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The role of building form in energy consumption: The case of a prismatic building in Athens

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ABSTRACT

This paper examines the behaviour in energy consumption of buildings that have polygonal and prismatic envelopes and are located in Mediterranean climates. More specifically, it aims at studying the differences in energy consumption of these kinds of buildings compared to orthogonal building envelopes. For this purpose a contemporary building was chosen and modelled in two different versions, one being the original prismatic form and the other a model of the same building with right angles, however retaining all area and volume data of the original prismatic building. Calculations reveal that the prismatic formed building has lower solar gains compared to its orthogonal counterpart and consumes less energy in an annual cycle. The results show a mean annual energy consumption difference of 7.88% in favour of the prismatic building envelope. Also, depending on the orientation, the difference in annual energy needs has a range between 2.51% and 16.01%.

1. Introduction

During the past decade contemporary architectural design shows an ongoing interest for nonrectangular angles and prismatic building envelopes. In addition, buildings with a prismatic form, such as the MAXXI [1] in Rome or the Casa da Musica [2] in Porto, have been in the forefront of several architectural journals and have acquired architectural awards and prizes. Taking into account that most of the built environment does not follow the fore mentioned design trend, as well as the fact that most energy consumption guidelines, as well as most simple building energy simulation software treat buildings as orthogonal, the main question that arises is at what percentage a polygonal prismatic building envelope can influence the energy consumption in comparison to its orthogonal counterpart.

Furthermore, literature review revealed gaps within energy performance regulations in Greece [3] and available software [4] for buildings with polygonal or prismatic form, which indicated the need for further research relating to the energy behaviour of such buildings. These gaps were mainly related to simulation inabilities of mainstream computer software, when calculating thermal behaviour results for buildings with prismatic form, such as buildings that are not clearly oriented because of their angular form, or are inclined from the vertical plane.

This paper addresses these issues and focuses on the comparison of the thermal behaviour of a case study building in Greece, whose envelope is inclined from the vertical plane. Previous work by Guedi Capeluto [5] has shown that inclined walls can attribute to the shading of the building envelope. Our work mainly aims to provide a new perspective, useful for low energy consumption architectural design of buildings with polygonal and/or prismatic form. The main part of the study presents the calculation of energy efficiency in the case study building. Our findings provide evidence that, when the shape of the external building envelope is considered, architectural design can significantly improve the energy consumption of a building.

2. Methodology

Taking into account the fact that solar heat gains are inextricably depended on the solar radiation's angle of incidence [6], as well as the fact that the variation in the solar absorption of any material, whilst dependant on many imponderable factors, is minimal between different angles of incidence [7], we can conclude that the main factor of solar absorption is the solar radiation's angle of incidence. Our research makes the suggestion that the energy consumption of two buildings with identical characteristics

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Fig. 1. Architectural representation of the new building of the Geodynamics Institute, Athens, Greece, 2009, Architects: Zerefos Tessas Architects, Chrysi Stavropoulou.

concerning their site, floor and wall areas, volumes, openings, materials and operating program, differs only due to the shape of its external envelope.

The case-study of the new building of the Geodynamics Institute of the National Observatory of Athens [8] was chosen to be tested, as it fulfills the above criteria (Figs. 1 and 2). In addition this research was a means to test the efficiency of the architectural design, so that minor changes could be made to improve the environmental qualities of the building, before the construction phase. The building site lies on a hill, at an altitude of 500 m above sea level, and complete electronic documentation was available, as well as on site climatic data. The southern façade of the building is divided into two sections forming an edge towards the south, with an angle of 143° between them. Western and eastern facades are inclined from the vertical plane by 7° and 4° respectively. Moreover, the roof is divided into four planes with different slopes, which have a negative angle to the sun of 65%.

In order to examine how the shape and the geometry of a building can affect its energy performance, two models were created. The first model was the original polygonal case-study building, whilst the second was identical to the first in terms of floor and wall areas, volumes, openings and materials, but the shape of the building envelope consisted of vertical walls and a flat roof instead. During the modelling process, each building model was split into different thermal zones according to different space uses. Special care was taken so that all the areas and volumes of the second model would be as similar to the original one as possible. Fig. 3 shows a thermal zone at the top floor of the simulated building in its prismatic and orthogonal versions. Due to the fact that we tried

Fig. 2. Architectural representation of the new building of the Geodynamics Institute, Athens, Greece, 2009, Architects: Zerefos Tessas Architects, Chrysi Stavropoulou.

