Impact of building shape on indoor building performance combined with cost of structure

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International Journal of Applied Engineering Research ISSN 0973-4562 Volume 11, Number 15 (2016) pp 8622-8630

Impact of Building Shape on Indoor Building Performance Combined with Cost of Structure

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Abstract
The paper focuses on the influence of basic shapes on the internal building performance considering the variables of indoor air temperature, heat conduction and cooling load with maintaining the same floor area in each model. The paper is leading the impact of energy building performance against structure cost which is a quite unique contribution to other architects and engineers to be aware of the influence of basic shapes at the early stage of design. The region of the examined models were the capital city of Saudi Arabia (Riyadh) which represent the hot and dry climate. In addition to that one of the most interesting models were examined in different orientations in order to seek more potential of results for future research. The cost of each shape structure was also investigated to provide more accurate recommendation for architects and engineers. It can be revealed that the performance of the shape with maintaining the same value it connected strongly with the number of the sides. The less number of sides in the shape, the better energy and environmental performance is expected. Moreover, circular shape is the lowest while the expenditure of pentagon and triangular shape was increased by 3% and 12%, respectively. Based on the research conducted, it can be concluded that although circular shape was found with lowest structure cost compared to all other shapes, triangle and pentagon can be the ultimate shapes to consider.

Keywords: Energy conservation**,** Building design**,** Building shape**,** Cost of structure**,** Cooling load**,** Basic shapes**,** Impact of orientation

INTRODUCTION
Most of the published work on professional sources focuses on the physical part of the building envelope such as phase change material, heat transfer and influence of thermal mass. However, little pay attention to the impact of the shape of the building regardless of its area. Building form is a considerable factor in sustainable and green buildings because of its importance impact on energy performance and total energy consumption as demonstrated (Wang, 2006). Moreover, Lomas, (2007) and Okeil, (2010) have observed that building geometry has an important influence on ventilation which will aid to control air movement within the building.
The study of Al Anzi *et al*., (2009) has highlighted the performance of the most basic shapes. The case study has been carried out in office buildings. The paper has come out with three main factors affecting building shape. The first one is the distance where buildings stand next to each other. This will has a result on the air speed around the building especially in the case of high rise buildings. Moreover, is the factor of glazing to wall ratio and finally is type of glazing system used in the building. Moreover, the total area of building shape also might be responsible for high differences in the amount of energy required for cooling and heating. This is due to the area of the external wall which is exposed t outdoor. It is accepted in energy building performance and thermal comfort that one of the most effective elements in heat transfer is the total area of external wall. Furthermore, the exchange with outdoor will become larger as the total area is increasing as stated by Al Anzi *et al*., (2009).

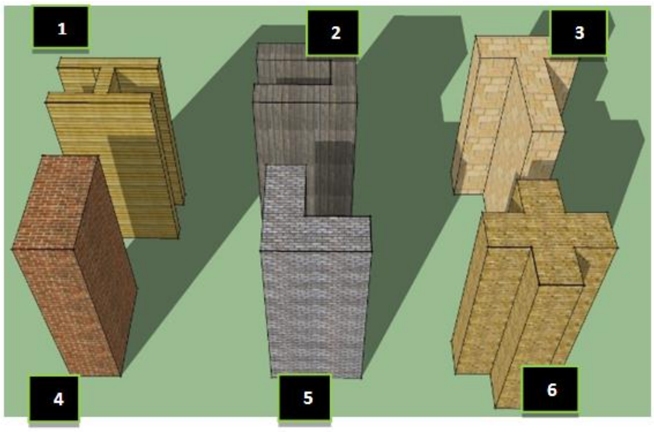


Figure 1: Forms of building analysed, where:
1. *Is the H shape*
2. *Is the U shape*
3. *Is the T shape*
4. *Is the rectangular shape*
5. *Is the L shape*
6. *Is the cross shape*

Source (reproduced) from AlAnzi (2009)

IMPACT OF ORIENTATION ON BUILDINGS
Orienting building can be considered as the easiest approach in architectural design in respect of passive solar strategy in order to achieve thermal comfort in building as well as reducing the total energy consumption. This approach does not require any mechanical means and has to be done at the first stage of design considering the local location of the site as demonstrated (Morrissey *et al*., 2011). In addition to that, Bekkouche *et al*., (2011) and Hamadani *et al*., (2012) have stated that orientation is in the prime principle of the knowledge of architectural design requirement.
In harsh climate regions, where temperature fluctuates dramatically, orientation is quite important Bekkouche *et al*., (2011), Assem, (2011) and Schlueter, and Thesseling (2009). The major concern in the region of Gulf countries is the

cooling load where temperature rises sharply over summer period as stated by Kruger *et al*., (2009). On the other hand, Hamadani *et al*., (2012) has reported that orientation does not has considerable impact on building energy performance, and thermal insulation has the major has more effect than orientation. Spanos *et al*., (2005) has stated that if the building was well orientated, this will reduce the total energy consumption by 20%. This should be emphasised especially on the roof, west and east walls as they exposed to the sun at most of the daytime (Assem, 2011). On the other hand, some other authors are of the opinion that orienting the building to the most appropriate way has a quite limited impact on building energy performance Hamadani *et al*., (2012). In the published work the author has investigated the implementation of orientation and thermal insulation. On top of that Raychaudhuri, (1965), has reported that the longer face of the building should be orientated north and south.

