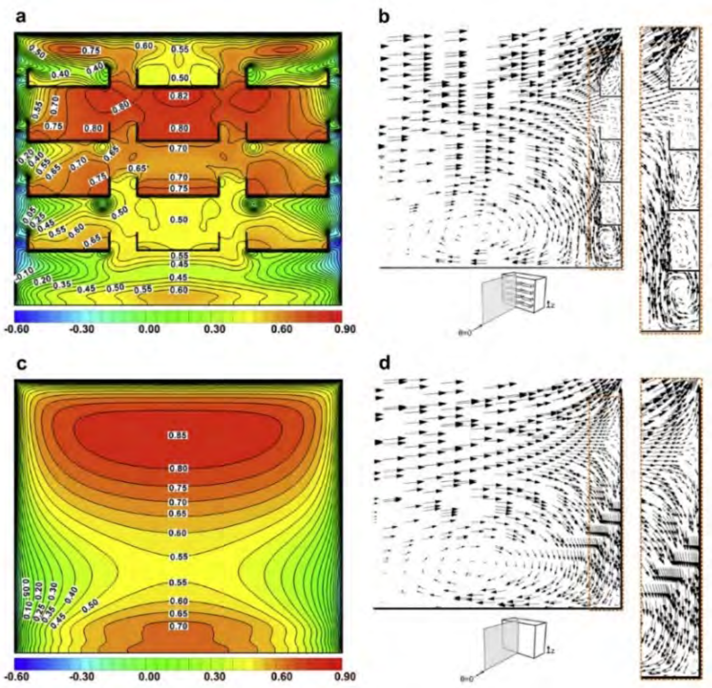

Figure 6. (a) The effect of balcony on the pressure coefficient (c_p) on windward facade, (b) Speed vectors near balcony, (c), (d) Compared to those of a building without a balcony is similar (Montazeri and Blocken 2013).

When the balconies are located on the windward wall, the positive pressures reduce and suction also decreases (Stathopoulos and Zhu 1988). Since, wind comfort and wind safety are considered as important factors in urban areas (Mochida and Lun 2008; Yoshie et al. 2007; Stathopoulos 2006; Blocken et al. 2007). The studies related to area and design information, including changes in the wind statistics that leads to the urban design, shape of the buildings (Blocken et al. 2012). Several studies have been carried out on the wind conditions at the pedestrian level around the buildings or around the urban environment of the complex (Takakura et al. 1993; He and Song 1999; Ferreira et al. 2002; Blocken et al. 2004; Janssen et al. 2013; Blocken and Carmeliet 2004; Blocken et al. 2011). Paying attention to the wind conditions, comfort and wind safety are of the most importance in the balconies of high-rise buildings because they can deal with strong winds and provide comfort and safety for pedestrians. Different sizes and shapes of balconies, closing the balcony or adding partition walls can be considered due to reduced wind discomfort in the balconies (Murakami 1990). The balconies with walls have a more significant effect on wind pressures than balconies without walls, because can prevent wind flow on the windward surfaces or reduce the effect of leeward- vortexes (Stathopoulos and Zhu 1988). During a study, the design of the second façade has been proposed as a way to protect the balcony area from strong winds, which includes a semi-open double skin facade (Montazeri et al. 2013), which shows the balconies without walls in general cause a slight decrease in measured suction in comparison with flat surfaces. It should be noted that pressure coefficients have been changed by the presence of balconies with walls; however, for balconies with longer walls, the mean pressure coefficient significantly decreases and their effect on the lower part is more significant (Stathopoulos and Zhu 1988). According to the results, ventilation performance in single ventilation- buildings with balcony, can be enhanced more and more rather than those without balcony (Mohamed et al. 2011). Based on studies, urban facades are PV potential especially balconies (Kanters and Wall 2016). Balcony is perceived as a multifunctional element, good option for building (parallel tubes or multi crystalline cells instead of fence to collect solar energy) (Munari Probst et al. 2013) and urban environment (shading on facades and help increase outdoor thermal comfort). Balconies are the well-known characteristics of facades with great potential namely movable awning and pilotis floor (Theodoridou 2012). What's more, balconies' shading effects can save energy significantly (Chan and Chow 2010). Table 1 shows different studies related to the effects of the urban façade geometry on air flow, thermal comfort and solar access.

Table1. The studies carried out about the effects of the urban façade geometry on air flow, thermal comfort and solar access.

Source	Subject of research	Research results
(Chand et al. 1998)	The effect of balcony on ventilation in low-rise buildings.	The presence of the balconies improves air flow and ventilation
(Bourbia and Awbi 2004)	The effect of Solar Shading of buildings in urban canyons in warm and humid climate.	The street orientation and geometry affect urban ventilation and city microclimates
(Toudert 2005)	The relationship between urban design and thermal comfort	The combination of high-rise buildings and shallow street can trap heat and reduce air flow, leading to the negative effect on the thermal comfort in the external environment during the summer.
(Johansson and Emmanuel 2006; Johansson 2006)	The effect of the ratio aspect and orientation on thermal comfort	The overhang improves the thermal comfort Urban geometry plays an important role in the solar shading and the duration of thermal comfort.
(Offerle et al. 2007)	Effects of building facades on wind flow and transmission of pollution in urban canyon.	Geometry affects the flow of heat exchange between urban levels.
(Pearlmutter et al. 2007; Gaitani et al. 2007; Watkins et al. 2007)	Study of thermal comfort and radiant flow	to improve the thermal comfort, portico can be used in the deep urban canyons

