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Residential Block Configurations and Passive Solar Strategies: Analyzing the Impacts of Design Parameters on Outdoor and Indoor Solar Access

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A B S T R A C T

Buildings are responsible for around 40% of world energy use and residential buildings as an important sector consumes a significant part of this energy. The main part of the energy used in residential buildings is consumed for space heating, cooling and lighting. Solar energy as an important constituent of climate could be utilized passively for heating and cooling living spaces and providing daylight. Designing residential blocks could affect the amount of solar radiation received by inside and outside the buildings. It is assumed that orientation, residential block form and landscaping are the main design factors which determine the optimum use of solar energy and hence the need for space heating or cooling of buildings by conventional energy sources. This paper aims to study the impacts of orientation, form and landscaping on solar access in order to find the optimal residential block configuration that benefits solar conditions and provides as much solar irradiation in colder seasons and shade in warmer seasons. In this regard, the current literature and evidence are reviewed. The results of these studies indicate that proper passive solar design should consider orientation, form and landscaping as key buildings' parameters in order to provide enough solar access in different seasons.

Keywords: passive solar design, orientation, residential block form, landscaping

1. Introduction

Buildings are responsible for at least 40% of energy consumption in most countries and also one third of global greenhouse gas emissions (UNEP, 2009). It has been predicted that the energy consumption of buildings will continue to increase in the future as a consequence of the growth in population, increasing demand for building services and comfort levels and the rise in time spent inside buildings (Perez-Lombard et al., 2008). Residential buildings as a significant sector consume an important part of this energy. According to US Energy Information Agency of the US Department of Energy (EIA, 2010) energy consumption in the residential sector was around 14% of world delivered energy consumption in 2007. EIA (2010) reported that the energy consumption in the residential sector will grow at an average of 1.1% per annum from 2007 to 2035. Major part of the energy used in residential buildings is consumed for space heating, cooling and lighting (Yan et al., 2010) (Figure 1).

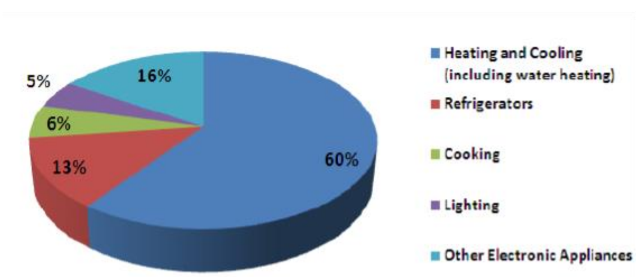

Figure 1. Average household energy consumption division (EIA, 2010)

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There are three main factors which could influence the amount of energy consumption in a residential building: outdoor and indoor design parameters (such as form, ratios, orientation, landscaping, and materials), systems performance parameters (such as efficiencies of lighting, boiler and other equipment) and residents' behavior. Among these factors design factors are extremely effective which could determine the potential for renewable energy supply and the use of low carbon technologies (Cheng et al., 2011). Among different renewable energy sources, the most pollution free, limitless source of energy is solar energy, which could be utilized with active and passive solar design strategies and technologies (Hangemann, 2005). Solar energy is an important constituent of climate and is highly important for human thermal comfort. Solar radiation could be utilized passively for heating and cooling living spaces and providing daylight. Designing urban blocks and open spaces could influence potential for passive solar gains inside and outside the buildings and therefore, outdoor and indoor environment. Therefore, designing residential urban blocks in a way which creates proper solar access could enhance the energy performance of buildings.

In order to utilize solar energy passively, the main complexity faced by the designer in shaping urban blocks and open spaces 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. This paper aims to find configurations of urban blocks with a residential function that benefits solar access and provides appropriate solar irradiation in cold seasons and shade in warm seasons. Hence, the current literature and evidence are reviewed in order to analyze the influence of urban and architectural parameters such as orientation, block forms, and landscaping.

