IMPACT OF BUILDING GEOMETRY ON ITS ENERGY PERFORMANCE DEPENDING ON CLIMATE ZONES

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ABSTRACT

This paper proposes a method to characterize the impact of shape on the energy performance of office buildings, considering a wide range of climate types. 16 modular building shapes, from one to 25 stories height, but with the same useful floor area and volume, have been simulated in the 17 climatic zones defined by the ASHRAE Standard. The results have been analysed to determine how the effect of building shape varies depending on the climate. Furthermore, the study defines a set of shape parameters that could be useful to determine the relationship between the shape and the key energy loads of buildings: lighting, heating and cooling.

INTRODUCTION

From long time ago, it has been recognized that shape has an important effect on environmental and energy performance of buildings. Since the early sixties, Olgyay V. (1968) defined some principles to optimize the building shape, based on the evaluation of site climatic characteristics.

More recently various authors, like Depecker et al. (2001), Ourghi et al. (2007) and Al-Anzi et al. (2009), developed diverse studies focused on establishing, in a systematic way, the relation between the energy performance of buildings and their geometric configuration. Most of these works were based on analysis derived from parametric simulations. However, there is a lack in the comparative analysis of the impact of building shape in very diverse climatic conditions. Similarly, there are few studies that attempt to analyse simultaneously the effect of shape in the three key energy loads: heating, cooling and lighting.

This is the main aim of this work, to evaluate the effect of shape on the key energy loads of office buildings, considering a wide range of climate conditions. The purpose is to contribute, at least in some extent, with information that leads to better architectural design criteria.

METHOD

This study was based on results from a parametric research generated with DesignBuilder/EnergyPlus building energy simulation programs. The key energy loads, heating, cooling and lighting, have been calculated for 16 building shapes, considering 17 climates. Heat gains and losses through surfaces have also been calculated, in order to establish the overall heat balance of each building shape. The main modelling criteria are explained in the following sections.

Climatic hourly data

In order to consider a wide range of climatic conditions, 17 geographical locations have been included in the research (Table 1). These locations are the same used by the DOE to develop the Commercial Prototype Building Models (CPBM) and are representative of the climate zones defined in the ASHRAE Standard 90.1-2010. The corresponding hourly weather data files were obtained from the EnergyPlus database. When possible, the TMY2 weather files originally associated to the locations were replaced with TMY3 weather files. Only two locations are from outside the United States: Riyadh and Vancouver. IWEC and CWEC weather files were utilized for these locations, respectively.

Table 1. Climate zones included in the study and its reference cities.

Clim. Zone	Reference City	Geographic Location			Data Source
		Lat.	Long.	Alt.	
1A	Miami	25.8	-80.3	11	TMY3
1B	Riyadh	24.7	46.8	612	IWEC
2A	Houston	29.6	-95.1	6	TMY3
2B	Phoenix	33.4	-112.0	339	TMY2
3A	Memphis	35.1	-80.0	81	TMY3
3B	El Paso	31.8	-106.5	1186	TMY3
3C	S. Francisco	37.6	-122.4	2	TMY3
4A	Baltimore	39.2	-76.7	45	TMY3
4B	Albuquerque	35.0	-106.6	1619	TMY3
4C	Salem	44.9	-123.0	61	TMY2
5A	Chicago	41.8	-87.8	186	TMY3
5B	Boise	43.6	-116.2	874	TMY2
5C	Vancouver	49.2	-123.2	2	CWEC
6A	Burlington	44.5	-73.2	104	TMY2
6B	Helena	46.6	-112.0	1167	TMY3
7	Duluth	46.8	-92.2	433	TMY3
8	Fairbanks	64.8	-147.8	133	TMY3

