Solar Energy Potential of Clusters on Sloped Terrains

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ABSTRACT: Rapid worldwide urbanizations are demanding more land for construction and many cities surrounded by hills have started to expand onto neighbouring slopes. Whilst building on flat terrains is well investigated and documented, there is sill limited published research on the potential of energy conscious building on sloped terrain. The present study is part of a long-term research project which aims to develop a better understanding of urban design on sloped terrains with focus on solar energy, by assessing the influence of topography and building forms on the amount of solar radiation received by the building envelope. In this study, three different building forms were identified, grouped in clusters and placed on three different sloped terrains. Self and mutual shadowing effects were analysed to assess each shape's solar energy potential and thermal performance. IES V.5.9.0 Virtual Environment (Integrated Environmental Solutions) was the software simulation tool used. Solar and thermal simulations were carried out using ModelIt, Suncast and Apache Thermal, packages, which are part of IES V.5.9.0. Results show the effect of different slope angles, building forms and site layout on the amount of solar radiation reaching building surfaces and identifies those clusters and shapes with more energy potential, but it also shows that shapes, other than the traditional rectangular form can also open aesthetic opportunities for designers and planners.
Keywords: energy, slope design, built form, clusters, tessellation, IES Virtual Environment.

INTRODUCTION

"*a real mountain, with real mountain views, all within twenty minutes of the skyscrapers of Broadway, the grandest residential viewpoint available to homeseekers in Southern California*." [cited in 1].

This advertisement posted by an estates agency reflects the popularity that sloping sites started to gain at the beginning of the 20th century [1], becoming a new living trend in places such as Los Angeles. But, examples of cities, towns, communities or isolated single detached houses located along hillsides can be seen in many countries around the World and throughout time. Hillside communities, for example, were once built for their strategic position, for defence, even for health reasons, but also for shelter (Fig.1). Later, however, due to development and increased population, it became for practical and economical reasons, more appropriate to build on flatland and the hill was left to farmhouses; for agricultural use or to accommodate houses exclusive to few.

Today's context is different and these hillside "paradises" have started to suffer the consequences of growing urban population, over development and high demand for more land to build. The *favelas,* which characterise the hills of Rio-de–Janeiro (fig2), are one of the so many examples seen in developing countries where this issue is most prominent, but dense occupation in the cities is also becoming an urban issue in many developed countries. Here land prices speculations are promoting the creating of the new "*favelas of the rich*" a symbol of social status, as a recent study report [2]. The fact is that hillside design is growing and as envisaged back in 1980's by Simpson [3] much greater use will be made of sloping sites and they will become refugees for city dwellers.

Figure 1: View of Santorini[4].

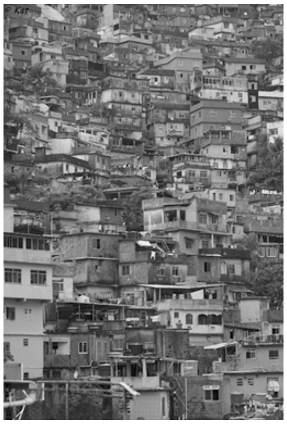


Figure 2: Favela da Rocinha, Rio de Janeiro,Brasil [5]

METHOD

Despite all the qualities, opportunities and uniqueness, of living on hill sites, research done so far has focused mainly on building on flat terrains. When planning to investigate the potential of building on sloped terrain, a number of questions were faced: What are the advantages of building on sloped terrains? Is there a need to build on slopes? Which building forms and orientations are most suitable for sloped terrain? Is there an ideal slope angle for a particular shape? What is the impact of urban design on sloped terrains?
This study is part of a continuous research which is concerned with the energy potential of different building forms and clusters on sloped terrains.

Research Tools *IES V5.9.0* [6] was the software used in order to perform a parametric study of shading and thermal calculations: *VE/ModelIt* was used to model the shapes and clusters; *VE/SunCast* was used to perform shading analysis and *VE/Apache Thermal* to conduct the thermal analysis. The climatic data (.wea) used was that for Lisbon.