2. Passive Solar Design: Definition and Benefits

Passive solar design can be described as the utilization of the sun's energy together with the characteristics of a local climate and selected building materials to maintain thermally comfortable conditions within buildings directly (Morrisey et al., 2011; Rabah, 2005). Therefore, passive solar design should arrange the form, fabric and systems of a building to use the energy from the sun for heating, cooling and lighting in order to reduce the consumption of conventional fuels (1). A passive solar system consists of four separate components: (1) collection, (2) storage, (3) distribution, (4) control. In a passive solar building, the solar components are parts of the building itself rather than separate subsystems (Passive Solar Handbook). Therefore, the building structures are used as a collector, storage, distribution and control mechanism, with a minimum amount of mechanical equipment. This definition fits most of the simple systems where heat is stored in the basic structure: walls, ceiling or floor.

Passive solar design represents lots of benefits [Passive Solar Handbook; Spanos et al., 2005) such as:

- Providing a flexible and attractive way to use renewable energy in buildings

- Enhancing the energy performance of buildings

- Improving owner's satisfaction through high resale value, low maintenance and independence from future rises in fuel costs

It has been proved that architectural and urban design parameters such buildings' orientation, form, and landscaping could provide the optimum use of solar gain and microclimatic conditions to minimize the need for space heating, cooling and lighting of buildings by conventional energy sources (Owens, 1992; Jabareen, 2006). Therefore, proper passive solar design should consider above-mentioned parameters as key buildings' parameters in order to provide enough solar access in different seasons.

3. The Role of Orientation in Passive Solar Design

Among the parameters that should be considered in the passive solar design of buildings, orientation is the most fundamental and generally, most easily addressed aspect of passive solar design (Chwieduk and Bogdanska, 2004). The orientation of a building influences the level of solar radiation which receive on the buildings' façade directly as well as shading and the performance of solar envelope Chwieduk and Bogdanska, 2004; Mingfang, 2002; Capeluto, 2003). There are a lot of benefits of optimal building orientation (Pacheco, 2012) such as:

- It enhances energy consumption of the building.

- It provides appropriate daylight and reduces the energy consumption for artificial light.
- It creates potential for additional savings from more complex passive solar techniques.
- It increases the performance of solar collectors.
- It is an inexpensive technique which could be applied in the initial steps of building design

It has been proven that the southern orientation is optimal in most climates in order to gain heat in the winter and control solar radiation in the summer (Mingfang, 2002; Capeluto, 2003; Pacheco, 2012). Therefore, the longer axis of the building should lie along east-west direction. Wong and Li (2007) examined the impacts of residential buildings orientation on solar access in Singapore by performing field measurements and computational energy simulations. Their research shows that the best orientation for a residential building in Singapore is to lie the longer axis of the building along east-west direction. They also found out that by following this orientation the cooling load for a residential building could be reduced to 8%-11%. This result is also has been proven by Gupta and Ralegaonkar (2007) who tried to find the optimal orientation of a building for various shape with the purpose of utilizing solar energy for different seasons. The results of this study illustrate that the optimal orientation is achieved when the longest facade of the building is oriented toward the south and north.

Furthermore, Shaviv (1981) conducted a study on the various orientation of the glazing façade of a building and concluded that the maximum energy saving could be obtained when the main glazing façade of the building faces south. The results of this study are shown in Table 1.

Table 1. Energy consumption of an office unit at three different orientations (Shaviv, 1981)

	Energy consumption at three orientations(KWh/year)					
	South	%	East	%	West	%
Heating	186	0	231	24	219	18
Cooling	281	0	286	2	369	31
Total	467	0	517	11	588	26
*T*max (◦C)	26.4		26.6		27.0	

In addition, Aksoy and Inalli (2006) analyzed the relation between heat demand and building orientation by using three models with various shape factors (1/1, 1/2 and 2/1). They studied these models with and without heating insulation. According to this study, by combining the orientation, shape and heating insulation the maximum heating energy saving (36%) achieves when the longest walls oriented toward the south (Figure 2).