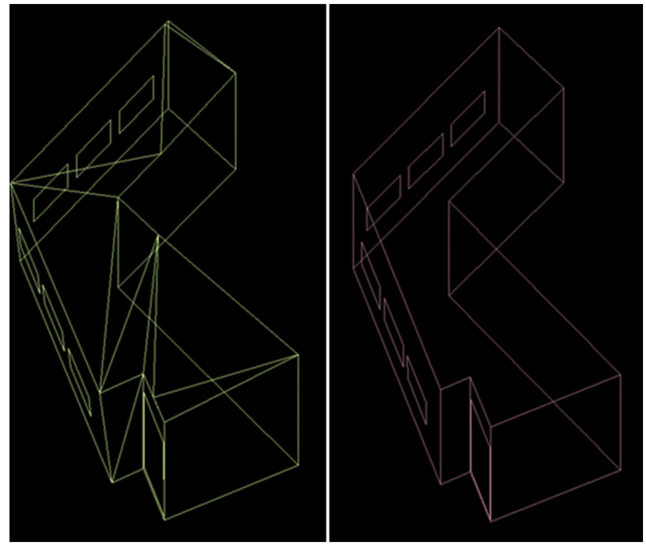

Fig. 3. Comparative geometrical models showing a thermal zone in the prismatic-polygonal model (left) and the orthogonal model (right).

to model an identical building in terms of areas and volumes but with different geometrical characteristics, we have measured each thermal zone and modified it so that the average deviation in wall area and volume in the two buildings was $\pm 0.7\%$ and $\pm 0.2\%$ respectively. It is worth mentioning that the floor areas, as well as the window and opening areas were modelled to be accurately identical. The materials and constructions with layered materials of the two models are also identical.

The next step was the comparative simulation of their energy consumption, by comparing the calculated heating and cooling loads in the prismatic model and its orthogonal counterpart respectively. The simulation was conducted for all the surfaces of the top floor in both models throughout an annual run. The total incident solar radiation in kWh/m^2 per month was calculated for each surface of the two models and was used to identify the difference in the energy consumption between the two models. Air flow around the building was also simulated, in order to study possible differences in wind velocity that could affect thermal calculations through natural ventilation procedures.

During the modelling phase, various assumptions had to be made concerning building elements, climate data and operating parameters for all zones. Building materials and construction details were provided from the construction drawings, so that the *U*-value of all building elements could be calculated. Climatic data [9] were provided by the station of the National Observatory of Athens in Penteli for the exact site. In addition, operating parameters for the zones, relating to the present operation, were defined by the management and personnel of the Geodynamics Institute through interviews. Data included operation schedules, lighting and ventilation regulations, desirable temperature, occupancy and other operational parameters for each space of the building.

3. Results

3.1. Solar radiation

For the purposes of the present study, incident solar radiation on the roof G, on the western and eastern façades was calculated comparatively for both building models by using formula

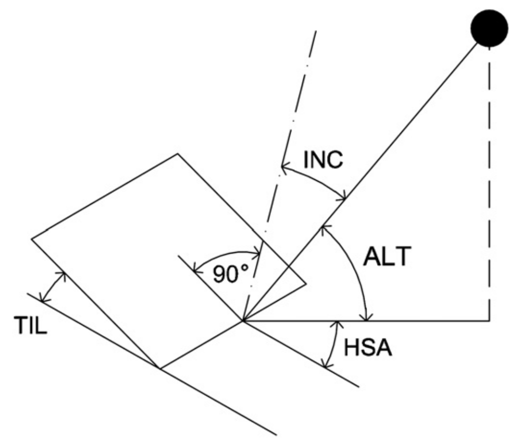

Fig. 4. The geometry of a tilted surface and the position of the sun.