Building Shape Three shapes were identified to conduct this study. They represent simplified building forms seen in the built environment but not so commonly used. These shapes were designed using the hexagon as the base grid and enclosing form, which allowed not only the insertion of the shapes inside its perimeter (Fig.3) but permitted also the construction of clusters. Apart from the common hexagon base, all the three shapes have also the same height (12m); floor area (300m^2); external surface area (1158m^2) and volume (3600m^3). These values represent a typical rectangular-shaped 4-story block of flats. The façades have no protrusions and voids and the shapes are placed on an inclined plan which can vary in angle, representing the inclination of a terrain. The study was conducted for south facing slope angles of 20°, 35° 50° and for locations at latitude 40°N.

Figure 3: Plan of the shapes

Clusters Tessellation was the method used to set and organise the clusters in order to help giving geometry and balance to the composition proposing, at the same time, the generation of different urban patterns. The use of tessellation in art and architecture has ancient roots and examples can be seen throughout the world and during different historical periods. This technique can also be applied to form generation and urban design, as shown in figure 4 and 5. To allow for this, the chosen geometry was the hexagon, because being a regular polygon it can tessellate.

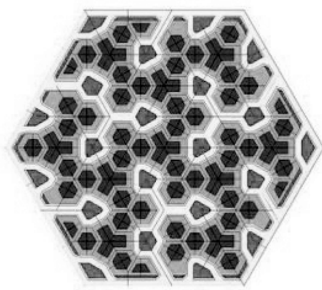


Figure 4: A neighbouring panning using Tessellation. [7]

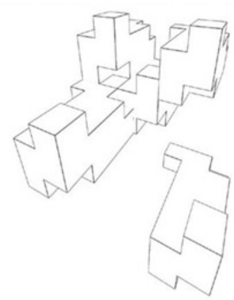


Figure 5: interlocking of spaces by 3D "tessellation" blocks [8].

Each cluster is composed of four shapes and in each of them one will be used as the reference studied shape. This shape is identified in a light grey (Fig. 6) and will be studied for solar shading and thermal analysis. This small cluster was then rotated 30° clockwise generating seven different compositions (Fig.6). The distance between the shapes is dictated by the size of the hexagon in which perimeter the shapes are designed.

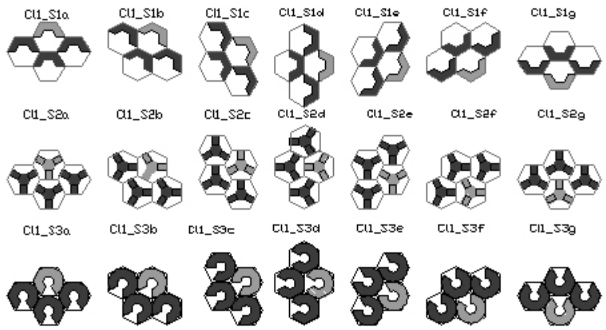


Figure 6: The three clusters: Cl1, Cl2 and Cl3 and the reference shape identified in light grey

RESULTS

Placed on three different south facing sloped angles at latitude 40°N, and using weather data for Lisbon, a series of solar shading and thermal studies were carried out using *IES V.5.9.0*, to evaluate the solar potential of the different clusters. These clusters are indentified as: CL1_S1; CL1_S2 and CL1_S3, where CL1 stands for Cluster 1 and S#, stands for the shape number. Each cluster is composed of seven variations (CL1_S# a to g). For the solar shading analysis, all the seven reference shapes were studied. The impact of the other three shapes that compose the cluster, in the external walls of the reference shape was quantified in terms of percentage of wall area exposed. In order to proceed with the thermal analysis it was decided that only the reference shape which resulted to be the most shaded in summer and the least shaded in winter would be tested.

Solar Studies Shading analysis obtained with *VE/SunCast* considered direct solar radiation only and were done choosing a typical day in summer (June 15th) and in winter (December 15th). The results are expressed in percentage of wall area exposed.

June results Results for June 15th show the influence of slope angle on the shadowing effect on the reference shape. Figure 7 shows that cluster CL1_S3 is the least exposed to solar radiation regardless of the slope angle. For the same slope angle and for all seven cluster variations, cluster CL1_S2 is shown to be slight more exposed to solar radiation than CL1_S1.