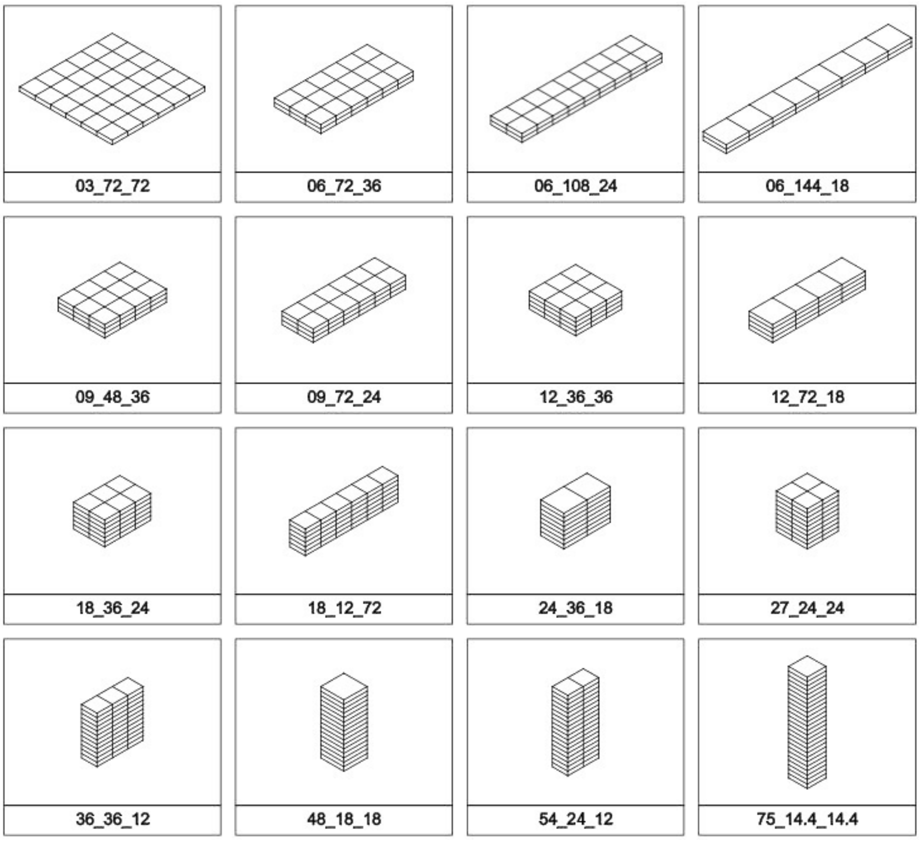

Figure 1. Modular definition of 16 orthoedric building shapes.

Building shapes

16 orthoedric building shapes were developed following a modular scheme (Figure 1). All the building shapes are composed of a certain number of squared modules: 11 shapes have 36 modules (12m by side); four shapes have 18 modules (18m by side); one shape has 25 modules (14.4m by side). Moreover, all building forms have 3m floor-to-ceiling height, a useful floor area of 5,184m^2 and an internal volume of 15,552m^3. This useful floor area is very close to the DOE Commercial Reference Buildings - medium office building, which is 4,982m2. The basic idea behind this approach is to generate a wide range of building forms, but standardizing their geometric characteristics.

Building forms with four or more stories were modelled in a simplified way, including only the top, bottom and one of the intermediate stories. A multiplier was assigned to the latest one in order to get the actual number of stories, while surfaces between stories were considered adiabatic.

Regarding the internal space arrangement, each story is divided into five thermal zones: one central and four perimeter zones (Figure 2). The internal walls that separate central from perimeter zones are always placed at 4.6m from the external walls. This setting is primarily designed to assess more accurately the influence of shape on the potential use of daylight, allowing to model light sensors in the perimeter zones but not in the central one.

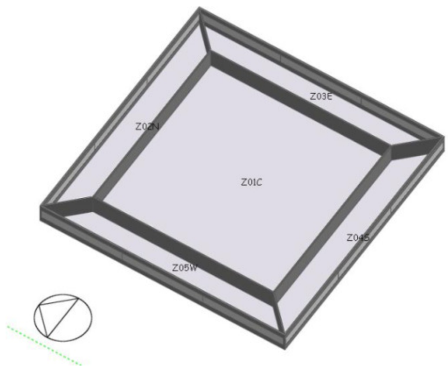

Figure 2. An example of internal distribution of each story in all the building shapes.

Fenestration areas in all building shapes have been modelled as continuous strips, considering a window-to-wall ratio (WWR) of 0.35 in each façade. This value corresponds well to the one used in the DOE CRB medium office building, which is 0.33. Therefore, the total glazing area varies in each building depending on its shape, as expressed in Table 2. It should be also noted that all the building shapes have been modelled with the largest façade facing the south.

Since the impact of shape on buildings energy performance is the main subject of this study, parameters that define shapes are particularly relevant. From a preliminary analysis the following parameters, which theoretically offer a greater poten-

Table 2. General dimensions and parameters of the building shapes. External walls area refers to net area (including glazing area).