Eq. (3.1.1) [9]:

$$G = Gh \times \cos INC \sin ALT + Gdh \times 1 + \cos TIL^2 + Gh \times r \times 1 - \cos TIL^2 \quad (3.1.1)$$

where *Gh* is the solar radiation on the horizontal plane, *Gdh* is the diffuse solar radiation on a horizontal plane, ρ is the reflectivity of the surface, *ALT* is the altitude of the sun, *TIL* is the tilt angle of the surface with the horizontal plane, INC is the angle of the surface with the suns' rays and is given from the formula Eq. (3.1.2):

$$INC = \cos[\sin\ ALT \times \cos TIL + \cos ALT \times \sin TIL \times \cos HSA] \quad (3.1.2)$$

where *HSA* is the vertical angle between the horizontal level and the suns' azimuth as depicted in Fig. 4.

Results were divided into two sections according to the heating and cooling seasons, in order to show the difference in energy consumption and how the latter is affected by the geometry of each building. It has to be noted that due to the high altitude and the location of the site on Mount Pendeli (500 m), the cooling season starts in May and ends in September, whilst the heating period is from October to April.

3.1.1. Roof

The roof of the prismatic building is separated into four parts with different slopes, "a", "b", "c", "d" as shown in Fig. 5. Due to the negative angles of the slanted roofs to solar radiation, all parts of the slanted roofs receive less solar energy and therefore are heated less during the cooling period compared to the flat roof. Table 1 shows the differences of the mean incident solar radiation per month for the parts of the slanted roof and the horizontal slab. More particularly the average difference of incident solar radiation between the slanted roofs and the flat roof is 5.67%, 2.11% and 5.18% for parts "a", "b" and "d" respectively during the cooling period. In the case of part "c", the flat roof performs slightly better during the period from August to September since it receives on average 0.55% less incident solar radiation than the flat roof. However, during the rest of the cooling period, part c receives more solar radiation by 0.22%. Concluding, the higher reduction of the sloped roof overall is observed in September at part "d" with a percentage of reduction up to 10.32%.

During the heating period, part "a" of the sloped roof does not have a steady behaviour, however it is overall less energy-demanding for heating than the flat roof since the average difference in incident solar radiation is 1.00%. The same applies to part "c" with a difference of 1.13%. The rest of the roof parts receive less solar radiation during the same months. The average difference of incident solar radiation between the rectangular and the prismatic building is 7.31% and 12.92%, for parts "b" and "d" respectively.

The comparative advantage of the sloped roof to the flat roof is evident in Fig. 6, which shows the annual comparison of incident solar radiation per sq.m. on the roof parts between the prismatic and the rectangular building. In Fig. 6 one can observe that the difference of solar radiation on sloped surfaces of the prismatic

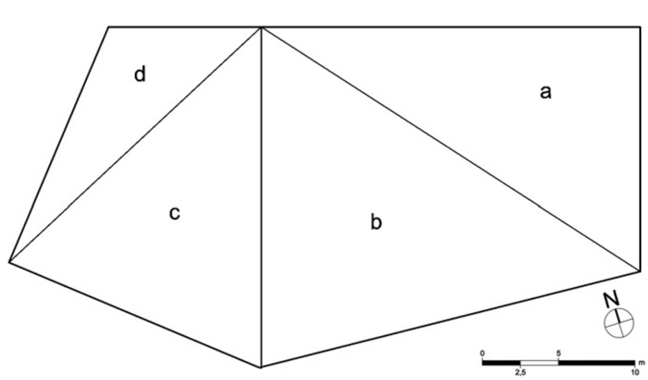

Fig. 5. The division of the sloped roof into four parts with different slopes.

Table 1
Mean incident solar radiation on the roofs of the two modelled buildings.

Month	Incident solar radiation, kWh/m^2				
	Sloped roof				Flat roof
	Part a	Part B	Part C	Part D	
January	12.28	10.15	11.53	9.12	11.87
February	16.30	14.61	16.00	13.39	16.23
March	35.03	33.43	35.27	31.74	35.43
April	69.44	70.21	72.44	67.51	72.61
May	84.93	89.24	90.49	86.40	90.39
June	110.58	116.45	118.45	113.82	118.11
July	107.11	112.78	114.49	109.68	114.20
August	96.21	98.81	101.28	95.41	101.80
September	64.89	63.95	66.72	60.83	67.11
October	32.67	30.35	32.42	28.13	32.86
November	17.64	14.77	16.56	13.49	16.99
December	11.90	9.28	10.74	8.36	11.19