Source	Subject of research	Research results
(Ng 2009)	The guideline for outdoor comfort condition and air movement in urban canyons under weak wind	Wind direction in urban canyon environment is the first step for air ventilation
(Li et al. 2010)	The effect of pressure coefficient and heating on air flow and transmission of pollution in urban canyon.	The wind pressure coefficient, pollutant emissions and turbulence is affected by parameters such as geometry, facade characters, wind speed and direction,.
(Krüger et al. 2011; Hwang et al. 2011; Yang and Li 2011; Erell et al. 2012)	Effects of urban geometry, investigating the H / W ratio and wind speed effects	When the H / W ratio is greater than 0.05, the normal flow against the wind direction or perpendicular to the urban canyons don’t have interaction with the urban canyons.
(Mohamed et al. 2011)	Investigating one-way ventilation and creating balconies in high-rise buildings.	Creating a suitable balconies and one-way ventilation will improve the performance of the air conditioning.
(Shashua-Bar et al. 2012; Makaremi et al. 2012)	The effect of urban physics on thermal comfort	The city form is considered as an important factor in wind temperature changes..
(Hang et al. 2013)	Measurement of natural ventilation and buoyancy in dispersion of pollutions in urban canyon.	The buoyancy changes around the facades by increasing the temperature of the urban canyon levels.
(Johansson et al. 2013; Andreou 2013)	Investigating the urban geometry on the pedestrian's thermal comfort	Solar shading reduces the ventilation of the bottom layers and reduces wind speed improves thermal comfort in tropical cities
(Montazeri et al. 2013; Montazeri and Blocken 2013)	Simulation of wind pressure coefficients in facades with balcony and without balcony. Investigating the wind flow in the balcony with a second skin façade.	The balcony causes significant changes in the distribution of wind pressure, static pressure, and turbulence on facades Two skin facades on the balcony improves wind speed and wind comfort.
(Park et al. 2015)	The effects of dimension ratio on the air quality in the urban canyon.	An increase in the height of the buildings and reducing the width of the canyon will worsen the air quality of the urban canyon.
(Nowak-Dzieszko and Rojewska-Warchał 2015; Chan 2015; Li et al. 2015; Saleh 2015)	The effect of the glass balcony on thermal comfort and energy consumption.	This system significantly reduces annual energy consumption.

Source	Subject of research	Research results
(Osińska-Skotak and Zawalich 2016; Kasim et al. 2016)	The effects of Land Use and openings change Urban ventilation.	Ventilation is affected by geometry, flow patterns, speed and pressure of the wind.
(Murena and Mele 2016)	The effects of balcony on air quality in urban canyon.	The design of the building façade with balcony reduces the accumulation of pollutants in the pedestrian level in the urban canyon.
(Rosado et al. 2017)	Effect of urban density and street barriers on sunlight, thermal comfort and ventilation	The duration of sunlight and the average radiant temperature affects thermal comfort of outdoor places.
(Karra et al. 2017)	The air flow in heterogeneous urban canyons	Variation and heterogeneity in the structure of the urban canyon affect the air flow pattern.
(Omrani et al. 2017)	The effects of balcony on ventilation and thermal comfort in high-rise buildings	The creation of balconies and one-way ventilation improves ventilation performance

Conclusions

This paper reviewed the impact of urban façade geometry on the urban microclimate in three main subjects:

- The effect of urban façade geometry on outdoor air flow
- The effect of urban façade geometry on outdoor thermal comfort
- The effect of urban façade geometry on outdoor solar access.

Furthermore, the most effective geometrical element of urban facades, balconies, was discussed.

The results from this paper are as follows:

- Urban façade geometry can change outdoor air flow pattern, thermal comfort and solar access.
- Distribution of temperature, air circulation and heat transfer between buildings and urban canyons are influenced by façade geometry.
- The buoyancy of facades is influenced by geometrical characteristics.
- Urban façade geometry can impact UHI and pollution intensity.
- Protrusive and reentrant facades can affect outdoor thermal comfort condition over a year.
- Shading is the most important passive strategy in each orientation to provide outdoor comfort condition which is possible by designing urban façade geometry properly.
- Urban façade geometry such as protrusive and reentrant facades increase or decrease SVF which is an indicating outdoor comfort conditions.
- Urban façade geometry is potential to access solar energy.
- The most important geometrical element of urban facades is balconies potential to install solar technologies and are considered as a passive element (shading and creating wind pressure difference) and change air flow characteristics.

Accordingly, design of optimal facades with energy approach can respond the issues arising from air flow and radiation patterns in urban canyons. Considering the effect of façade geometry (namely protrusive or reentrant balconies) on the air flow behavior and access to solar radiation, the future studies should focus on this area. The optimal design of urban facades, the effect of the optimal design of balconies in the thoroughfares or their geometry, the dimensions and optimal position on pollution dispersion or UHI should be studied in future.

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