NAME Height (H) Length (L) Width (W)	**General dimensions and external surfaces areas**									**Shape parameters**				
	H (m)	L (m)	W (m)	No. of Levels	Walls (m^2)	Roof (m^2)	Floor (m^2)	Ext. Surf. (m^2)	Glazing (m^2)	Vol. / Ext.Surf.	Ext.Surf. / Vol.	Wall / Ext.Surf.	Wall / Vol.	Roof / Vol.
03-072-072	3	72	72	1	864	5,184	5,184	11,232	302	1.38	0.72	0.08	0.06	0.33
06-072-036	6	36	72	2	1,296	2,592	2,592	6,480	454	2.40	0.42	0.20	0.08	0.17
06-108-024	6	24	108	2	1,584	2,592	2,592	6,768	554	2.30	0.44	0.23	0.10	0.17
06-144-018	6	18	144	2	1,944	2,592	2,592	7,128	680	2.18	0.46	0.27	0.13	0.17
09-048-036	9	36	48	3	1,512	1,728	1,728	4,968	529	3.13	0.32	0.30	0.10	0.11
09-072-024	9	24	72	3	1,728	1,728	1,728	5,184	605	3.00	0.33	0.33	0.11	0.11
12-036-036	12	36	36	4	1,728	1,296	1,296	4,320	605	3.60	0.28	0.40	0.11	0.08
12-072-018	12	18	72	4	2,160	1,296	1,296	4,752	756	3.27	0.31	0.45	0.14	0.08
18-036-024	18	24	36	6	2,160	864	864	3,888	756	4.00	0.25	0.56	0.14	0.06
18-072-012	18	12	72	6	3,024	864	864	4,752	1,058	3.27	0.31	0.64	0.19	0.06
24-036-018	24	18	36	8	2,592	648	648	3,888	907	4.00	0.25	0.67	0.17	0.04
27-024-024	27	24	24	9	2,592	576	576	3,744	907	4.15	0.24	0.69	0.17	0.04
36-036-012	36	12	36	12	3,456	432	432	4,320	1,210	3.60	0.28	0.80	0.22	0.03
48-018-018	48	18	18	16	3,456	324	324	4,104	1,210	3.79	0.26	0.84	0.22	0.02
54-024-012	54	12	24	18	3,888	288	288	4,464	1,361	3.48	0.29	0.87	0.25	0.02
75-014-014	75	14.4	14.4	25	4,320	207	207	4,735	1,512	3.28	0.30	0.91	0.28	0.01

tial to determine the relationship between shape and energy performance, have been selected:

- **Vol. / Ext.Surf.** - *Total internal volume* divided by *Total external surface area* (Compactness).
- **Ext.Surf. / Vol.** - *Total external surface area* divided by *Total internal volume* (Form factor).
- **Wall / Ext.Surf.** - *Total wall surface area* divided by *Total external surface area*.
- **Wall / Vol.** - *Total wall surface area* divided by *Total internal volume*.
- **Roof / Vol.** - *Total roof area* divided by *Total internal volume*.

Table 2 shows these parameters for the 16 building shapes, together with its general dimensions. It is important to note that the *Total external surface area* includes walls, roof and external floor.

Building envelope

The same set of constructions, whose global thermal properties are shown in Table 3, was used in all the simulation models. External constructions have a U-Value of 0.60 W/m^2•K while the set offers a medium level of thermal mass (internal heat capacity). These properties have been chosen to represent an average construction system, which plays a relatively neutral role in the thermal performance of the buildings.

Air infiltration caused by cracks on the joints of constructive elements, and even by small pores in them, has been modelled by using the EnergyPlus's object *ZoneInfiltration:DesignFlowRate*. A flow rate of 0.0004 m^3 per second per m^2 has been assigned to all external surfaces (or 1.44 m^3/hr-m^2), which means heat gains/losses due to infiltration are also affected by the building shape: a wider exposed surface represents higher flow rates. Nevertheless, no effects were considered due to the difference between internal and external temperatures, or wind speed.

Table 3. Constructions global thermal properties.

Construction	**U-Value** ($W/m^2 \cdot K$)	**Int. Heat Capacity** ($KJ/m^2 \cdot K$)
External wall	0.60	81.4
Partition	1.77	91.2
Roof	0.60	111.6
Internal floor	1.65	136.0
External floor	0.60	136.0

Finally, all building forms were modelled separated from ground, so that the external floor of lower story is exposed to the outside air, but not considering the effect of neither wind nor solar radiation.

Internal gains

In this study internal gains, which are strongly linked to the usage of buildings, have been organized into three general categories: occupancy, equipment and artificial lighting. In order to simplify the analysis, the simulation models include only one space type, which corresponds to a single set of internal gains data (although the models have been zoned, such zoning is intended to adequately model the potential use of daylight, and has nothing to do with space use or classification).

The maximum gains rates considered for occupancy, equipment and lighting are shown in Table 4. These values were calculated as weighted averages of data for three space types: open offices, cellular offices and common areas, with a percentage of floor area of 25%, 57% and 18%, respectively. The specific values for each space type were obtained from various sources, and have been devised to represent a standard office building.

Table 4. Model data associated with occupancy-related internal gains.

Category of internal gains	**Zone**	**Max. Gains Rate** (W/m^2)
Occupancy	All	9.3
Equipment	All	10.1
Lighting	All	13.4

Those maximum gain rates are modified during simulations by the fractional values defined by the schedules displayed in Figure 3.