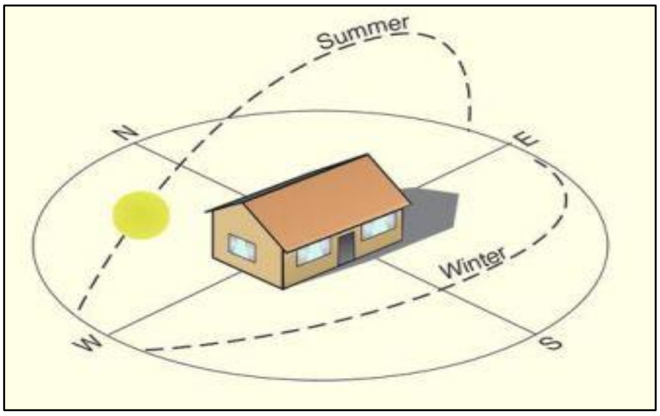


Figure 2: the impact of orientation in the exposure of sunlight on external surfaces

It seems that there is an argument on the effectiveness of applying orientation into buildings. Most of which indicate that orientation has a significant impact on buildings regardless of its local location. However, when it comes into comparison with other technique such as providing thermal insulation, orientation may not be the most efficient way.

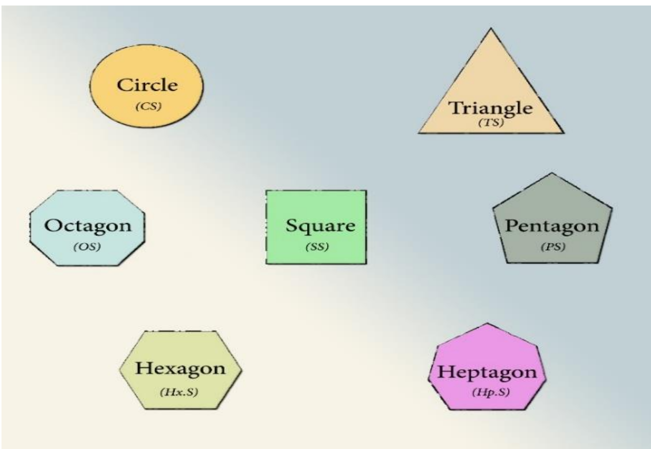


Figure 3: the investigated models which has the same building volume and various shape

VALIDATING TAS EDSL TOOL

The main purpose to use TAS EDSL in this research is to measure indoor air temperature, in order to insure high quality of results and recommendations, a validation of the software will be validated to measure indoor air temperature as well as relative humidity. The location is in Taif city in Saudi Arabia, where four data loggers were set in selective bedrooms as shown in figures 4 and 5, and one was set outdoor to measure actual outdoor temperature beside relative humidity. The results show high accuracy of the predicted results derived from the computer modelling compared to the actual data recorded from the data loggers.

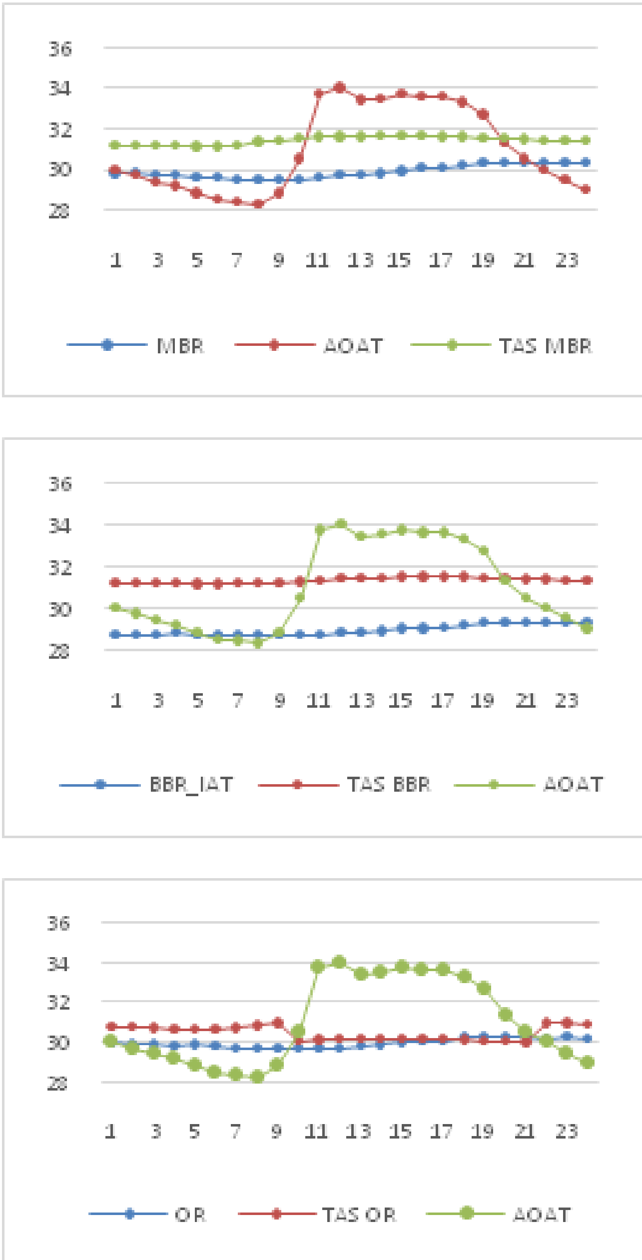


Figure 4: Actual and predicted IAT on Day 184 of main bedroom (MVR), boy's bedroom (BBR) and office room (OR)