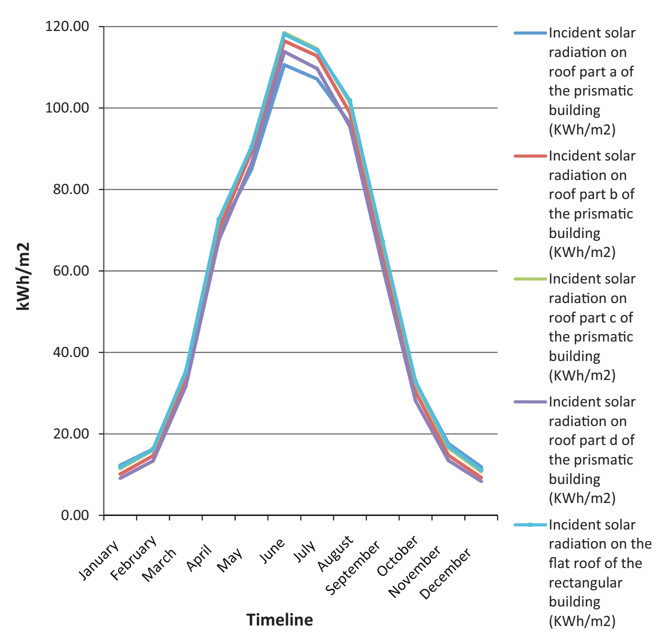

Fig. 6. Annual comparison of incident solar radiation per sq.m. on the roof between the prismatic and the rectangular building.

Table 2
Mean incident solar radiation on the eastern facade of the two modelled buildings.

Month	Incident solar radiation, kWh/m²		Difference (%)
	Prismatic building	Orthogonal building	
January	18.02	18.59	3.06
February	19.24	20.42	5.81
March	28.70	30.76	6.69
April	48.15	51.82	7.07
May	51.05	55.14	7.41
June	58.85	65.22	9.77
July	60.95	67.16	9.25
August	65.16	70.27	7.27
September	51.81	54.95	5.72
October	34.20	36.08	5.22
November	20.39	21.47	5.03
December	15.97	16.72	4.48

building compared to the rectangular one is higher during the cooling period. Meanwhilst this difference is much smaller during the heating period, indicating that the sloped roof is more advantageous compared to the flat roof.

3.1.2. Eastern façade

The eastern façade of the building is designed at an angle of 4° from the vertical axis. Table 2 shows the mean incident solar radiation on the eastern façade of each building and their difference in percentage. During the cooling period, the inclined wall receive 7.98% less incident solar radiation than the walls of the orthogonal building, indicating that the inclined wall is less energy-consuming since it receives less solar radiation during the cooling period (Fig. 7). Respectively, during the heating period (Fig. 8) the inclined wall of the prismatic building receives on average 7.26% less incident solar radiation, which shows that in this case the inclined wall is more energy consuming. As will be shown later the inclined wall at the eastern side of the prismatic building performs better compared to its orthogonal counterpart. The two main factors that attribute to this result is the decreased incident solar radiation during the cooling period, as well as the higher energy demanded for cooling than heating.

3.1.3. Western façade

The western façade of the building is designed at an angle of 7° from the vertical axis. Table 3 shows the mean incident solar radiation on the western façade of each building and their percentile difference. During the cooling period, the western wall of the prismatic building receives on average 37% less incident solar radiation than the orthogonal building which again indicates that the inclined wall is less energy-consuming (Fig. 9). Similarly during the heating

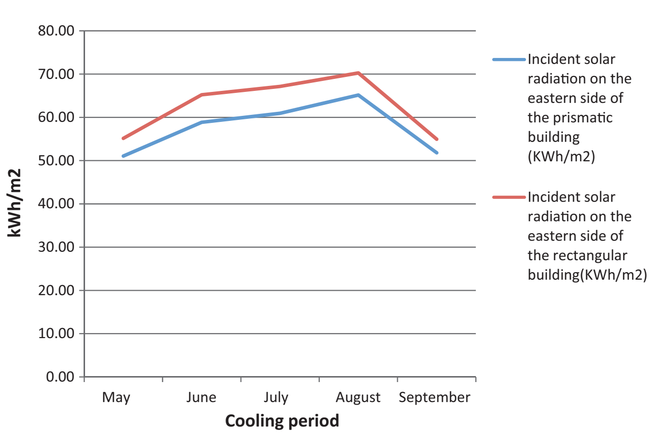

Fig. 7. Cooling period – Schematic comparison of incident solar radiation per sq. m. on the eastern facade between the prismatic and the rectangular building.