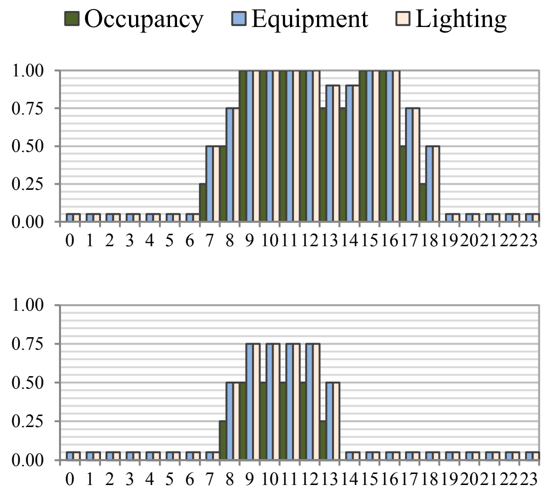

Figure 3. Schedules for internal gains used on Weekdays (above) and Saturday (below).

Regarding the artificial lighting, in perimeter zones (not in the central ones) its control has been modeled with basis on daylight availability. Light sensors were included to measure the amount of daylight and gradually increase/decrease artificial light in order to maintain the required level of iluminance (in this case 445 lux) during occupied periods. The intention of these modeling criteria is to evaluate, as realistically as possible, how building shape determine the potential use of daylighting.

HVAC Systems

HVAC systems were modelled with the EnergyPlus object *IdealLoadsAirSystem*. According to the EnergyPlus documentation, this object represents an ideal HVAC system modelled as a VAV terminal unit that supplies cool or hot air, at variable temperature and humidity, until the zone loads are met. In this case, no restrictions have been considered regarding the capacity of HVAC systems, so they can meet any present load. The main HVAC settings are the following:

- Heating system operates during occupied periods with a setpoint temperature of 21ºC, and during unoccupied periods with a setpoint of 12ºC. Cooling system operates just during occupied periods with a setpoint temperature of 25ºC. The main setpoints are within the ranges advised by the Standard EN 15251:2007.
- Both setpoints are based on operative temperatures, which means that heating and cooling systems have to meet both convective and radiant component of the global thermal balance. This approach offers greater sensitiveness to compare the performance of different building shapes.
- The models include hygrostats-based humidity control. The relative humidity setpoint for humidification is 30%, while for dehumidification is 60%. It means that internal air relative humidity is maintained between 30% and 60% during occupied periods.
- Regarding the mechanical ventilation, a fresh air rate of 10 l/s•person has been considered.

RESULTS

By mean of the parametric simulations, monthly energy loads have been calculated for the 16 building forms in the 17 climates, including loads associated with HVAC systems (heating and cooling) as well as energy consumption by lighting. The **global energy load** (heating + cooling + lighting), is proposed in this study as an inclusive data to measure, compare and predict the energy performance of the building shapes.

Additionally, heat gains and losses through surfaces have been calculated, which together with internal gains and zone contributions from HVAC systems, allow establishing the overall thermal balance of each building shape. This data has been used to identify in more detail the effect of shape on the buildings energy performance.

Performance of the analysed building shapes

Table 5 shows the global energy loads values of the 16 shapes in the 17 climates. The cells in the table have been shaded with a colour scale ranging from green (low load) to red (high load). Yellow colour would indicate medium values. This simple plot allows fast identification of the shapes with the best and the worst performance in each climate.

The best-performance shapes in warm climates tend to be those relatively low-rise (2-3 stories) and not excessively compact. Opposite to this, shapes with better performance in cold climates tend to be more compact (6-9 stories). In general, the taller shapes offer the worst performance in hot climates, while lower shapes offer the worst performance in cold climates. It is clear that this behaviour correspond to greater solar gains and lesser heat dissipation through envelope in the first case, as well as to greater heat losses through envelope and lower solar gains in the second one.

Table 5. Global energy load values for the 16 shapes in the 17 climates (kWh/m2•year).