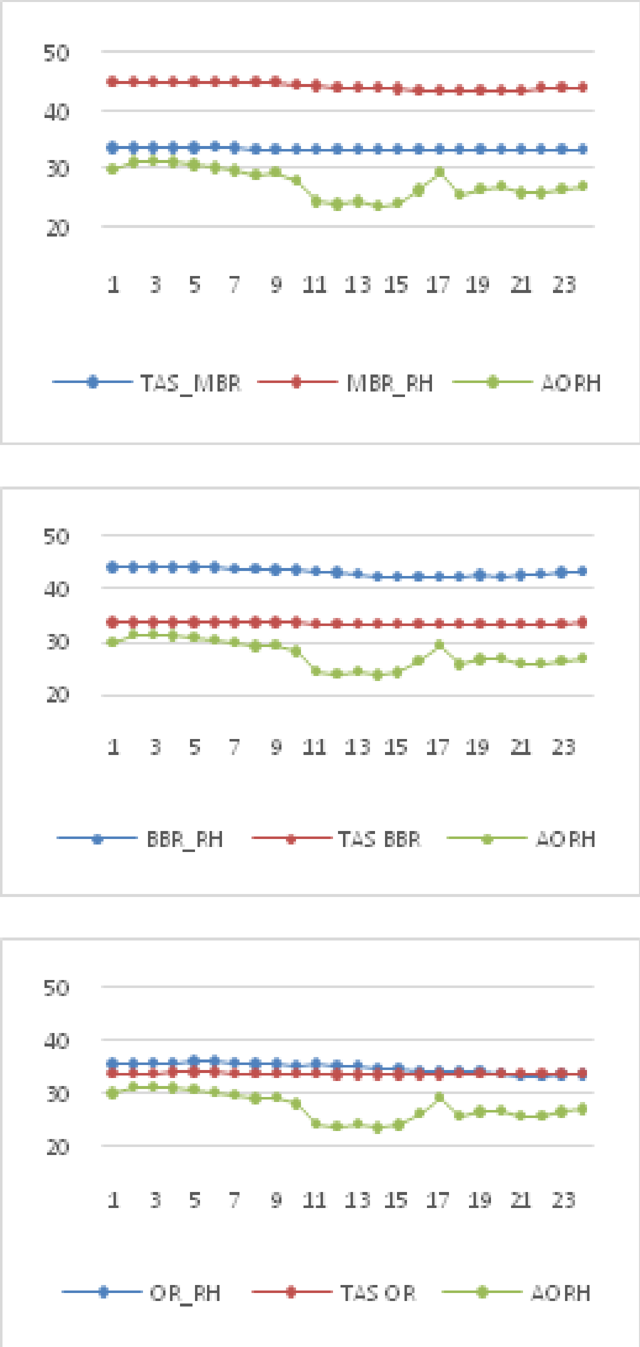


Figure 5: Actual and predicted RH on Day 184 of main bedroom (MVR), boy's bedroom (BBR) and office room (OR)

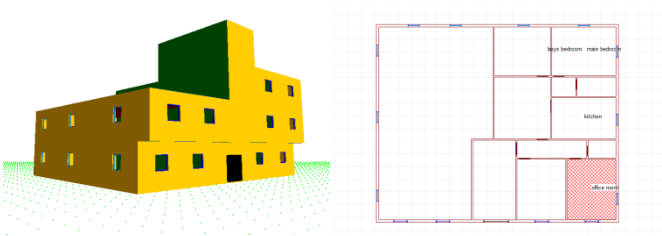


Figure 6: A.Perspective of the building used for validation. B. It is the site place of the building. C: A photo of the building in the city of Taif. D. The data logger used to monitor indoor dry bulb temperature and relative humidity in a selective number of rooms shown in figure B

METHODOLOGY

The research major aim is to investigate the connection between the shape of building and its implementation on the energy performance with respect to the cost of its structure. The research will highlight the seven basic and popular shapes (fig 3) which are considered as the main elements in architectural design that many designer use them to form their buildings, with maintaining the same building volume here. Each building subsist of two storeys with height of 3.5m per level. The models have been analysed using one of the most powerful energy modelling tool (TAS EDSL) which has been used globally. The tool has been validated by Alwetaishi, (2015) the tool's results have been compared with actual data derived from energy equipment. Building fabrications has been specified as shown in table (1) including its properties such as layer width, conductivity and total U-value or shading coefficient. The paper will highlight several aspects such as indoor air temperature, heat conduction by external walls and solar heat gain through glassing system.

The other method in this research is going to be determine the structural cost and time analyses. These analyses based on a comparison between the construction cost and time required for each structure shape. The structural system used for each slab shape was the Flat slab system with marginal beam supported directly on columns. Before starting this part, model verification was conducted by comparing its results with the manual calculation performed for typical conditions and spans Flat slab designed manually using direct design method. The results obtained from model fulfil the manual design to an acceptable degree of accuracy. The most important factors that controlled the Flat slab design are the punching slab stress and edge beam torsion. The first factor is controlled by the slab thickness where the second is controlled by the numbers of outer columns. For these reasons the structure system is different from one structure shape to another as shown in fig 8.

International Journal of Applied Engineering Research ISSN 0973-4562 Volume 11, Number 15 (2016) pp 8622-8630

Table 1: building fabrication proporties of examined shapes

	Layers	Width (mm)	Conductivity W/m.°C	Total U-value
External wall	Internal paint	100	999.9	0.294
	Brick	100	1.10	
	Polystyrene	100	0.033	
	Brick	100	1.10	
Roof	Concrete	150	0.87	2.491
	Concrete screed	50	1.28	
	Plastic	10	0.5	
Ground	Yellow paint	0.1	999.9	0.294
	Brick	100	1.33	
	Polystyrene	100	0.82	
	Brick common	100	0.82	
Glassing system				
Shading coefficient	layers	Width (mm)	Solar transmission	Total U-value
0.709	clear float	6	0.630	1.803
	Cavity	10	0.00	
	clear float	6	0.630	

RESULT AND DISCUSSION

External heat conduction

Exposed construction surfaces to outdoor environment play a major role in determining the state of internal condition. Although all the models examined have the same value, they all have different area of external walls exposed to the sun in various direction. This is the key element of nominating the right shape in the early stage of design. In order to determine the expected indoor air temperature (IAT), heat conduction and also solar heat gain are of prime importance to consider, this border line is to separate the internal environment from outdoor one.

