APPROPRIATE GEOMETRICAL RATIO MODELING OF ATRIUM FOR ENERGY EFFICIENCY IN OFFICE BUILDINGS

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Abstract
Atrium refers to an open interior space that can be potentially related to an exterior environment. Indeed, atrium is considered as a filter and obstacle blocking undesirable exterior environmental phenomena such as rain, snow and wind. A well designed atrium can contribute to have a significant effect on both; the building's energy performance and indoor environmental conditions. In this paper, the aim is to study the effect of atrium ratio on energy efficiency and comfort of the occupants in an office building in the city of Tehran. In this work, the length to width ratio of the office buildings is identified and the average height of these buildings and validated appropriateness are examined by field studies. The simulation modellings of Design Builder Software is used to model various aspects of the building such as building materials, architecture construction, heating, cooling and lighting systems. One way ANOVA and Duncan's multiple range tests are used to determine the differences of daylight and compare their averages in different models. It is shown that by decreasing the ratio of atrium to total building area from 1:2 to 1:10, the annual energy consumption reduces i.e., the highest and lowest annual consumed energy belong to the ratio of 1:2 and 1:10, respectively. Whereas from 1:2 to 1:10 ratio, regular downtrend has been occurred to received daylighting factors by the models. According to ANOVA performed on the intensity of daylight's received height, significant differences were detected in different models with different atrium area ratios.Overall, the results show that ratio of atrium to total building area of 1:4 is the most efficient selection in terms of energy performance, daylighting and thermal comfort.

Key words: Atrium, energy efficiency, office buildings, optimal ratio, simulation.

INTRODUCTION

Terminologically, atrium refers to an open interior space that can be potentially related to an exterior environment (Sekkei, 1989). The oldest use of atrium goes back to the Roman houses in which a building would be designed with a large entrance, a central court and a semi-public roofed space. Together with the exterior spaces, the main function of an atrium was to let in the controlled light and fresh air (Kutzer, 2004). In fact, atrium acts like a filter against the impacts of unwanted exterior environmental phenomena such as rain, snow, wind and etc. (Brown and DeKay, 2001). Meanwhile, atrium makes the suitable exterior environmental elements such as sunshine and fresh air usable (Laouadi et al, (2002), Bryn, (1993)). The first atrium was introduced in the western countries in the 19th century. In the late nineteenth century, the cognizant natural lighting was introduced to increase the light where atria played a major role (Saxon, 1986). There are numerous applications for atrium in admin and public buildings such as its usage in hotels, banks, and commercial and shopping centers worldwide. One of the most famous buildings is Headquarter Bank in Hong Kong, which has a very tall atrium in the center of the building that can directly benefit from the sunshine in the interior environment of the building by a sun scoop (Magnago and Lampugnani 1993).

To this end, designers included and applied the atrium in their designs in central, integrated, linear, linked and peripheral forms in conformity with the main building. Being aware of energy problem in the building, designers also used atrium as a means to control energy optimization as they knew about the damages of improper use of energy to the environment (emission of hazardous gases). Since then, designing atrium was considered as a scientific method to benefit from optimal heating comfort using less energy (Hung, 2003). Atrium space is increasingly used in modern architecture and creates desirable benefits and conditions within the interior environment, while it reduces energy consumption as well (Sharples and Lash, 2004). The importance of light in an atrium has gained the interest of the researchers such that daylight and its modeling has been well studied in the literature (Aizlewood et al, (1997), Littlefair, (1994), Boubekri, (1995), Aschehoug, (1992) and Iyer-Raniga, (1994)). Prediction of light intensity has been formulated by the zone methods or analytical equations (Boubekri and Anninos, (1996), Liu, et al (1991), and Aizlewood,et al (1996)). The designers of large spaces such as atrium in which the light intensity is very important, also benefit from improving the interior environmental conditions and reduction of energy costs compared to the regular glasses (Robinson-Gayle et al, 2001). Simulation results can be utilized to manifest the aforementioned fact. In early stages of the design, simulation can be used to optimally combine the construction plan to obtain appropriate environmental conditions with minimum energy consumption. Many literature have discussed the changes of the light entering an atrium in geometrical view of atrium mouth, shape of atrium mouth and the number of glasses covering atrium wall (Liu et al, (1991), Boubekri and Anninos, (1996), Kristl and Krainer, (1999), Wright and Letherman, (1998), and Kim G., and Kim J.T, (2010)).

In this work, atrium has been emphasized as a suitable space to provide comfort in office buildings. Yet, the question which arises is what ratio of atrium (atrium area to the total area of the building) provides the optimal conditions in terms of energy efficiency? Due to the differences in terms of energy efficiency in atrium for different climate conditions, the effect of atrium ratio on the energy efficiency and daylighting in office buildings in a semi-arid climate is examined.