A closer look at the data, it is also possible to conclude that for CL1_S1 there is in average more wall area exposed when shapes are place on a slope 20°, while CL1_S2 has in average more wall area exposed when placed on a flat surface. Of all the seven variations of CL1_S1, the least exposed to solar radiation is shape 1g. Results for CL1_S2, show that Shape 2g, has in average the least wall area exposed to solar radiation when placed on any of the studied slope angles, except for flat terrain, making it the ideal shape for summer design. Cl1_S3 will have least wall area exposed to summer solar radiation if placed on a flat terrain, while it will have more wall area exposed and by consequence subject to over heating if located at either a slope20° or slope 35°. Of all the seven variations of CL1_S3, reference shape 3d is the least exposed to solar radiation, whatever the slope angle it is placed, making it the ideal shape if potential heat gains are to be avoided during summer.

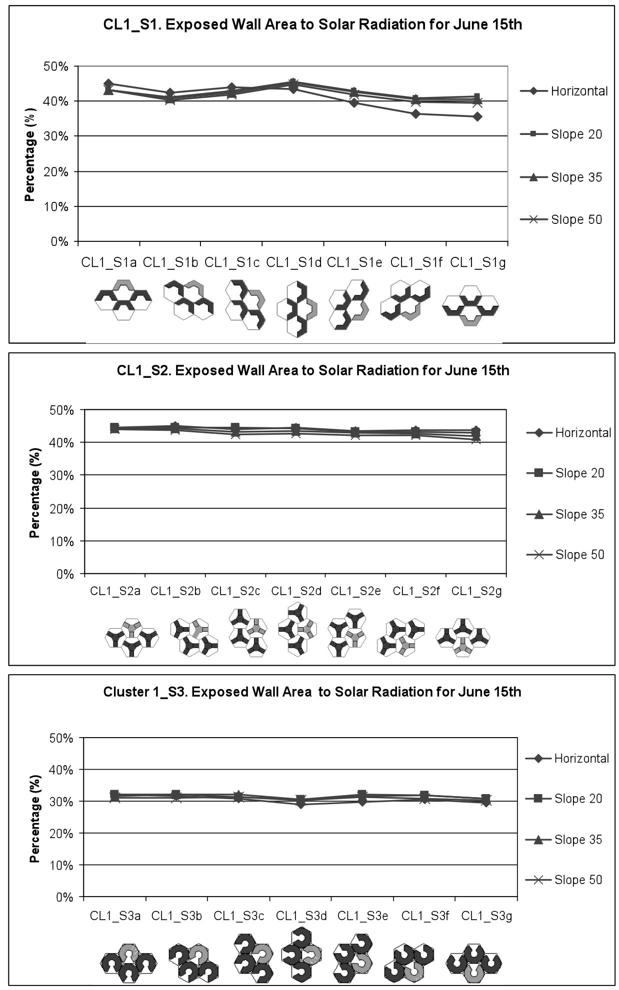


Figure 7: Clusters versus slope angle. Percentage of wall area exposed to solar radiation in June 15th

December results While in summer, the aim is to avoid overheating; in winter the aim is to take the best advantage of the low winter solar rays in order to warm the internal spaces. In both cases, the geometry of the shape and its orientation is essential. Taking these considerations into account, will limit or even eliminate the need to install HVAC systems and reduce the expenses for heating and cooling.

The following analyses take 15th of December as a typical winter day. The difference between the results obtained for summer and those for winter are evident. In December, slope angle seems to have a great influence in the amount of solar radiation reaching the external walls of the reference shape. Wall area exposed to solar radiation increases with slope angle, being the "worst case" obtained when shape are placed on a flat terrain. Another reading from the graphs (fig 8) show that for the same slope angle (slope 50°) all the seven variations of CL1_S2 have, in average, more wall area exposed to solar radiation compared to those of CL1_S1 and CL1_S3. The results also show an increase in percentage of wall area exposed to solar radiation as the cluster starts rotating clockwise. As a consequence of this rotation the reference shape becomes gradually less obstructed by the neighbouring shapes and more exposed to the low winter solar rays.