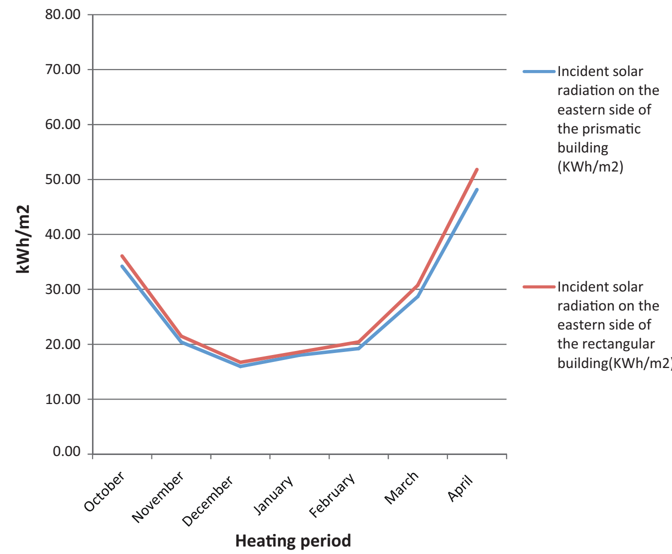

Fig. 8. Heating period – Schematic comparison of incident solar radiation per sq. m. on the east side between the prismatic and the rectangular building.

Table 3
Mean incident solar radiation on the western facade of the two modelled buildings.

Month	Incident solar radiation, kWh/m²		Difference (%)
	Prismatic building	Orthogonal building	
January	0.00	0.00	0.00
February	0.03	0.04	30.23
March	0.26	0.46	42.11
April	1.54	2.43	36.43
May	2.85	4.73	39.80
June	5.47	8.56	36.09
July	4.70	7.40	36.51
August	2.75	4.37	37.14
September	0.83	1.28	35.23
October	0.14	0.20	32.16
November	0.00	0.02	87.50
December	0.00	0.01	100.00

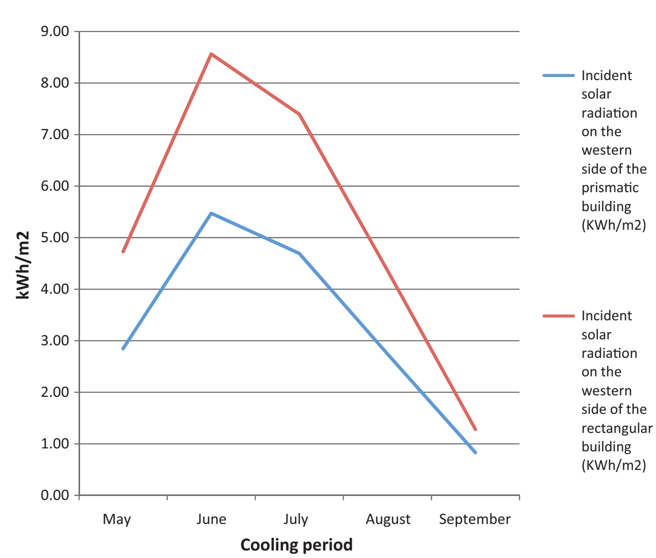

Fig. 9. Cooling period – Schematic comparison of incident solar radiation per sq. m. on the east side between the prismatic and the rectangular building.

period the western wall of the prismatic building receives on average 37.78% less incident solar radiation (Fig. 10). It has to be noted that in absolute values the differences are very small since during the winter months the incident solar radiation is almost zero for this part of the building.