PRELIMINARIES

This research was conducted in the city of Tehran (51º 2' to 51º 36' E) which is depicted on the map shown in Figure 1. Tehran is a metropolis and the administrative center of Iran and features a semi-arid, continental climate with hot and dry summers.

Figure 1: Location of Islamic Republic of Iran and Tehran City (http://irangeo.net/irans-land-boundaries/)

As seen in Figure 2, the air temperature in the coldest times of the year in this region is between 1 to 5 and 35 to 39 ° C in the hottest days. These numbers reflect the fact that different climatic conditions in warm and cold seasons was high and it is difficult to design. Figure 3 shows that Maximum monthly relative humidity in Tehran was 72 percent at the end of December and the monthly minimum relative humidity was equal to 13.2 percent in July.

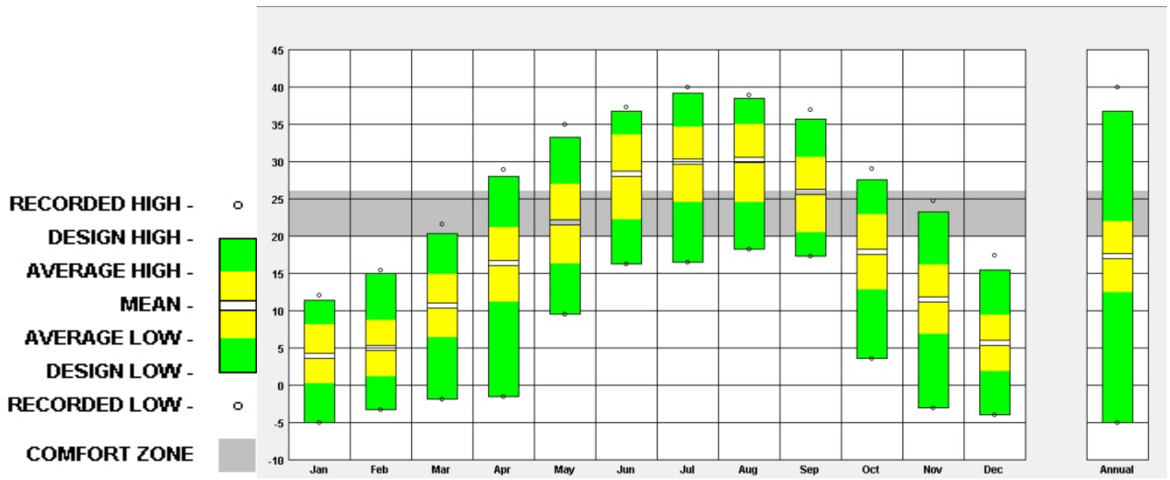

Figure 2: Mean monthly and annual temperature °C of Tehran (Climate Consultant simulation software).

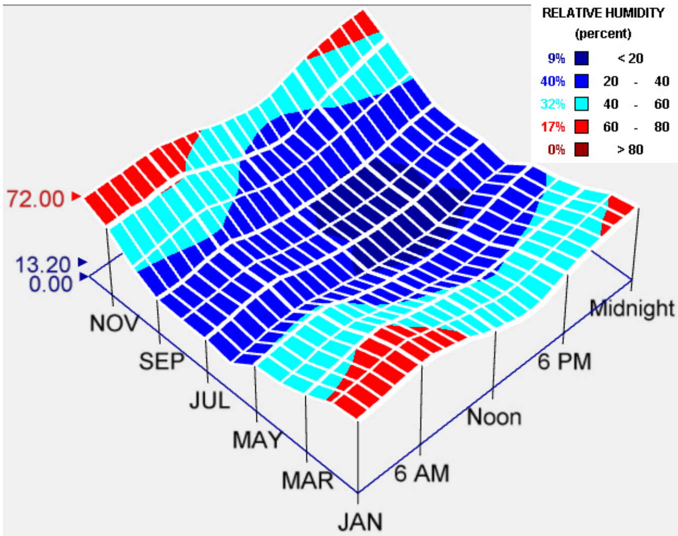

Figure 3: Mean monthly humidity ratio of Tehran (Climate Consultant simulation software)

In this study, first, through field inspections the length to width ratio and the average height of the office buildings were investigated. Version 3.2.0.070 of Design Builder Software is used to model various aspects of the building such as building materials, architecture construction, heating, cooling and lighting systems. As it is represented in Figure 4, Tehran Railway construction as an office building with atrium has been simulated to validate the software as a tool to simulate the real environmental conditions. The actual data of this building, such as layered wall, ceiling, heating and cooling systems, etc. were used to run this simulation. In this building, starting from 13 June 2013, temperature and relative humidity were recorded using a data logger device for three successive business days to validate the model. Moreover, Lux meter device was used to record the intensity of daylight (Mansour Kamaruzzaman et al, 2006). The annual energy consumption in this building was calculated according to the energy bill (electric and gas). The so-obtained data from the actual building was compared with the acquired data from a model shown in
Figure 5-a, b and c. The basic model with the following average characteristics in Tehran was simulated in the software to validate the model: length to width ratio 1.5 with the east-west elongation a height 14 floors (each floor 4 meters) and a total area of 1350 square meters. This model was simulated according to the technical and standard specifications of the office buildings in Iran.