Shape	1A	1B	2A	2B	3A	3B	3C	4A	4B	4C	5A	5B	5C	6A	6B	7	8	Ave.
03-72-72	206	242	189	191	189	166	79	208	184	154	243	213	170	283	255	338	494	**224**
06-72-36	203	201	168	166	151	135	51	149	133	102	167	141	108	182	161	209	303	**161**
06-108-24	205	206	169	168	151	137	49	150	132	102	170	142	109	185	162	213	313	**163**
06-144-18	209	212	171	172	153	137	47	151	132	104	173	145	112	190	166	219	327	**166**
09-48-36	207	197	168	166	144	134	54	135	123	90	147	123	93	155	135	173	248	**147**
09-72-24	208	199	168	167	144	133	51	135	122	90	148	123	93	157	136	176	256	**147**
12-36-36	212	203	177	176	150	146	73	138	133	95	147	126	97	151	134	166	235	**151**
12-72-18	213	205	175	176	148	142	65	136	129	93	148	124	96	153	133	170	249	**150**
18-36-24	219	208	181	182	150	150	62	135	132	92	143	122	93	143	127	156	223	**148**
18-72-12	221	216	179	186	149	147	62	133	129	129	147	122	94	151	130	168	255	**154**
24-36-18	224	215	183	188	152	153	74	134	133	92	143	122	93	143	125	155	227	**150**
27-24-24	228	220	187	194	155	138	78	137	138	94	144	126	96	144	128	156	224	**152**
36-36-12	235	231	189	201	156	159	69	136	137	93	148	126	96	148	129	163	247	**157**
48-18-18	247	247	200	217	168	174	81	146	149	101	155	137	104	155	138	168	247	**167**
54-24-12	249	249	200	217	166	172	75	144	147	99	156	135	103	156	137	171	260	**167**
75-14-14	265	269	214	239	179	190	88	153	161	109	164	147	112	162	146	175	262	**179**

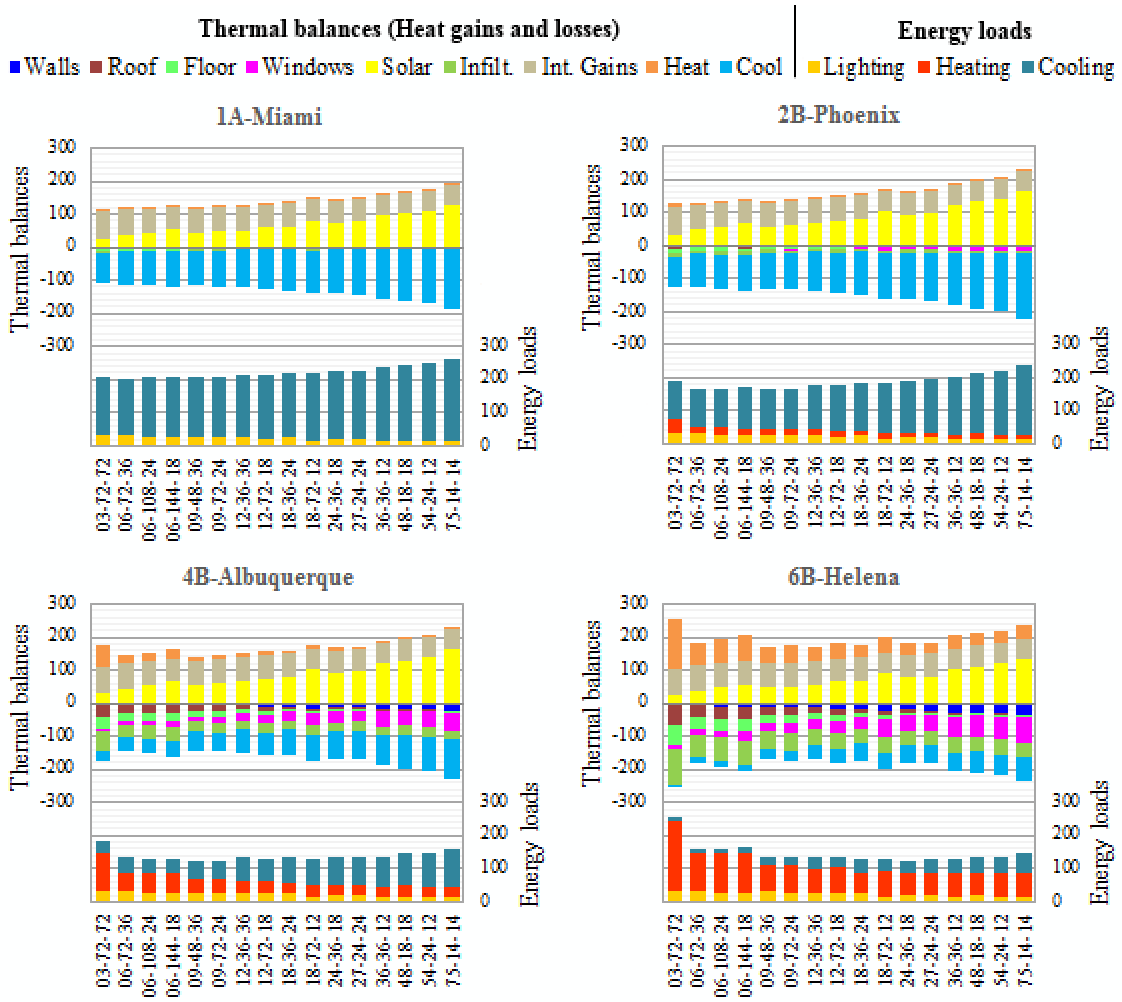

Figure 4. Annual thermal balances and energy loads related with selected climates (kWh/m2•year).