3.1.4. Natural ventilation

The shape of the building can affect natural ventilation [10], since areas of low and high pressure influence it. For that reason the air flow around the two buildings was simulated using CFD WinAir 4.0 software. Measurements were taken at the window sill level of the last floor (Figs. 11 and 12). Although no significant differences were observed between the two models, there were some areas with different airflow rate. At one case, there was an area at the southeastern side of the prismatic building, with lower airflow rate compared to the rectangular building. This relates to the fact, that the polygonal roof creates a more extensive zone with

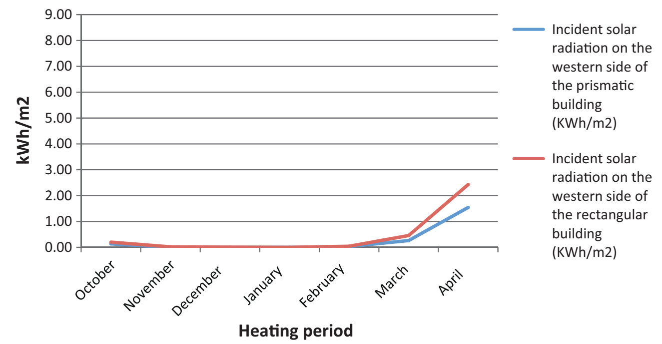

Fig. 10. Heating period – Schematic comparison of incident solar radiation per sq. m. on the east side between the prismatic and the rectangular building.

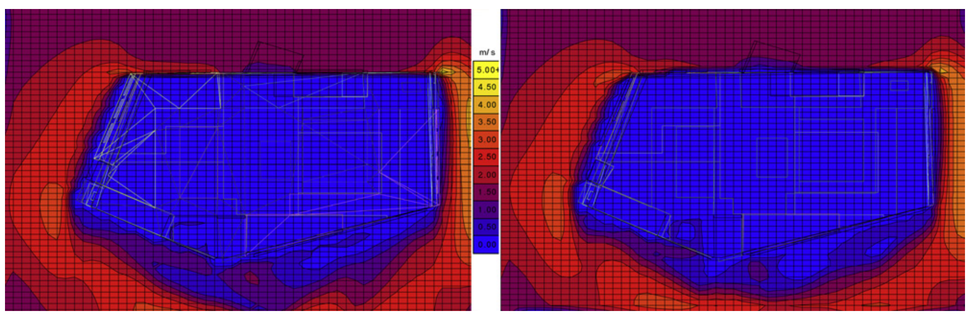

Fig. 11. Plan showing air speed and flow around the prismatic model (left) and the orthogonal model (right) for a north-northeastern prevailing wind of 5 m/s.

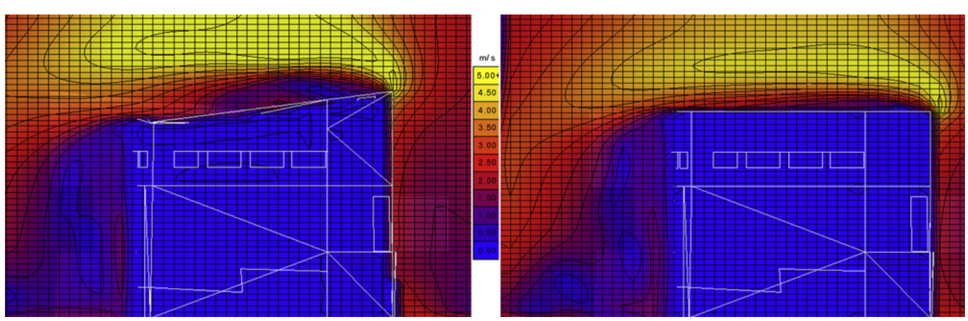

Fig. 12. Section through the models showing air speed and flow around the prismatic model (left) and the orthogonal model (right) for a north-northeastern prevailing wind of 5 m/s.

Table 4
Annual energy consumption of the three modelled thermal zones for heating and cooling.