However, orienting the longest wall of the building or urban block is not always possible, particularly due to definite orientation of the site as it could be longer on the west and east sides. In such cases, designing the plan of the building could be really effective and vital. For instance, auxiliary spaces, kitchen, bathrooms and staircase should be places in the west façade as this side of the building receives the most solar radiation in the summer and afternoon. Moreover, in order to minimize solar heat gain, openings should be avoided on the west or sufficiently shaded by using verandahs (Ahsan, 2009).

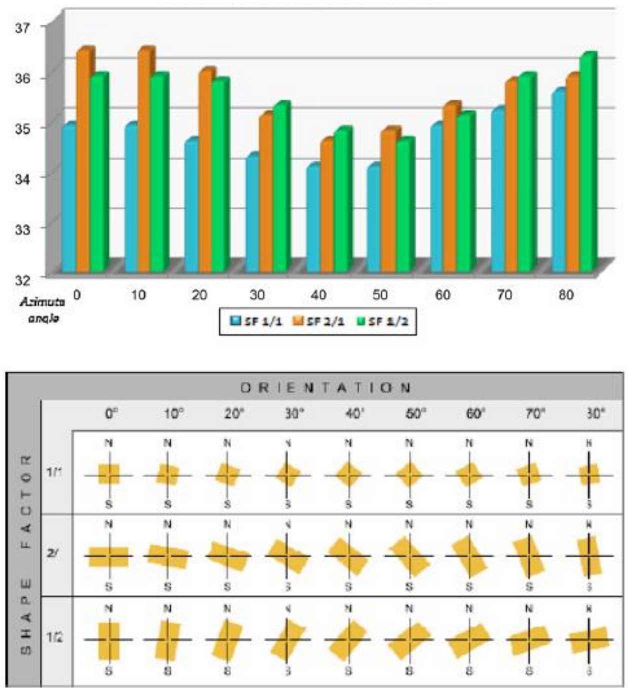


Figure 2. Heating energy saving, depending on shape and orientation (Aksoy and Inalli, 2006)

4. Impacts of Residential Block Form on Solar Access

Solar energy falling on an urban area is received either by buildings facades and roofs or by the ground between buildings (Okeil, 2010). It is obvious that the configuration of the buildings (in a small scale) and urban blocks (in a medium scale) could affect the amount of solar radiation which is received by above-mentioned surfaces and solar access outside and inside the buildings. An appropriate residential block form could provide proper solar access and shadow in different seasons and therefore enhance thermal comfort both outside and inside the buildings and consequently reduces energy demand for heating and cooling (Feng, 2004). As a result, designing residential block form in a way which utilizes solar access is significantly influential on improving energy performance of the building.

There are three basic types of built forms (Okeil, 2010; Feng, 2004; Al-Qeeq, 2010) (Figure 3):

- The first type is pavilions or isolated buildings which could be single or in a cluster and surrounded by large open spaces.

- The second type is the linear urban form or street urban canyon, which is formed by two typically parallel rows of buildings separated by a street or open spaces.

- The third type is courtyard and created where the configuration of the built form provides an open space which is surrounded by walls. This type could appear in different forms such as U-shapes, Terrace-courts, Pavilion-courts and courts.

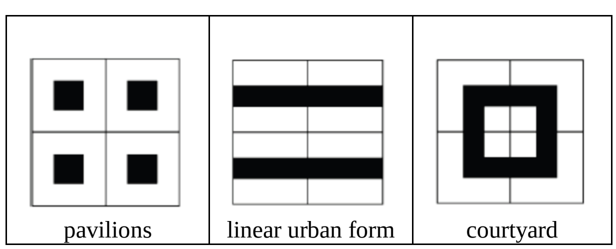


Figure 3. Three basic types of built forms (Huang et al., 2008)

There are several studies which have evaluated the impacts of built form on solar access in different climates and seasons. Robins and Macdonald (1999) 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. This study illustrates that street width significantly affects the total solar radiation which is received by the streets' surfaces. For all studied street canyons, increasing street width from 15 m to 20 m increases gaining solar radiation with 17–20%. In another research, Ali-Toudert (2005) studied the effects of street configuration on solar access in different seasons in a hot-dry climate. In this regard, she introduced three street form patterns for this study: 1) urban canyons with galleries, 2) asymmetrical urban canyon with large openness to the sky, and 3) asymmetrical urban canyon with overhanging façade, including galleries and with a smaller openness to the sky (Figure 4). Results of this study show that the asymmetrical form with overhanging façade provides more shading in summer and more internal solar access in winter.