In order to get a deeper understanding of the building shapes performance, the heat balances and their relationship with the energy loads have been reviewed. The graphs in Figure 4 show the annual thermal balances and the associated energy loads of four selected climate zones: 1A-Miami, 2B-Phoenix, 4B-Albuquerque and 6B-Helena. These cases were selected because adequately represent four general patterns identified:

1. Cooling demand throughout the year, with almost no heating demand.

2. Heating and cooling demand, with clear cooling predominance.
3. Heating and cooling balanced demand.
4. Heating and cooling demand, with clear heating predominance.

The climate 1A shows a marked predominance of cooling demand. In this case, the heat balance components corresponding to the envelope are very small, which means that its losses and gains are well balanced. Instead, the effect of solar radiation is evident, with a gradual increase while augmenting the building height (and therefore the amount of glazing). It has also shown that consumption for lighting gradually decreases, although its weight is relatively low.

The climate 2B shows the occurrence of heating loads, but these remain small compared with cooling loads. This may be associated with a slight increase on heat losses due to envelope and infiltration. As in the previous case, a strong link between solar gains and cooling loads is present. One aspect that should be highlighted is the evident increase of loads, particularly heating, in the model 03-72-72. This is because this particular model has lower solar gains and larger envelope and infiltration losses.

The climate 4B shows balanced energy loads, with cooling gradually increasing as the heating loads are reduced (toward the right of the graph). It is evident that the increase in heating load corresponds with the greater heat loss due to envelope and infiltration, and simultaneously with the decreasing of solar gains.

Finally, the climate 6B shows a clear predominance of heating loads, even though these gradually decrease towards the right of the graph. Again, increasing heating loads are directly related to the increase on heat losses due to infiltration and conduction through envelope.

Impact level of shape in the different climates

One important question in this research is about the impact level of building shape in different climates. Figure 5 is a boxplot diagram showing the distribution of global energy loads shown in Table 5.

The boxes in the diagram (interquartile ranges) are between quartiles 1 and 3, and show the distribution of the middle 50% of the values. The central line of each box indicates the median value. The lower and upper whiskers show the distribution of bottom 25% and top 25% of the values, respectively. The red mark (X) indicates a distance of 1.5 times the interquartile range, measured from the top of the box. By convention, values beyond this mark are considered atypical. In sum, the boxplot diagram allows to identify the degree of dispersion and the symmetry of the data.

As expected, a large variability in the values of global energy load is observed in the different climate types. This feature is clearly shown by the vertical position of the boxes. For example, the climate 3C has the lowest level, with the median of around 70 KWh/m^2, while climate 8 has the highest level, with the median of around 250 kWh/m^2. However, the vast majority of cases are located within a range between 90 and 200 kWh/m^2.

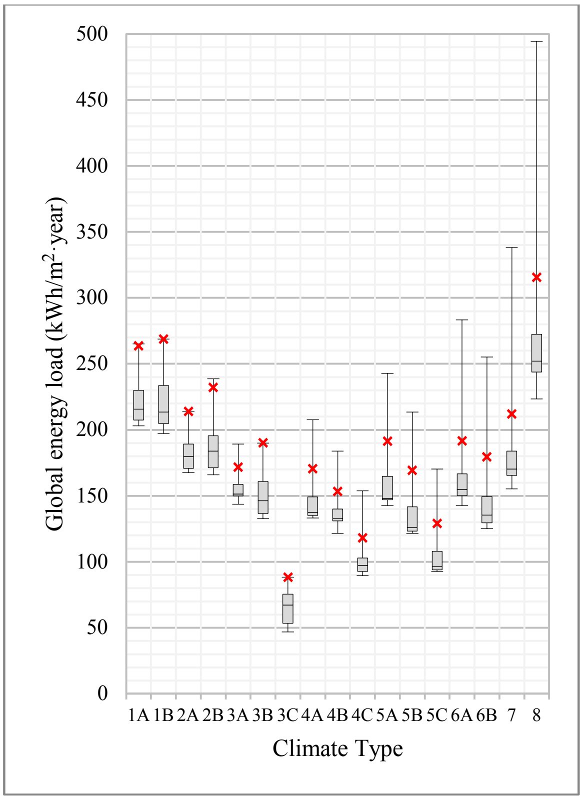

Figure 5. Boxplot showing distribution of global energy loads.