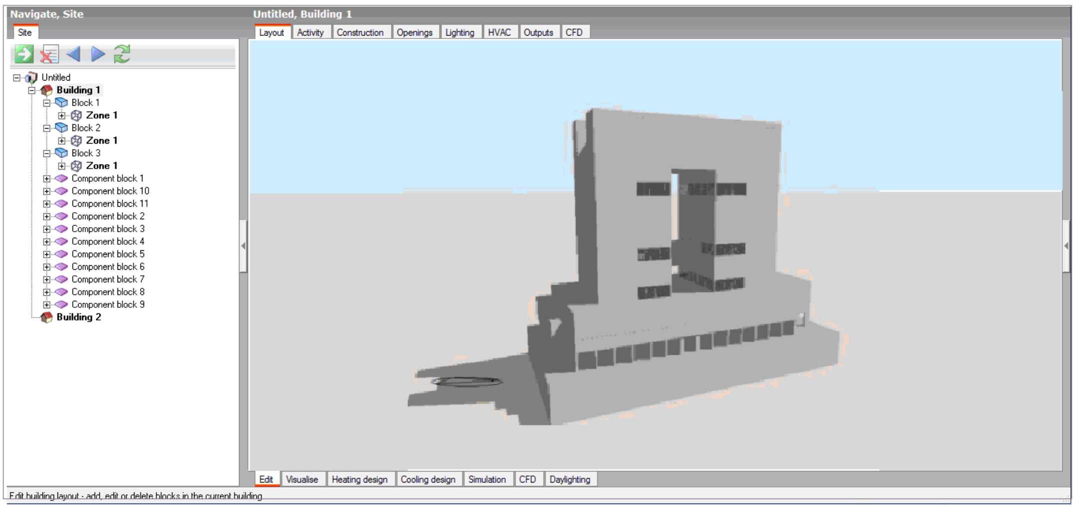

Figure 4: Geometric model of Railroad building

Actual materials were chosen based on the proposed materials by the software that had the most consistency with the real materials in our office buildings. In all models, the ratio of windows is defined as 30 percent and as single glazing which has been tabulated in Table 1, 2, 3, 4, 5 and 6. To have a neutral effect on the tested floors, as it is depicted in Figure , while performing the modeling, the middle (7th) and the last floors (14th) were first drawn as building blocks and other floors as adiabatic. This has been done by using the Design Builder option to create adiabatic components. Next, different ratios from 1:2 to 1:0 were modeled in the central atrium in order to determine the most appropriate ratio (atrium area/total area). It should be noted that as Figure shows, in all models, the total area of construction is stable. Levene test was used to evaluate the homogeneity of variances of the data. The intensity of natural light in all models were compared using ANOVAs and Duncan's multiple comparison tests. All statistical analyses were performed using SPSS (version 16).

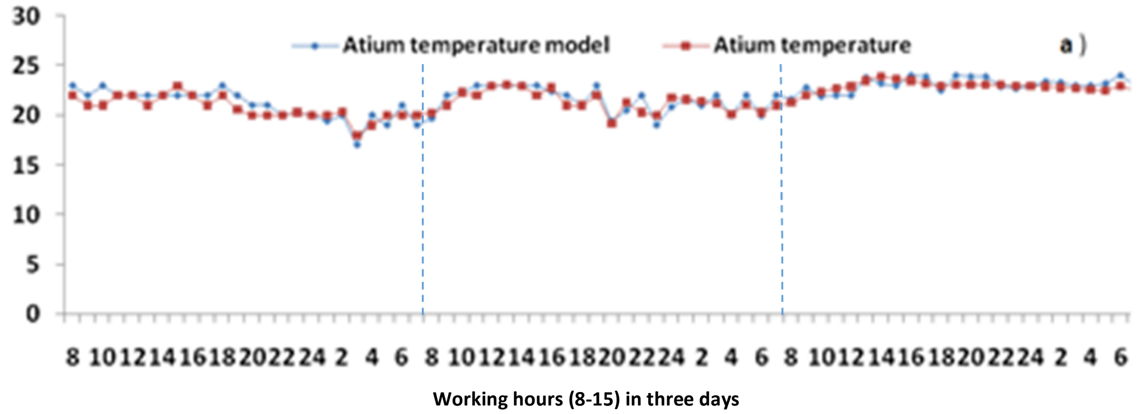

Figure 5.a: Comparison of the recorded temperature by data logger in the Railroad building and the simulated temperature by Design Builder software in three business days.