As outdoor temperature rises, dramatic heat gain take place through external walls. At noon time the amount of heat conduction through the external walls reduce to be at just below 1500W. However, the devolving of heat rises once again. This is due to the vertical incidence of direct sunlight. The figure shows that the Heptagon, Square and Octagon are the worse in terms of the amount of heat conduction that have been conducted. It seems that they are the most shapes which have more external walls area to be exposed to the sun especially in south, east and west directions which receive most of the amount of solar radiation (see table 2). On the other hand, pentagon and triangle shapes were the best in terms of the amount of heat conducted through external walls. They have more area of external walls exposed to north, north east and North West than other shapes. These directions as known receive less amount of solar radiation. These shapes seems like they protect them self from the sun (self-shading techniques). As a result, it is recommended to use such shapes in hot regions in order to conserve the building from harsh climate. However, the scenario might be different if the aspect of orientation was considered in each shape.

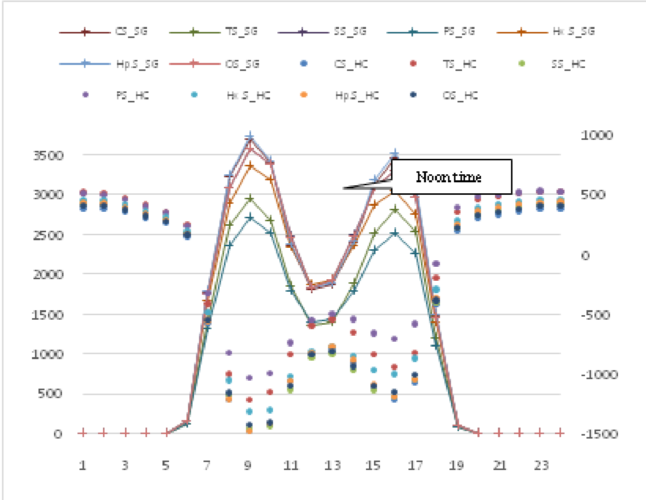
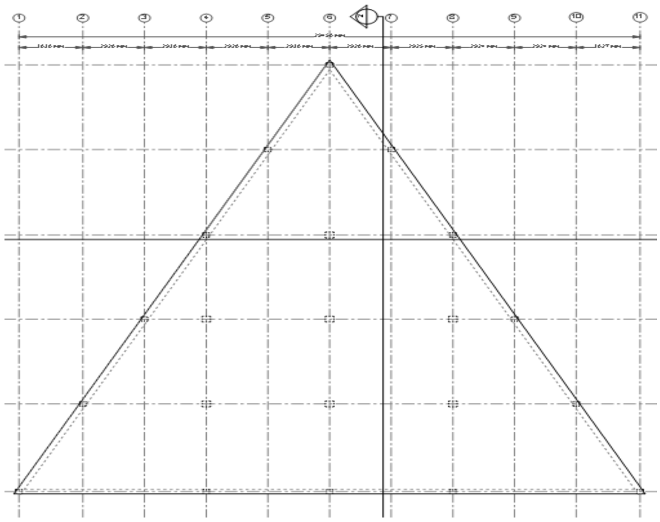


Figure 7: solar heat gain and heat conduction in summer

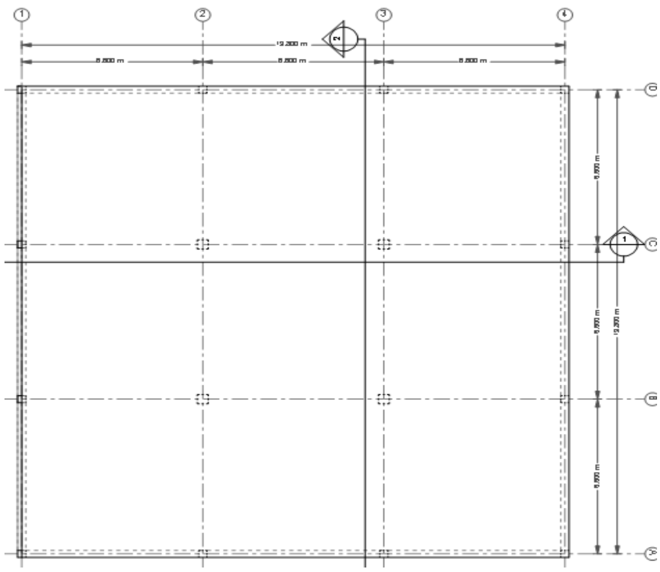
Solar heat gain (through glazing system)

Solar heat gain is a major factor in affecting the amount of heat loss (+) and gain (-), thus, in influencing total heating and cooling load in such regions where outdoor temperature varies dramatically during summer and winter, and also during day and night. As far as the result of solar heat gain of the selected models are concern, Heptagon, circle and octagon shapes were the worst. The result of the amount of SG is quite connected to the shape of the building as well as the possibility to adjust the windows on a proper external walls. Based on table (3) it is clear that these shapes do not aid to set the windows soon after from south, east and west directions. For instance, circle shape has its external walls facing all directions in 360º. This will not assist the building to be self-protected from the solar radiation.