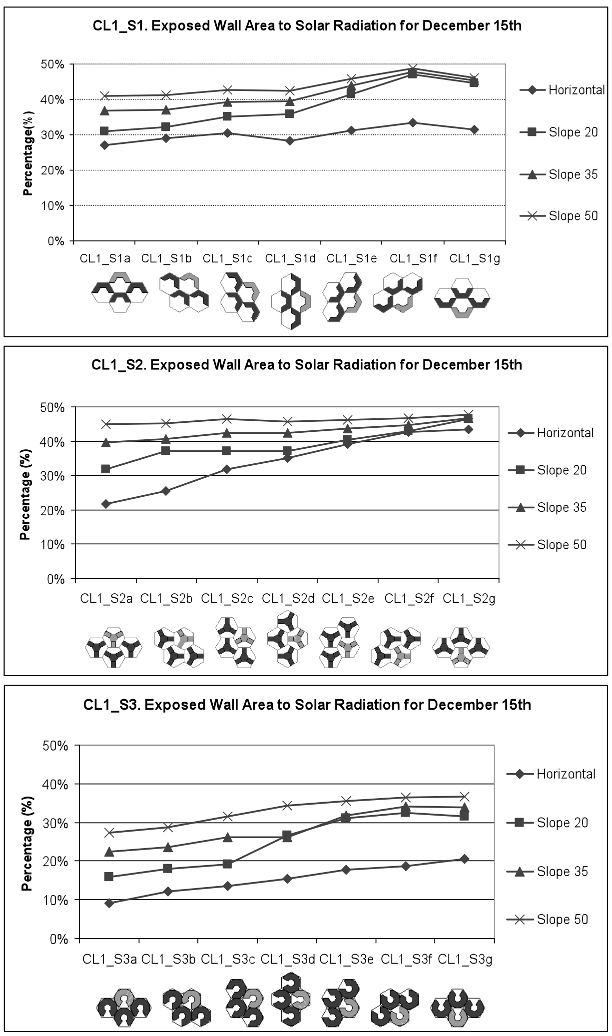


Figure 8: Clusters versus slope angle. Percentage of wall area exposed to solar radiation in December15th

Thermal Analysis Thermal calculations were undertaken using IES/Apache thermal to access the thermal performance of the shapes. The program uses real weather data for the calculations. In the present study the shapes have no openings and the thermal template chosen in IES considers the internal spaces as 'Unheated Spaces' with no HVAC implemented.

All the shapes are constructed as follow:

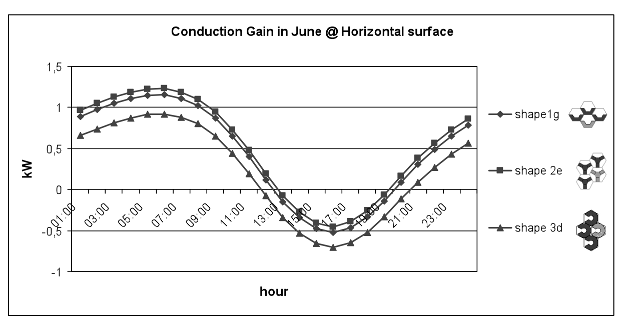
a) External wall with insulation on the outside. U-value of:0.6418 W/m2K

b) Super insulated roof. U-value: 0.17 W/m2K

c) Super insulated floor. U-value: 0.2756 W/m2K

June results Due to the lack of HVAC systems and the fact that there are no openings the air will be trapped inside the shape being its only temperature controller the thermal mass of the façade. An analysis of the simulation studies reveals that during the day, as the sun strikes the external walls of the shape, its surface temperature starts to rise. Solar energy absorbed during the day by the external walls will then be carried on all the way through to the inside of the wall and heat the internal space at night. Then, air trapped overnight within the shape will start moving to the outside. The graph (fig.9) shows the peak point between 5am and 6am, after which the heat will slowly be released out of the internal space and this is the reason for the heat losses shown in the graphs. This transfer of heat from the inside to the outside takes several hours revealing the high thermal mass of the building envelope.