Month	Prismatic building Southeastern thermal zone		Orthogonal building		Prismatic building Northern thermal zone		Orthogonal building		Prismatic building Northwestern thermal zone		Orthogonal building	
	Heating (kWh)	Cooling (kWh)	Heating (kWh)	Cooling (kWh)	Heating (kWh)	Cooling (kWh)	Heating (kWh)	Cooling (kWh)	Heating (kWh)	Cooling (kWh)	Heating (kWh)	Cooling (kWh)
January	368.87	0.00	370.21	0.00	76.74	0.00	85.77	0.00	157.05	0.00	155.93	0.00
February	368.74	0.00	369.81	0.00	86.13	0.00	95.77	0.00	171.56	0.00	170.23	0.00
March	236.49	0.00	237.11	0.00	45.97	0.00	51.30	0.00	99.69	0.00	98.47	0.00
April	20.36	0.00	20.35	0.00	2.77	0.00	2.95	0.00	7.30	0.00	7.08	0.00
May	0.00	47.12	0.00	63.53	0.00	21.23	0.00	39.14	0.00	20.94	0.00	28.85
June	0.00	289.47	0.00	341.89	0.00	116.24	0.00	153.77	0.00	146.84	0.00	165.42
July	0.00	476.50	0.00	516.51	0.00	173.64	0.00	199.49	0.00	258.52	0.00	260.62
August	0.00	622.04	0.00	631.45	0.00	203.75	0.00	225.68	0.00	324.14	0.00	325.35
September	0.00	179.30	0.00	209.28	0.00	68.04	0.00	91.12	0.00	86.40	0.00	97.41
October	57.49	0.00	57.63	0.00	7.04	0.00	8.32	0.00	19.24	0.00	18.93	0.00
November	26.37	0.00	26.42	0.00	3.59	0.00	4.57	0.00	10.14	0.00	9.92	0.00
December	140.97	0.00	141.26	0.00	28.71	0.00	34.43	0.00	64.26	0.00	63.69	0.00
Total	1219.28	1614.43	1222.79	1762.66	250.95	582.90	283.11	709.21	529.24	836.85	524.24	877.65

low airflow rate around it and in front of the southern façade as opposed to the flat roof. The prismatic building also presented a wider leeward area in its southern part compared to the rectangular building. However, the tangent planes to the exterior walls presented the same air pressure at both cases. Consequently, there was no specific difference in the field of natural ventilation.

3.2. Energy consumption

Energy consumption was calculated for three distinct thermal zones of office use, situated at the northwestern, the southeastern and the northern sides of the top floor of the building. Simulation results showed that in the northwestern zone, which incorporates the western inclined wall mentioned in Section 3.1.3, as well as part "d" of the sloped roof, the heating load was 0.95% higher in the case of the prismatic building, whilst the cooling load was 4.65% lower than the rectangular building. The total annual load reduction for this zone was 2.51%. Regarding the northern zone, the only difference between the two models was related to their roof which corresponds mainly to part "a" of the sloped roof. For this thermal zone the heating load was reduced by 11.36% and the cooling load by 17.81% in the case of the prismatic building, thus resulting in a total annual load reduction of 16.01%. Respectively for the southeastern zone, which incorporates the eastern inclined wall mentioned in Section 3.1.2, as well as part "a" of the sloped roof, the heating load was reduced by 0.29% and the cooling load by 8.41% in the case of the prismatic building, thus resulting in a total annual load reduction of 5.12%. Table 4 shows the annual energy consumption for heating and cooling in all three thermal zones. As a step further the buildings were remodelled to include a single thermal zone, in which the annual energy consumption of the prismatic building was on average 7.88% lower than that of the orthogonal building.

4. Conclusions

Simulation results from the two models revealed that the prismatic building under study performs better in the fields of incident solar radiation and energy consumption compared to the rectangular building. This is due to the fact that the inclined walls and roofs decrease the incident solar radiation in a larger percent in the cooling periods than in the heating period. This helped for the prismatic building to achieve lower energy consumption when compared to the rectangular building. The total annual energy load reduction was 2.51% for the northwestern zone, 16.01% for the northern zone and 5.12% for the southeastern zone. Similarly, an average reduction in energy of 7.88% was calculated for the total building area favouring the prismatic building.

Concerning the natural ventilation, it appears that the building shape does not essentially affect its performance, due to the fact that air speeds and airflow around the models do not show any significant differences when measured at the level of the openings. Moreover, the prismatic building presented a wider leeward area in its southern part compared to the rectangular building. However, the tangent planes to the exterior walls presented the same air pressure in both cases. It has to be noted that if the ventilation were conducted through the roof of the building instead of the windows the results would have been different to some extent.

We can therefore conclude that the external shape of a building can change its energy consumption regardless of the materials and its usage in terms of schedule. In the climatic conditions of Mount Pendeli that this research took place, geometry that creates high angles of incidence from solar radiation is – in the cases presented in this study – more favourable in energy consumption reduction than orthogonal geometry, since cooling loads are reduced in a higher extent than heating loads.

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