It is important to note that the levels of global energy load do not seem to fit accurately to the climatic classification. For example, climate 6B shows lower levels of energy loads than climate 5A, even if it is theoretically more demanding. In general, climates type C (marine) show a marked decrease in energy loads levels.

The graph makes also evident the amplitude of the global energy loads ranges, expressed as the difference between the minimum and maximum loads. These ranges may express the impact degree of shape in each climate type. We hypothesized that, the higher load range, greater influence the building shape has, and, therefore, more attention has to be dedicated to this architectural design parameter. In general, the graph shows that shape has a greater impact in dry than in wet climates, at least in warm climates. Also shows that, even more markedly, shape has greater impact in cold than in warm climates.

A more detailed review of internal ranges offers information of great interest. For example, it is clear that bottom 25% has very small ranges of energy loads in all climates, while top 25% shows very high ranges. Even more, top 25% in climates from 4A onwards far exceed the 1.5 IQR value. This may indicate that while the best performing forms show little difference from each other, there are a few forms that can cause exaggerated energy loads and maybe should be avoided.

Relation between shape parameters and loads

A correlation analysis between shape parameters and energy loads was carried out. The main objective was to link variations in energy loads to variations in parameters values. Firstly, in each of the 17 climates, linear correlations and coefficients of determination (R^2) were calculated in order to link the five shape parameters originally selected (Table 2) and five load types: Global (Cooling+Heating+Lighting), Cooling+Heating, Cooling alone, Heating alone and Lighting alone. The outputs were examined to determine which shape parameters have a stronger correlation with the different load types.

Table 6 offers a synthesis of the correlation analysis, showing the averages of the calculated coefficients of determination. For example, the cell corresponding to the *Volume / External surface* parameter and the *Global* load shows the average of the coefficients of determination calculated between these items in the 17 climates.

Table 6. Average coefficients of determination (R^2) between shape parameters and energy loads.

Load type	Vol. / Ext.Surf.	Ext.Surf. / Vol.	Wall / Ext.Surf.	Wall / Vol.	Roof / Vol.
Global	0.40	0.51	0.34	0.31	0.45
Cool+Heat	0.35	0.43	0.36	0.36	0.38
Cooling	0.50	0.43	0.92	0.87	0.70
Heating	0.81	0.98	0.47	0.34	0.88
Lighting	0.36	0.39	0.89	0.95	0.68

The results show clearly that none of the shape parameters itself is sufficient to explain the variations in the global energy loads, nor even heating and cooling loads together. In such cases, all averages are very low, which means that in many climates the correlation is very weak.

The situation changes radically when results for single load components are reviewed. For lighting loads, very high coefficients of determination were identified in almost all climates for the *Wall / Volume* parameter. Something similar happens between heating loads and the *External surface / Volume* parameter, and between cooling loads and the *Wall / External surface* parameter. In other words, *Wall / Volume*, *External surface / Volume* and *Wall / External surface* parameters show a clear correlation with lighting, heating and cooling loads, respectively.

Regression graphs could be a more detailed way to see the correlation between shape parameters and energy loads. As an example, Figure 6 shows graphs of simple regression relating the lighting, heating and cooling loads with *Wall / Volume*, *External surface / Volume* and *Wall / External surface* parameters, respectively. Previously selected climates, 1A-Miami, 2B-Phoenix, 4B-Albuquerque and 6B-Helena, are included. It has been employed second-degree polynomial regression curves, which in all cases offered the best fitting. It can be seen that the R^2 values are always very high. In resume, the analysis demonstrates that in this case it is possible to find shape parameters that keep high correlation with individual energy load components.

CONCLUSION

The research addressed a method to determine, by mean of a parametric approach, the effect of shape on the energy performance of buildings, in this case offices, considering a wide range of climates. Besides the selection of such climates, the developing of the method implied the definition of a set of comprehensive modular building shapes, as well as establishing the adequate modelling and simulation criteria. The method also included various analysis procedures in order to make useful and significant the results of the parametric simulations.

Even considering its limits, the study provides information that may be the basis for general recommendations about the shape of office buildings during the early stages of architectural design, in order to minimize energy loads. This information may also be useful in the field of building energy regulations, since it identifies the specific weight that shape can have on energy performance of buildings depending on climatic conditions. The main findings of the study can be summarized as follow:

A. Clear patterns of association between the building shape and its energy performance have been identified, according to climatic conditions. The best-performance shapes in warm climates tend to be those relatively low-rise and not excessively compact. Instead, shapes with better performance in cold climates tend to be more compact. In general, the taller shapes offer the worst performance in warm climates, while lower shape offer the worst performance in cold climates. Above all, it has been shown that extremely low, high or extended forms tend to present the worst performance.