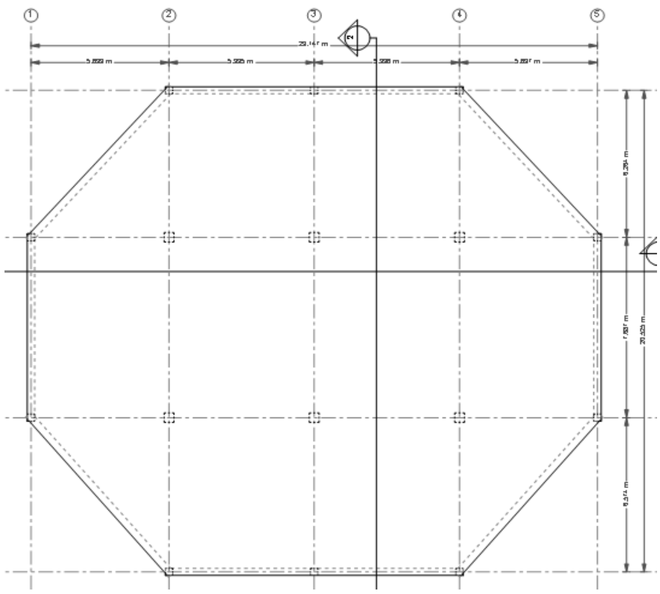
On the other hand, pentagon, triangle and hexagon were found the best in comparison with all the models. The shapes of these buildings aid to align the glassing system on directions that is not directly facing sun bath which will minimise the amount of SG. For example, triangle shape has no single wall facing east or west. Based on many published research, west direction is one of the worse direction that contribute to massive amount of heat gain. Consequently, tringle shape can be utilise to avoid considerable amount of heat loss as long as considering the right orientation of the shape.



a. Triangular slab shape



b. Square slab shape



c. Octagon slab shape

Figure 8: Flat slab structural system

Table 2: total area of external walls in each directions

	No of sides	North	North-east	East	South	South-east	West	South-west	North-west
Circle *(CS)*	0 (1)	-	-	-	-	-	-	-	-
Triangle *(TS)*	3	0	227.5	0	205.8	0	0	0	227.5
Square *(SS)*	4	140	0	140	140	0	140	0	0
Pentagon *(PS)*	5	-	84	0	126	105	0	105	84
Hexagon *(Hx.S)*	6	98	83.3	0	98	83.3	0	83.3	83.3
Heptagon *(Hp.S)*	7	0	147	0	105	65.8	0	65.8	147
Octagon *(OS)*	8	84	58.1	53.2	84	58.1	53.2	58.1	58.1

Table 3: total area of glazing system in each directions

	No of sides	North	North-east	East	South	South-east	West	South-west	North-west
Circle *(CS)*	0 (1)	-	-	-	-	-	-	-	-
Triangle *(TS)*	3	0	7.2	0	7.2	0	0	0	7.2
Square *(SS)*	4	7.2	0	7.2	7.2	0	7.2	0	0
Pentagon *(PS)*	5	0	3.6	0	7.2	3.6	0	3.6	3.6
Hexagon *(Hx.S)*	6	7.2	3.6	0	7.2	3.6	0	3.6	3.6
Heptagon *(Hp.S)*	7	0	7.2	0	7.2	3.6	0	3.6	7.2
Octagon *(OS)*	8	7.2	0	7.2	7.2	0	7.2	0	0

Indoor air temperature

Indoor air temperature (IAT) is the final indication of the energy performance of and building. It is affected by many aspects such as heat transfer, occupant use and many other variables. The most important element which can be highlighted is the shape of the building and its impact on indoor air temperature.

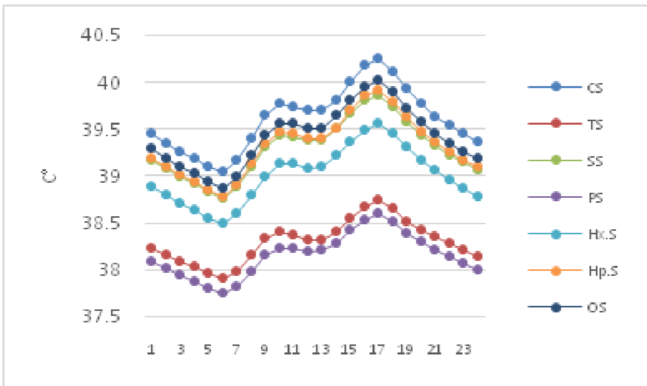


Figure 9: indoor air temperature tasted models in summer

Circle shape, **octagon** and **heptagon** were found with higher IAT which peaked at around 40ºC. On the other hand, **triangle** and **pentagon** had the lowest IAT in certain fluctuation at around 38 to 38.5ºC. A likely explanation is that these frequent temperatures are a result of amount of heat conduction and solar heat gain. In terms of the heat conduction findings, octagon and heptagon shapes were found to have maximum amount of heat conducted through its external walls while triangle and pentagon came at the bottom of the list. Similarly, with regard to solar heat gain through glassing system, the worse two shapes mentioned above came at the same rank beside the circle shape, while, triangle and pentagon performed with the best figures once again.
Table 2, (above) which present the area of external walls exposed in each direction provide some remarkable figures. For instance, triangle shape has zero exposed external wall to the following directions east, west, south-east and south-west. These directions receive a considerable amount of direct sunlight which will lead to rise in the amount of heat conduction through building fabrication generally, and through external walls specifically. Beside, this shape has 455m² of external walls facing north-west and north-east directions which admit minimum amount of solar radiation compared with other directions. In contrast, heptagon shape has more than 235m² of external walls facing south, south-west and south-east directions. It might be aground that these shapes rely on its orientation. However, all of them have been set to the default orientation as they well know.