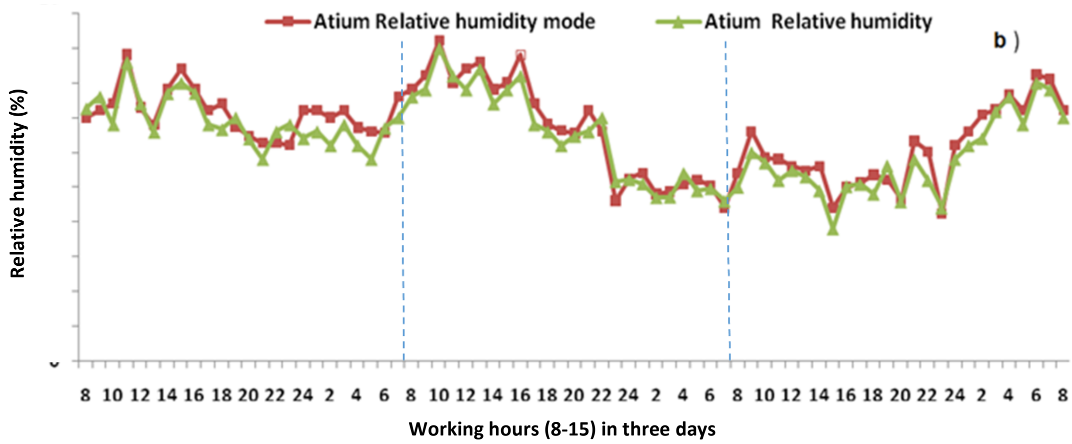

Figure 5.b: Comparison of the recorded relative humidity by data logger in the Railroad building and the simulated temperature by Design Builder software in three business days.

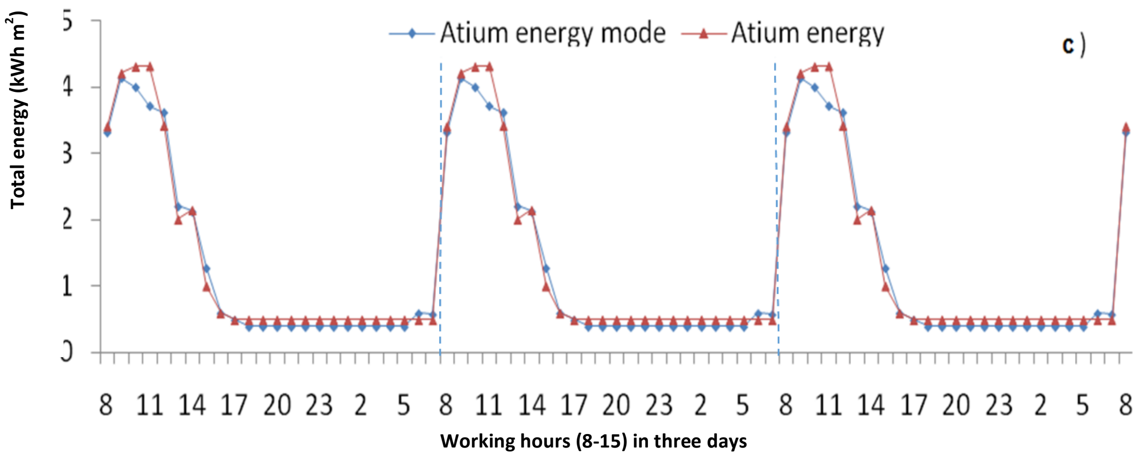

Figure 5.c: Comparison of the recorded annual energy consumption based on annual bill in the Railroad building and the simulated temperature by Design Builder software in three business days.