B. A clear relationship between the annual heat balances and energy loads patterns were found in each of the studied climates. For example, independently of the composite of envelope constructions, shapes with greater solar gains and lesser heat dissipation through envelope tend to increase the cooling loads. Likewise, shapes with greater heat losses through envelope and lower solar gains tend to increase the heating loads.

C. The impact of shape on building energy performance, both in absolute and relative terms, varies significantly depending on the climate. In

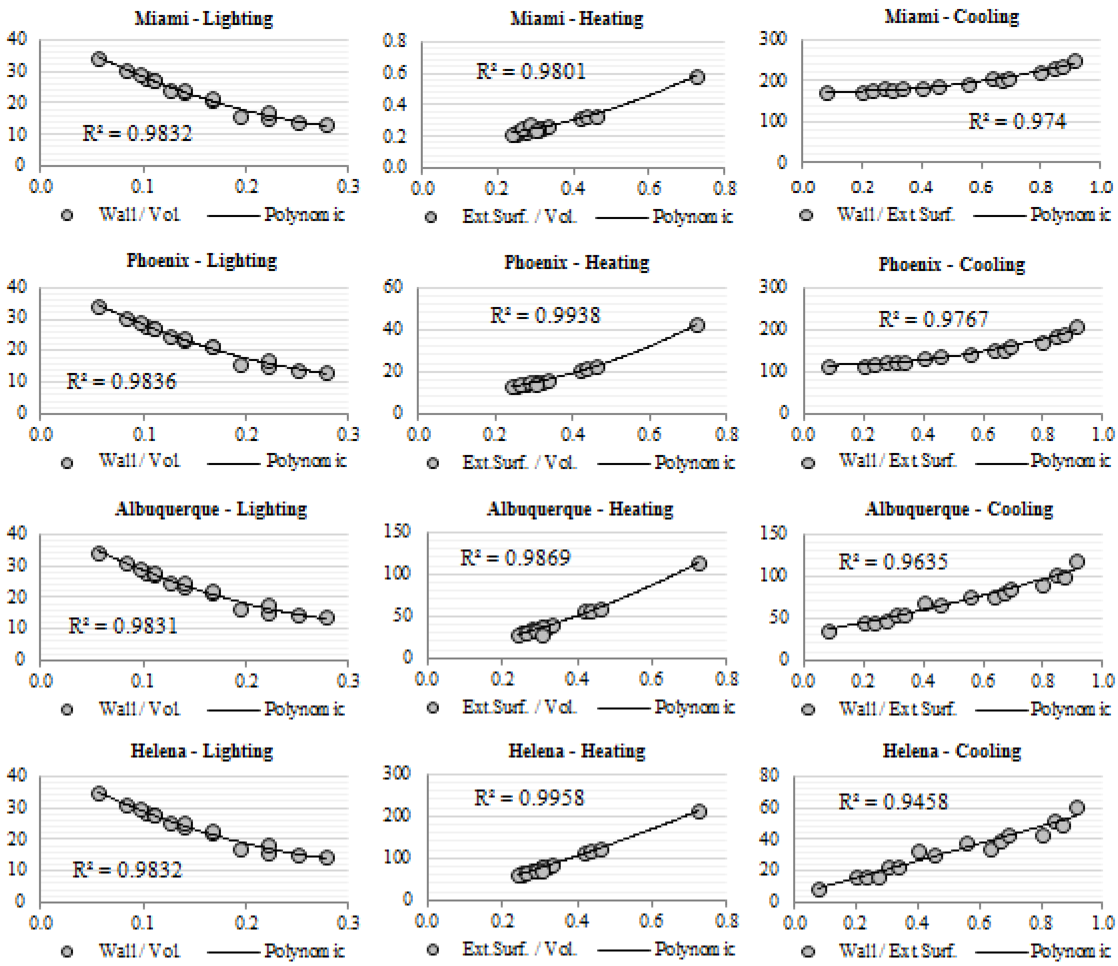

Figure 6. Polynomial regression graphs for representative climates. X-axis shows the parameter-related ratios, while Y-axis shows the global energy loads (kWh/m^2·year).

general, the building shape has greater impact in dry than in wet climates, at least in warm climates. Likewise, even more markedly, building shape has greater impact in cold than in warm climates.

D. While it has not been possible to identify a parameter that itself can explain the global energy loads in all climates, this research has concluded that each of the components of energy loads is strongly correlated with one of the parameters analyzed. So, the *Wall / Volume*, *External surface / Volume* and *Wall / External surface* parameters show a clear correlation with lighting, heating and cooling loads, respectively. If extended, this information could be useful for the development of predictive models.

Note: This study is part of a wider research, which will include more complex geometries as well as different sizes of buildings. Similarly, the influence of other design variables such as window-wall ratio and different levels of insulation and thermal mass, among others, will be considered.

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