A closer look at the results (fig.9) show that for equal slope angle, shape 1f and shape 2g behave in a very similar way, while shape 3d and 3g have slightly less heat gains at night but higher heat losses during the day than the other shapes. The mean inside temperatures measurements were relatively constant in all the shapes, as it can be read in table1 and this is again due to the thermal mass of the external envelope (table 1). To be noted however, that there is a slight temperature decrease as the slope angle increases. The "coolest" shape is shape 3g being also the less exposed to solar radiation during summer. It is therefore the most recommended for summer cooling. Conduction gains for shape 2 decrease with increase slope angle, coinciding with the decrease of wall area exposed. Although graphs show a very close relationship between CL1_S1 and CL1_S2, the latest has in average slightly more area exposed during summer and generates more heat gain.



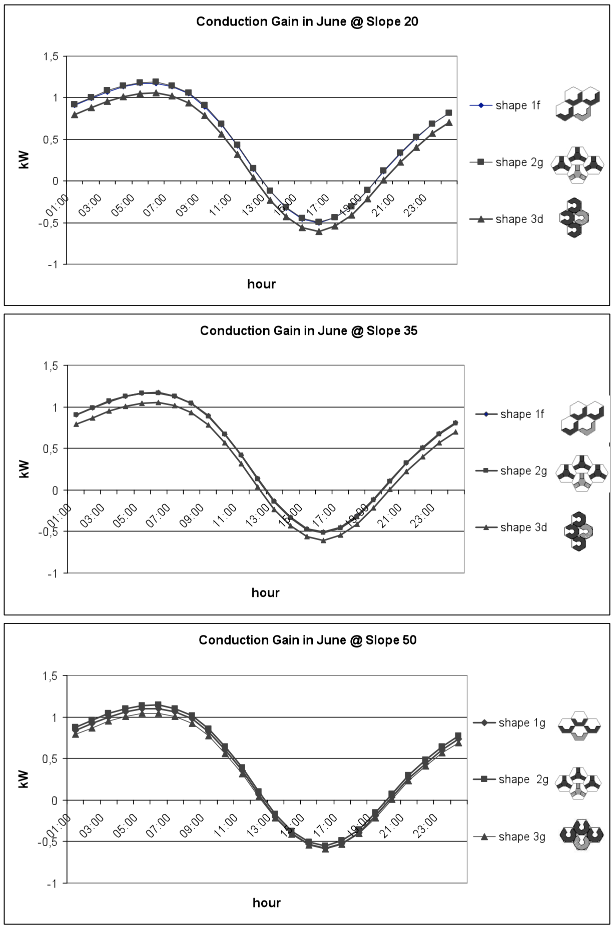


Figure 9: Clusters versus slope angle. Conduction gains in June.

Table 1: Shape's mean air temperature in June

Slope 20	**shape 1f**	**shape 2g**	**shape 3d**
	30,1°C	30,1°C	29,5°C
Slope 35	**shape 1f**	**shape 2g**	**shape 3d**
	30,0°C	30,0°C	29,5°C
Slope 50	**shape 1g**	**shape 2g**	**shape 3g**
	29,7°C	29,8°C	29,6°C

December results Although the thermal behaviour of the shapes is the same throughout the course of the day, showing heat gains during the night and heat losses occurring during the course of the day, heat losses/gains are less in December (fig 10) than in June (fig 9). There is a close relationship between slope angle, wall area exposed and conduction gains in the results obtained for December. As the slope angle increases, the wall area exposed increases and by consequence the shapes will gain more heat. As can be read in figure 10, the graphs show a great distinction between Cl1_S3 and the other two clusters, Cl1_S1 and Cl1_S2. The latest are closely related while the self-shading and mutual shading effects on CL1_S3 contribute to the greater shaded area and the least heat gains. Conduction gains/losses in December and solar shading analysis, show that Shape 1f and shape 2g should be considered for winter design.