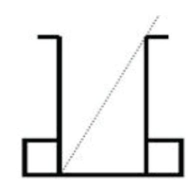
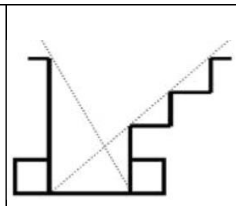
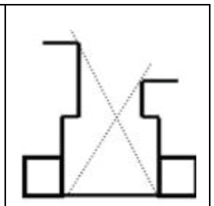
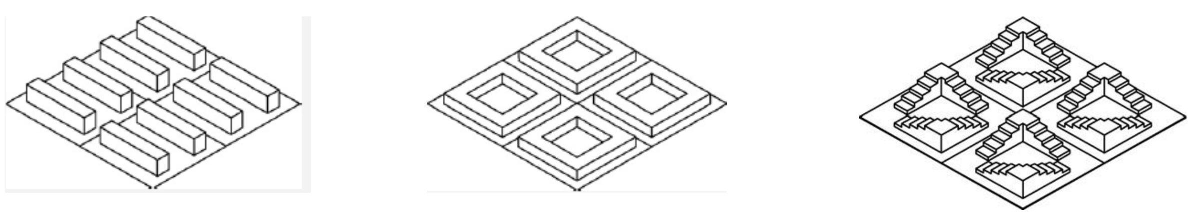
		
urban canyons with galleries	asymmetrical urban canyon with large openness to the sky and	asymmetrical urban canyon with overhanging façade

Figure 4. Three street form patterns introduced by Ali- Toudert (2005)

In addition, Okeil (2010) tried to find an optimal residential block form in order to minimize solar gain in summer and maximize solar access in winter. In this regard, he compared the direct solar radiation distribution on urban surfaces among three generic forms: tow conventional forms (linear urban form and courtyard) and one proposed form which was called Residential Solar Block (RSB) (Figure 5). The computer program CITY SHADOWS, was used to carry out solar exposure calculations.



Urban form: Linear Urban Form: Courtyard Urban form: Residential Solar Block

Figure 5. Three generic urban forms studied for incident solar radiation (Okeil, 2010)

The results of the simulation are shown in table II. According to this table, it could be concluded that the RSB received more solar radiation in winter in comparison with the linear urban form and courtyard. In summer, the RSB results in a decreased solar radiation falling on facades compared to courtyards and an increased solar gain in compared to linear urban form. In March/September the RSB solar exposure is very similar to that of the linear form and slightly higher than that of the block form (Okeil, 2010).

Table 2. Percentage of daily direct solar radiation distribution on urban surfaces of selected urban forms at Latitude 48.00 under clear sky conditions (Okeil, 2010).

Urban form	Urban Surfaces	Month			
		Mar.	Jun.	Sep.	Dec.
	Roof	24.4	24.4	24.4	24.4
	Facades	35.4	23.3	31.8	60.1
Linear	Ground	40.2	52.3	43.8	15.5
	Roof	39.1	39.1	39.1	39.1
	Facades	28.6	18.1	25.2	41.7
Block	Ground	32.3	42.8	35.7	13.1
	Roof	27.6	30.1	27.6	24.4
	Facades	28.1	19.3	28.1	67.0
RSB	Ground	44.3	50.6	44.3	8.6