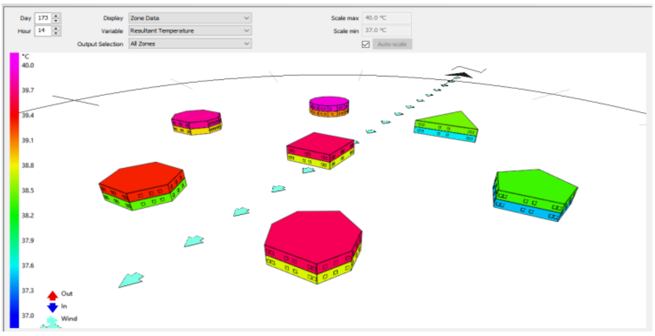


Figure 10: perspective view of the examined buildings in TAS EDSL. It can be noted that Triangle and pentagon have green and blow colours which are indicating that they have lower indoor air temperature

Based on the discussion, it can be revealed that the performance of the shape with maintaining the same value it connected strongly with the number of the sides. The less number of sides in the shape, the better energy and environmental performance is expected. Triangle and pentagon were found as bet tested models. In contrast, hexagon, octagon and circle were found the worse. It can be observed that shapes with less amount of sides can protect its self by self-protection from direct solar radiation while shapes with larger number of sides tend to let its surfaces exposed to the sunlight. As a result, it is recommended that at the early stage, to avoid these shapes with larger number of sides, and replace them with shapes such as triangle and pentagon. As far as square shape is concern, it might has better results than what have been observed in this research. But, it has further investigation to test the impact of orientation on this shape. It is expected that it would have less trend of indoor temperature.

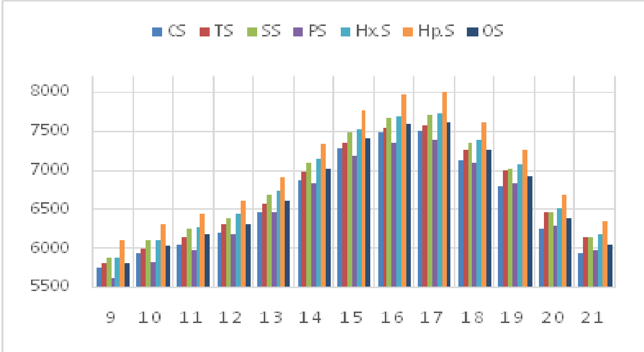


Figure 11: cooling load in the examined models in summer, W

Cooling load investigation
In order to determine the amount of cooling load in a certain building, many variables are involved such as temperature difference in between indoors and outdoors, properties of the building envelope and any other aspects from the building itself, for instance, occupant use. It has to be mentioned that the desired indoor air temperature was sit at 24ºC, which is the optimum temperature to insure better energy consumption performance.
Fig 11 indicates that pentagon and triangle are the best shapes in terms of cooling load required in summer, while heptagon is the worse. This result has a positive agreement with the previous findings of heat conduction through external walls as well as solar heat gain through glassing system.

Impact of various orientations of triangle shape
Based on the previous findings and discussion, it was observed that triangle has the optimum performance in terms of amount of heat conduction, solar heat gain and energy required for cooling load. In this section, this shape will be investigated with regard to its patter with various orientation as the fig 12 shows that.

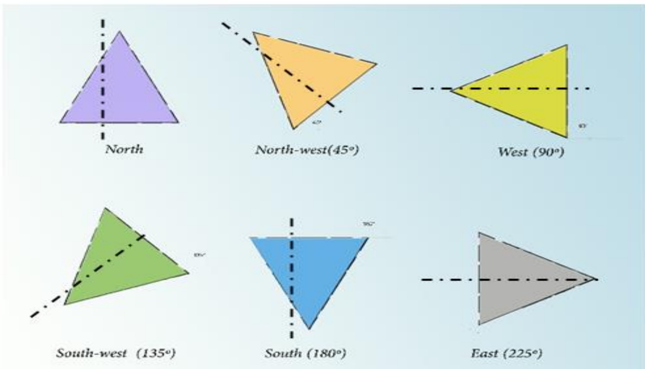


Figure 12: Further investigation in various orientation in the triangle shape

Although fig 14 Shows that there is a noticeable different in terms of the indoor air temperature in various orientation. However, it was minor gap which as high as one degree Celsius. Surprisingly, north facing building had the highest IAT. Despite the fact that it called north facing, however, it is the only shape which has one of its sides facing south perpendicularly. On the other hand, west facing triangle building had the lowest indoor air temperature compared with all investigated orientations. This also support the finding that in orienting any building, south orientation has to be avoided, particular, with perpendicular external walls.

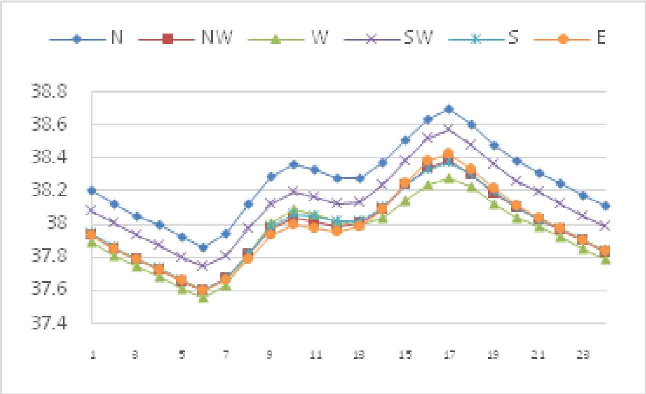


Figure 13: indoor air temperature of triangle shape in various orientations

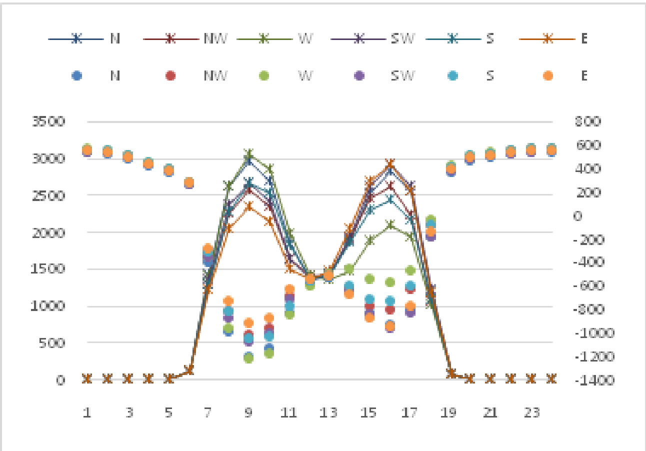


Figure 14: external heat conduction and solar gain of triangle shape in various orientations