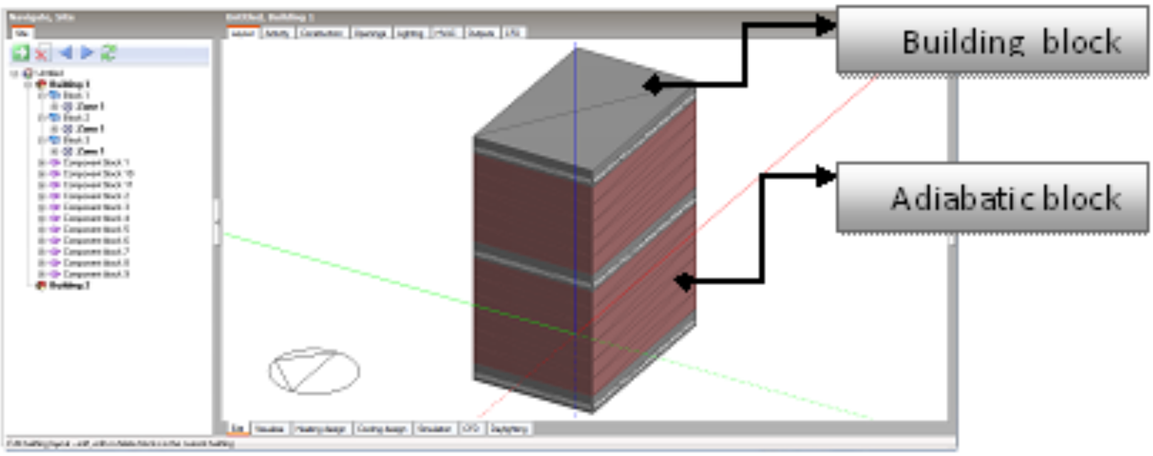

Figure 6: The basic geometric model of the office buildings in Tehran

Table 1: Thermal characteristic of materials

Materials	Conductivity [W/m.k]	Specific heat [J/kg.k]	Density [Kg/m3]
Granite	2.8	1000	2600
Cement/plaster/mortar-cement	0.72	840	1860
EPS Expanded polystyrene (Standard)	0.04	1400	15
Cement/plaster/mortar-cement	0.72	840	1860
Air gap 25mm (downwards)	No	yes	0.19
Gypsum Plasterboard	0.25	1000	900

Table 2: Settings for the internal heat loads

Activity	Light office work/Standing/Walking	123.000[W/Person]
Metabolic	Winter Clothing [Clo]	1.00
	Summer Clothing [Clo]	0.50
Occupancy		0.1110[People/m2]
Environmental control	Heating set point temperature	22
	Heating set back	12
	Cooling set point temperature	26
	Cooling set back	26
Equipment	Computer	5[W/m2]
	Office equipment	11.77[W/m2]

Table 3: Settings of windows

Openings		
Window		Single glazing clear, no shading
	Glazing type	Sgl 6mm
	Lay out	Preferred height
	Dimension	Various
	Window to wall ratio	30%
	Sill height	0.8 m
Frame	Type	Aluminium window frame[no break]
	Width	0.020 m
Dividers	Horizontal dividers	1
	Vertical dividers	1
	Shading	NO

Table 4: Settings of heating and cooling systems

HVAC		
System type		General energy code
Mechanical ventilation	Outside air definition method	Min fresh air (sum per person +per area
Heating	Fuel	natural gas
	Heating system cop	0.62
	Heating type	Convective
Supply air condition	Maximum air humidity temperature [c·]	35
	Maximum air humidity ratio[g/g]	0.0156
	Schedule	ON
Cooling	Fuel	natural gas
	Cooling system cop	1.32
Supply air condition	Maximum air humidity temperature [c·]	12
	Maximum air humidity ratio [g/g]	0.0077
	Schedule	ON
DHW	System type	Instantaneous hot water only
	DHW CoP	0.85
	Fuel	natural gas
	Delivery temperature [c·]	65
Water temperatures	Mains supply temperature[c·]]	10
	Schedule	ON
Air temperature distribution	Distribution mode	Mixed

Table 5: Lighting settings

Lighting		
General lighting	Lighting energy	5 [W/m²-100Lux]
	Schedule	ON
	Luminaire type	Suspended
	Radiant fraction	0.42
	Visible fraction	0.18

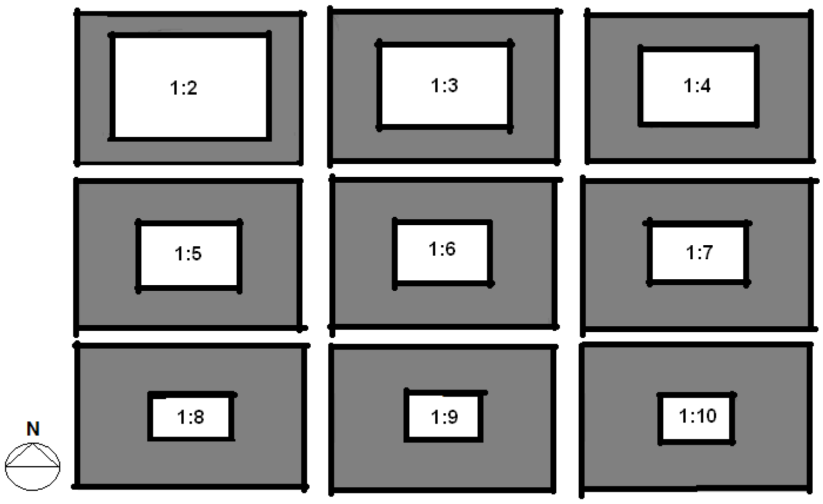

Figure 7: Different ratios of atrium (atrium area/ total construction area)