Furthermore, Al-Qeeq (2010) compared the amount of solar radiation and shadow falling in the surfaces of two different U-shaped block forms in a temperate climate: rectangular and radial forms. The measurements of the annual shaded area generated in the two south-facing forms illustrate that the annual shaded area is greater in the case of the rectangular U-shape and thus it is more proper for cooling requirements, while the radial form could be more sufficient for heating requirements. In addition, by analyzing the calculations of the annual shaded area of the radial and the rectangular forms in the three different orientations (south facing, north facing and east facing), it became evident that in all identical orientations, the rectangular U-shape is always more shaded than the radial one and therefore it is more appropriate for hot and temperate climates. Moreover, it has been concluded that as the radial form is less shaded than the rectangular U-shape, predominantly in winter, this form is more beneficial in the cold and mountain areas. This makes the radial form more effective in gaining winter sunrays and consequently heat when it is crucial in the cold climates (Al-Qeeq, 2010).

5. Landscaping in Passive Solar Design

Landscaping plays a significant role in creating the microclimate of a place. Appropriate landscaping could enhance the solar energy performance of the buildings. It is an efficient way to provide a protection from direct sun and reflected light carrying heat into a building from the ground or other surfaces particularly in summer (Meier, 1991). There are three main properties of vegetation which could influence the microclimate of a place directly: (1) shading, (2) evapotranspiration, and (3) windbreak (McPherson, 1994). In order to create proper landscaping, these properties of vegetation should be considered according to site comfort requirements (Ali-Toudert, 2005). In addition, width of planting area around the building, size and shape of vegetation, and location of them are other important design factors which could affect the indoor and outdoor comfort and thermal performance of buildings (Passive Solar Handbook, 2012).

Trees as a main element of landscaping contribute significantly to utilize the solar energy received the building. Trees could provide solar protection to buildings in summer and therefore, reduce the energy demand for cooling. A study by Shashua-Bar and Hoffman (2000) illustrates that the cooling effects of shade trees at small urban green sites, courtyards and streets is about 1 K and up to 3 K at the hottest hour of the day. However, trees efficiency is dependent on orientation (McPherson and Simpson, 1995). McPherson and Simpson (1995) found that a tree placed for shading a west facing wall is as efficient as two identical trees on the east.

As a result, in order to utilize solar energy by landscaping, trees and vegetation should be placed in an appropriate orientation based on their properties. Hence, deciduous trees which provide shade in summer and sunlight in winter should be planted on the west, southwestern, and south side of the buildings. In contrast, evergreen trees should be planted on the north and north-west of the building in order to provide shade around the year. In addition, using dense trees and shrub plantings on the west and southwest sides of buildings is a natural solar passive strategy to obstruct the summer setting sun (McPherson, 1994; Canton and Cortegoso, 1994). However, if landscaping is not designed correctly, it could affect the microclimate negatively. For instance, planting deciduous trees for summer shading might decrease the desirable solar gains in the winter up to 30-40% (McPherson, 1992).

6. Conclusion

Solar energy is the most pollution free and limitless sources of energy which could be utilized passively for heating, cooling and providing daylight for living spaces. It has been established that architectural and urban design parameters such as orientation, configuration, and landscaping could influence the amount of outside and inside solar access and therefore energy performance of the buildings. Among above-mentioned parameters, orientation is the most important which affects the solar gain, shading, and the performance of solar envelope. It is evident that the optimal orientation is achieved when the longest facade of the building is oriented toward the south and north. Southern orientation provides residential blocks with heat gain in winter and solar radiation control in summer. In addition to orientation, the configuration of the residential blocks is other fundamental parameter which should be considered in passive solar design. Different types of built forms provide different amount of solar radiation for various climates. Therefore, designing the form of residential blocks should be based on the climatic condition of the place. Moreover, appropriate landscaping could improve the solar energy performance of the buildings through shading and protecting from reflected light carrying heat into a building from the ground or other surfaces. In order to utilize solar energy by landscaping, trees and other vegetation should be placed in an appropriate orientation based on their properties.

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