As far as the external wall heat conduction in the various orientation are concerned, it can be noted that west and north facing triangle buildings have the highest rate of heat conduction through external walls compared with other triangles. This is due to orienting the largest amount of the external wall to south and west orientations which well known as the most exposed spots to the solar bath. These directions should be averted in such regions where the amount of solar radiation is tremendous. On the other hand, east facing triangle has the lowest amount of heat conduction with outdoor. This result indicate the difference in between east and west facing. It is reported by many authors that these directions are equals. However, many other sources are against this. Moreover, the amount of solar radiation in early morning is always by far lower than in later afternoon. As a result, the amount of solar radiation which be exposed external surfaces of external walls in these directions should be differ. The result of the amount of solar heat gain in each direction is also in agreement with this.

The investigation of the impact of orientation on triangle shape has indicated that orientation has a minor effect on the indoor air temperature compared with the influence of various shape design. However, the amount of glassing system which influence the amount of solar heat gain was limited and fixed in the investigated models. Further investigation might be beneficial in future research.

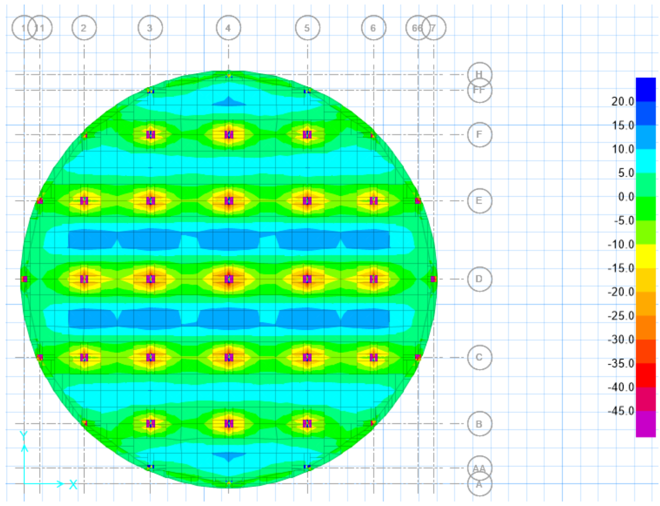


Figure 15: Illustration of flat slab bending momentfor Circular slab shape

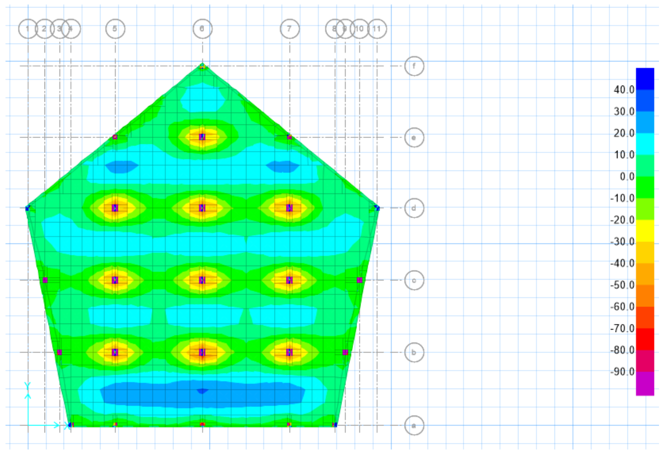


Figure 16: Illustration flat slab bending moment for Pentagon slab shape

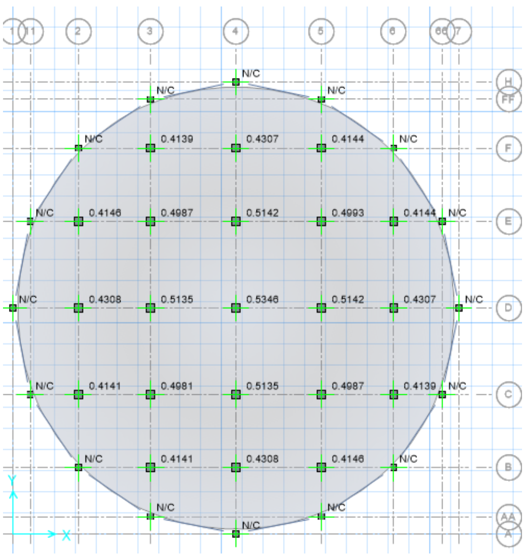
Cost analysis and time frame of each shape examined

The structural design conducted using 3-D finite element model available in SAFE software package. The purpose of this part of study is to point out the advantage and disadvantage of each structure shape in practical reality side.

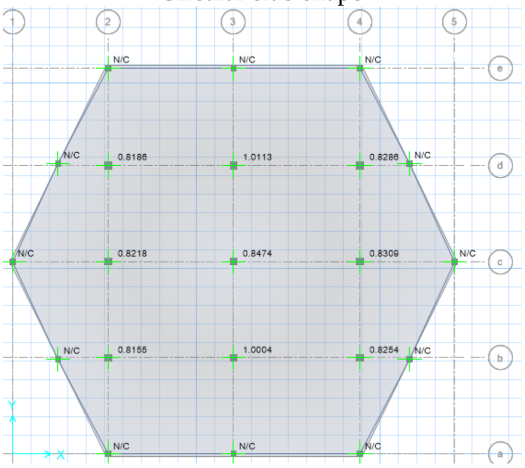
Total construction amount of each structure could be measured by time and cost of structural elements; for this reason the results will be focused on the comparison between the cost and time required for each structure shape. The designed moment in north direction obtained for Circular and Pentagon shapes shown in figure 11 and 12.