RESULTS

Energy consumption

The results of the annual energy consumption for different atrium area to total building area ratios from 1:2 to 1:10 showed that decreasing this ratio lowers the annual energy consumption. The highest and lowest annual energy consumption belong to the ratio of 1:2 and 1:10, respectively and is represented in **Error! Reference source not found.**-a. Investigations showed that the amount of heating and cooling consumed energy in summer and winter is almost the same (Figure 8-b). Hence, as shown in **Error! Reference source not found.**, the highest and lowest amount belong to the ratio of 1:2 and 1:10, respectively. Atrium is increasingly used in modern architecture and creates suitable indoor conditions and reduces the energy consumption as well. Yet, its performance depends on the proper design and choosing the right ratio (Rong et al, 2012). Larger atriums let a high intensity of sun light in the building and hence, cause thermal stratification in the summer (Abdullah et al, 2009). A high amount of energy is used to cool the environment and make thermal comfort. Also, large atriums in winter, increase the connecting surface with the cool environment outside. Therefore, in this study, considering high energy consumption in 1:2 ratio seems reasonable. Well-designed atrium as a way to improve the thermal comfort along with lower energy consumption is being addressed in (Hung, 2003). Aizlewood (1995) stated that the appropriate intensity of light directly to atrium can be desirable, but too much of it resulting in unprincipled area of atrium can cause the rising temperature of the atrium, residents abuse and high energy consumption.

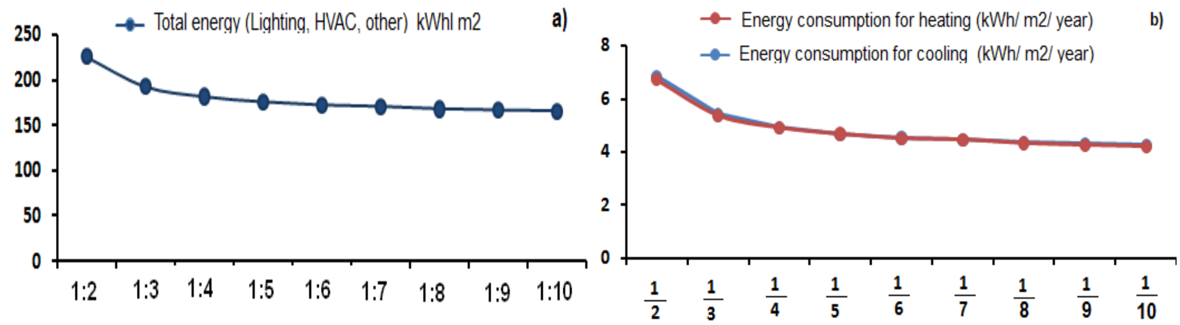

Figure 8: The amount of annual energy consumption (a), heating and cooling energy consumption (b) in the office building with different ratios from 1:2 to 1:10.

Daylighting and atrium ratio

According to ANOVA performed on the amount of natural light's received height, significant differences were detected between different models (with different atrium area ratio) as depicted in Table 6. Based on Duncan's test, the natural light was significantly higher in 1:2 ratio than that of other ratios, while the lowest natural light was observed in the 1:10 ratio. From 1:2 to 1:10 ratio, regular downtrend has occurred. There was no significant difference between ratios of 1:2, 1:3 and 1:4 as it has been displayed in Figure 9.

Table 6. Results of ANOVA performed between ratios in terms of the intensity of received daylighting

	Sum of squares	Df	F	Sig
Between groups	65.45	8	7.97	**.000***
Within groups	98.75	96		
Total	163.9	104		

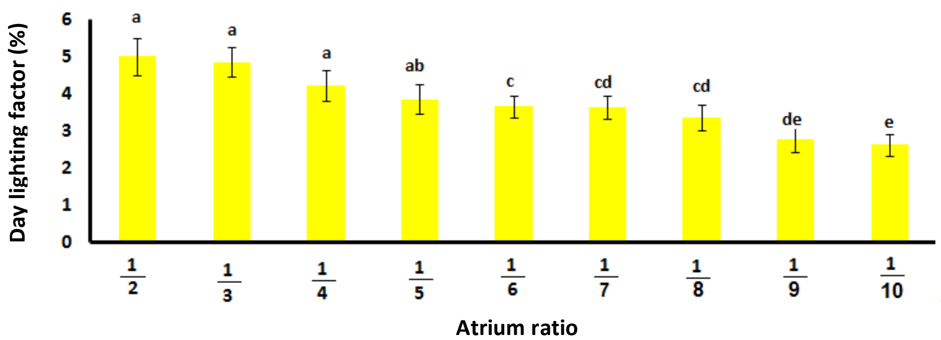

Figure 9: Central atrium with ratios from 1:2 to 1:10 in relation to the intensity of daylight (DF)

In 1999, Chartered Institution of Building Services Engineers (CIBSE) stated that a room with DF=5% has no need to use artificial light and adequate lighting sense. Such conditions are indicative of access to daylight. According to the reduced annual energy consumption between the ratios of 1:2 to 1:10, the natural light in the building was higher in the ratios of 1:2 to 1:5 and was close to 5 percent. Therefore, model 1:4 is an example of better energy efficiency and the amount of daylight was determined as explained in Figure 10 and Figure 11. Studying the monthly consumed electricity for lighting, heating and cooling in optimum models of the central atrium (model 1:4) showed that the amount of electricity consumed for lighting was approximately the same in all months of the year. Nonetheless, a large amount of energy was consumed for cooling and heating purposes in hot and cold months, respectively.