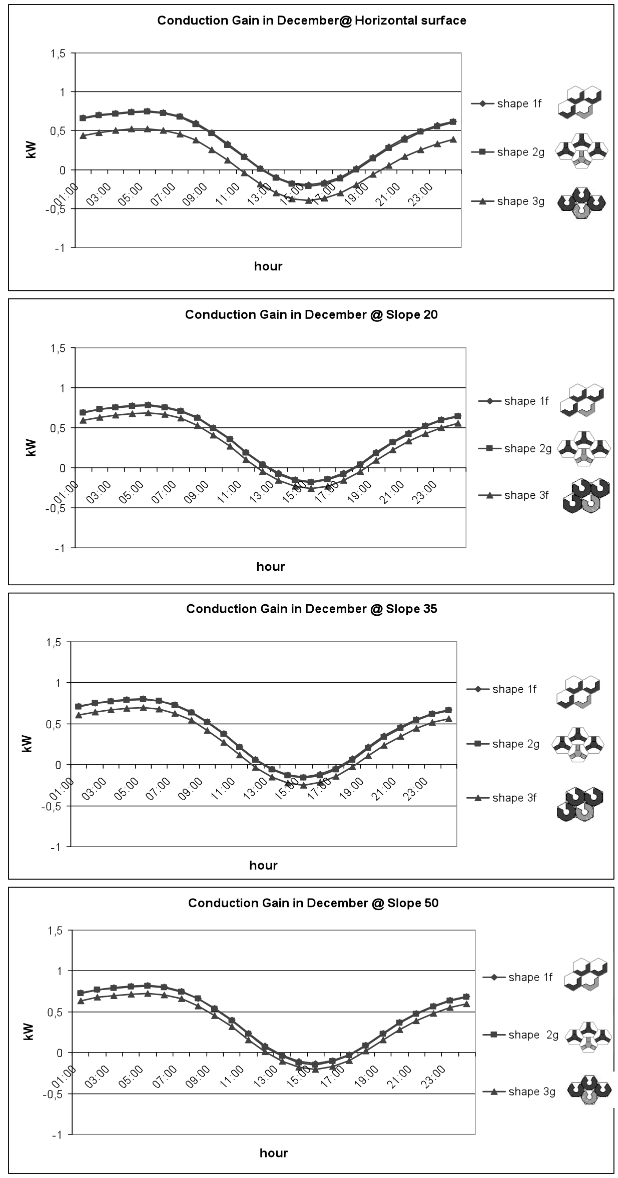


Figure 10: Clusters versus slope angle. Conduction gains in December

CONCLUSION

Growing urban population and scarce land availability are currently important issues in our modern cities. Pressure imposed on rapid urbanizations is forcing cities to expand towards areas where land is still available and this is one reason for the growing popularity of hillside design, making this research timely.

The methodology proposed in this study consisted on the generation of different small urban clusters, which represent different options of urban design on sloped terrains. Solar shading analysis and thermal calculations were computed for each cluster and in all the identified cases, slope angle and shape's orientation have shown to influence the solar potential of each cluster. The results have also shown that for the same slope angle different clusters with different orientations present promising potentialities, for both summer and winter design. Furthermore, because slope angle has an influence on the self-shading and mutual shading between the shapes part of a cluster, the same cluster may behave differently according to the different slope angles where it is placed. All these relationships between slope angle and shading effect will also influence the thermal behaviour of the studied shape. Most shaded shapes will have less heat gains and will then be the most recommended for summer cooling, while least exposed shapes will have more heat gains and will therefore be most recommended for heating requirements. The approach taken in this study aims to function as a guide to architects and urban planners at the very first stages of the design process.

Considerations and Further Research The present study is part of an on-going PhD thesis. Although not presented in the present paper the on going research considers also Ralph Knowles' "solar envelope" concept. The generations of the solar envelope concept using the three studied clusters not only tested its applicability and potentiality as form generator on slope terrain design, but also aimed at learning its solar energy potential, by conducting solar shading analysis and thermal performance calculations. A few considerations and further research ideas are described in this subsection:

a) The presented model is a very simplified representation of an urban built form. No balconies, no windows, no obstructions, no voids were considered during the modelling of the shapes. For a more realistic study, these and other variables should be model. For the thermal analysis other construction materials should be tested and openings should be designed to account for solar gains.

b) Solar shading analysis with *VE/SunCast* considered direct solar radiation only, while calculations results passed into *VE/thermal* calculations contain results for both direct and indirect. This can create some discrepancy when comparing the results obtained for wall area exposed; solar radiation collected and thermal calculations.

c) The use of air-conditioning was not introduced in this study, but it would be interesting to simulate such scenario to help build up a more realistic energy consumption study

d) It would also be interesting to study the PV solar potential of the shapes.

e) The applicability and potentiality of using tessellation as an urban design methodology seems promising and can open up towards more research in this field.

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