The results shown in table 6 indicated that, the cost of pentagon and heptagon shapes increases by 3% from the circular shape, where the triangular shapes increases by 12% from circular shape. The time required for column construction of triangular slab is 50% less than the time required for circular slab shape. On the other hand, the time required for column construction of pentagon and heptagon slabs are 40% and 30% less than the time required for circular slab shape respectively.

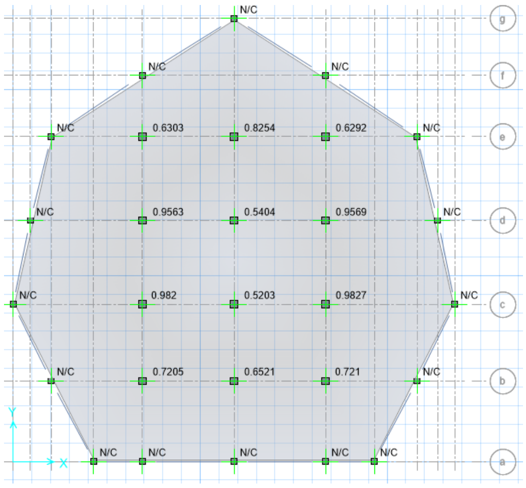
Based on the obtained results from the investigation of cost and time frame of structure, it can be concluded that, construction cost of circular structure is the lowest, where the cost of pentagon and triangular structure shapes increase by 3% and 12% from circular structure shape respectively. Time of construction required for column supported the triangular slab and pentagon slab are 50% and 40% less than the time required for circular slab shape respectively.



Circular slab shape



Hexagon slab shape



Heptagon slab shape

Figure 17: Ratio between actual and allowable punch stress

Table 4: Steel rebar quantity take off required to reinforce Flat Slab

Bar Diameter / Shape	Circular	Triangular	Square	Pentagon	Hexagon	Heptagon	Octagon
10 mm				0.71			
12 mm	1.79	2.3	3.18	1.34	3.55	3.4	3.48
14 mm	0.17	0.73	0.85	0.42	0.37	0.58	
16 mm	0.43	1.19		0.86	0.63	0.04	
18 mm	0.22	1.45	1.18	1.43	0.54	0.35	1.51
Total weight (Mton)	2.61	5.67	5.21	4.76	5.09	4.37	4.99

Table 5: Steel rebar quantity take off required to reinforce columns

Bar Diameter / Shape	Circular	Triangular	Square	Pentagon	Hexagon	Heptagon	Octagon
8 mm	1.08	0.57	0.42	0.67	0.59	0.78	0.44
12 mm							
14 mm	0.93	0.81	0.70	0.81	0.70	0.93	0.58
16 mm	2.12	0.71	0.40	1.01	0.91	1.21	0.61
18 mm							
Total weight (mton)	4.13	2.09	1.52	2.49	2.19	2.92	1.63

Table 6 : Cost analysis of each structure shape

Shape		Circular	Triangular	Square	Pentagon	Hexagon	Heptagon	Octagon
Concrete for Slabs	Slab thickness (mm)	200	220	280	200	250	200	250
	Quantity (m^3)	160	176	224	160	200	160	200
	Cost (1 unit)	160	176	224	160	200	160	200
Concrete for Columns	No. Of columns	37	21	16	24	21	28	16
	Quantity (m^3)	33.6	16.66	12.04	20.02	17.64	23.52	13.02
	Cost (1.3 unit)	43.68	21.658	15.652	26.026	22.932	30.576	16.926
% of construction time decrease from Circular		**0%**	**50%**	**64%**	**40%**	**48%**	**30%**	**61%**
Steel Rebar slabs	Quantity (ton)	5.24	11.34	10.4	9.5	10.18	8.74	9.98

	Cost (10 unit)	52.4	113.4	104	95	101.8	87.4	99.8
Steel Rebar columns	Quantity (ton)	4.13	2.089	1.523	2.49	2.193	2.92384	1.6264
	Cost (10 unit)	41.3	20.89	15.23	24.9	21.93	29.2384	16.264
Total		**297.38**	**331.95**	**358.88**	**305.93**	**346.66**	**307.21**	**332.99**
% of cost increase from Circular		**0%**	**12%**	**21%**	**3%**	**17%**	**3%**	**12%**

CONCLUSION

This paper focused on the impact of basic shapes on internal building performance combined with structure cost investigation. This paper is leading the concept of investigating the building performance against cost of structure itself. This is derived from the phenomenon of energy conservation as the cost of building structure effect the total of building estimation expense. The paper looked at the indoor air temperature as a result of building shape with taking into account that each one of the examined shape has the same total area of floor. Moreover, all the shapes was oriented toward the north direction in their original set and position.

Considering the previous discussion, it can be reported that the pattern of the shape with maintaining the same value is related strongly to the number of the sides within the building shape. The less number of sides in the shape, the better energy and environmental performance is expected. Triangle and pentagon were found as best tested models. In contrast, hexagon, octagon and circle were found the worse. In addition, the research conducted observe that buildings with less amount of sides has the ability to protect itself by the technique of self-protection from direct solar radiation whereas buildings with more number of sides ted to let more direct solar radiation to reach the external face of the building, hence, more heat gain is expected.

As far as the structure cost of each model is concerned, structure cost of circular shape is the lowest while the expenditure of pentagon and triangular shape was increased by 3% and 12%, respectively. Moreover, duration required for column supported the triangular slab and pentagon slab are 50% and 40% less than the circular slab shape, respectively. Furthermore, it can be revealed that circular shape was found as the quickest shape to build, and octagon shape is the worst which its time frame was increased by 61%.

Based on the research conducted, it can be concluded that although circular shape was found with lowest structure cost compared to all other shapes, triangle and pentagon can be the ultimate shapes to consider for architects and engineers in the design stage. Their expenditures were only 12% and 3% higher than circular shape, respectively.

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