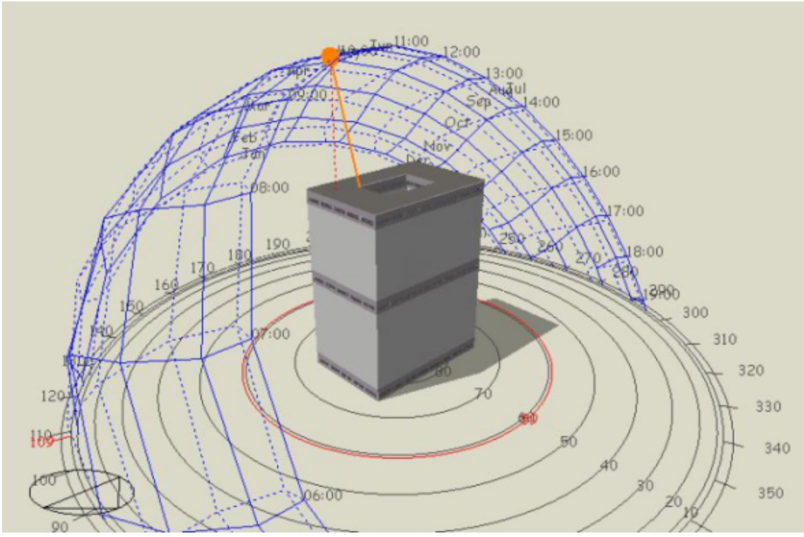

Figure 10: Selected model in the ratio of 1:4

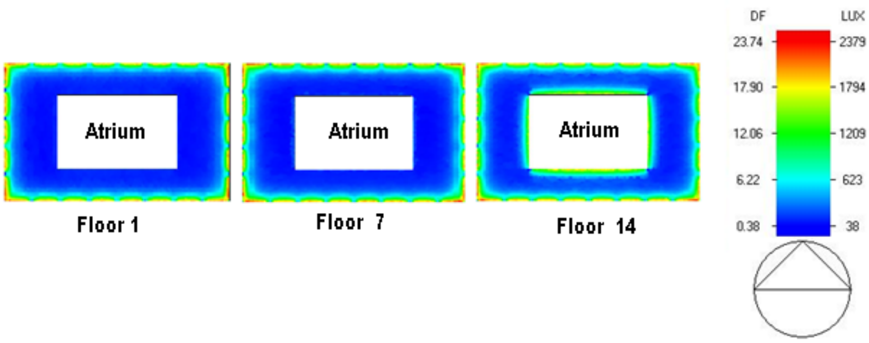

Figure 11: Daylighting in 1:4 ratio

Thermal Comfort analysis

The predicted mean vote index (PMV) (ASHRAE 55, 2013) with the ratio range of 1:2-1:10 is analyzed. These ratios refer to the coldest and the hottest months of the year which are January and July respectively. The Fanger PMV indicates that the ratio of 1:2 with the value of 0.9 during July, is the closest ratio to the comfort zone that is ± 0.5 (ASHRAE 55, 2013).As the surface area of the atrium decreases with respect to the overall area of the building, the internal state of the building will be hot during summer and result in thermally uncomfortable conditions (Figure 12).

Analysis of the Fanger PMV (ASHRAE 55, 2013) in January with the ratio and value of 1:10 and -0.58 respectively, concludes that it is the closest state of the comfort zone (Figure 13). Diminishing the atrium's surface area with respect to the overall building's area, causes less thermal exchange during winter. That is since the internal-external contact, the atrium and outside, lessens and subsequently results in having the comfort zone condition and its validity is verified through the outcome of this scientific research.

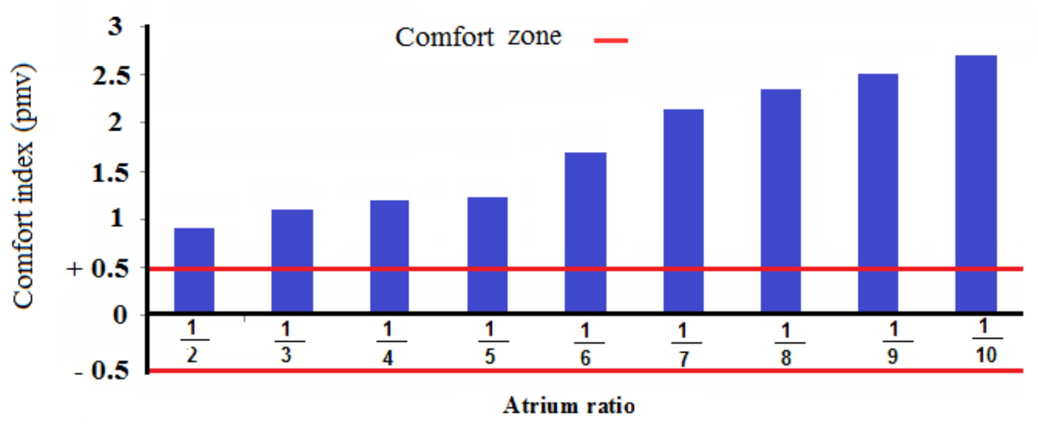

Figure 12: A comparison of PMV index between different atrium area ratios of 1/2 to 1/10 in the hottest month (July) of Tehran

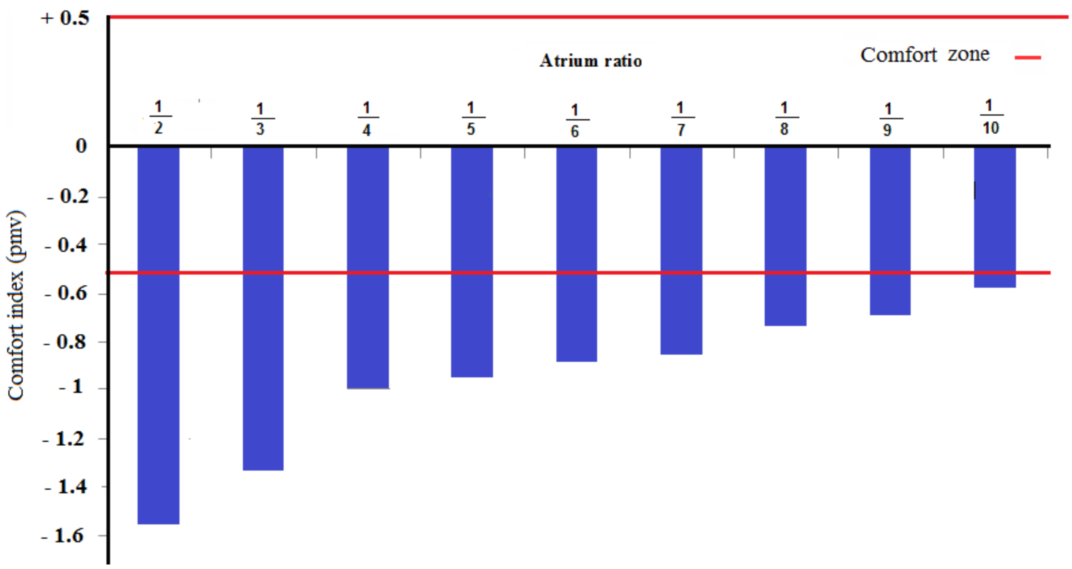

Figure 13: A comparison of PMV index between different atrium area ratios of 1/2 to 1/10 in the coldest month (January) of Tehran

CONCLUSIONS

Atrium is increasingly used in modern architecture and creates a suitable indoor condition and can reduce the consumed energy in the building. However, the percentage of the consumed energy reduction highly depends on the proper design and ratio of the atrium. This research is aimed to investigate the effect of geometrical ratio of atriums on energy performance of office buildings. Different simulation modeling was conducted and examined through Design Builder simulation software.

The results of the annual energy consumption between different atrium to construction area ratios showed that decreasing this ratio reduces the annual energy consumption. The highest and lowest annual energy consumption belong to the ratio of 1:2 and 1:10, respectively. The results also showed that, the amount of energy consumed for heating and cooling purposes in winter and summer is almost the same. Thus, the highest and lowest of the energy consumption amount is related to the ratio of 1:2 and 1:10, respectively. Significant differences were detected between different models with different atrium area ratio. Based on Duncan's test, the daylight amount was significantly higher in 1:2 atrium ratio than that of other ratios, while the lowest daylight amount was observed in the 1:10 ratio. It also shows by decreasing the atrium area ratio to total building area, the amount of daylight reduced in the simulated models. From 1:2 to 1:10 ratio, regular downtrend has occurred.

Analysis of the Fanger PMV in the hottest and coldest months shows that the ratio of 1:2 and 1:10 respectively are the closest state to the comfort zone. Overall, considering different analysis including energy consumption and daylighting, there was no significant difference between ratios of 1:2, 1:3 and 1:4. While, the analysis of PMV shows that the atrium area ratio of 1:4 was closer to thermal comfort specified zones, therefore, this model was chosen as an example which possesses better energy efficiency and the amount of daylight was determined for this model. Further studies are needed to evaluate the impact of different atrium geometric forms from the point of view of building total energy consumption and indoor environmental quality such as thermal and visual comfort.

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