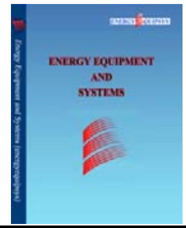
Energy Equip. Sys./ Vol. 7/No. 3/Sep. 2019/ 211-234

Energy Equipment and Systems

http://energyequipsys.ut.ac.ir
www.energyequipsys.com



Energy consumption of atria; the case of a commercial-office center in the semi-arid climate of Tehran

Authors

Ghazanfari Fatemeh[a]
Kaboli Mohammad Hadi [b*]

[a] Department of Architecture, West Tehran Branch, Islamic Azad University West Tehran Branch,Tehran,Iran

[b] Department of Architecture, Islamic Azad University, Damavand branch, Damavand, Iran

Article history:

Received : 5 September 2018
Accepted : 29 December 2018

ABSTRACT

According to the energy crisis in the world, optimization of energy consumption is indispensable. Technological advances in constructions and application of renewable energy resources demand saving energy. Atrium, as one of the construction elements, catches sufficient daylight and acts as a passive solar element and results in a decline of energy consumption.
This research seeks to evaluate the impact of different positions of atrium on its energy performance; this embraces modelling three groups of spatial configuration of atriums in a given four-story building. The total volume and area of atriums in all three groups are equal. DesignBuilder, the energy simulation software, is the platform for simulation and comparison.
The results show that the number of atriums does not have a noticeable impact on energy consumption; however, the spatial configuration of atriums, specially the distance of atriums to external walls have a little impact on the annual energy consumption. Based on the purpose of a specific design, one can decide on whether to take into account the discrepancy.

Keywords: Atrium, Daylight, Passive Solar Systems, Energy Simulation, Atrium Geometry.

1. Introduction

Approximately, 40 percent of country's annual energy use is traceable in the building sector. [1] Renewable sources of energy such as solar energy is a way to reduce fuel consumption in the building.

Lighting in large public places demands for energy. It is difficult to provide sufficient light through external walls due to the large size and depth of the building; so the use of artificial light increases the electric energy consumption. The use of natural light in indirect ways can greatly reduce the use of electrical energy [2].

The impact of this saving will be greater in the office and educational spaces that have the most activity throughout the day. Lighting energy consumption accounts for about a third of the whole building energy consumption in modern office buildings and large department stores; [3] hence, daylight has become an important design strategy for better passive performance of building [4].

In this regard, the use of some architectural elements such as atrium, if designed properly, not only can minimize electrical energy consumption, but also

* Corresponding author: Kaboli Mohammad Hadi
Department of Architecture, Islamic Azad University, Damavand branch, Damavand, Iran Email: hadikaboli@damavandiau.ac.ir

reduce the energy needed for air-conditioning the building [5].

Atrium can help to energy saving by providing daylight into occupied spaces, so it reduces artificial lighting and the consequent thermal loads. Atrium can be a buffer zone between indoor and outdoor environment and as a result, heat transfer from building surfaces to the outdoor environment decreases. In the summer, atrium and adjacent occupied zones can be ventilated naturally by stack effect. Also Energy saving strategy of atrium in the winter is based on greenhouse phenomena [6].

Some factors make difficult to predict thermal performance of atriums: (1) atriums usually have large areas in the ground they cover, their glazed roofs, and the walls they consist; Therefore, solar heat creates significant buoyancy flows. (2) Mixed forced and natural convection and complex radiation–convection interactions often lead to thermal stratification within the atrium [1, 5, 7].

Inappropriate design may result in thermal discomfort due to the high temperature regions, air stratification resulting from solar heating, strong buoyant flows, glare, and potentially, rapid spread of a fire and smoke [7].

Therefore, identification of effective factors in the design of these buildings is very important. Among these factors, geometry, form, location and number of atriums in the building have significant effects on the design of architectural plan and the interior design of buildings. In other words, these are architectural factors to be studied about the atriums. In this research, the emphasis is on the number of atriums which is important to create various interior spaces. A building with several atriums, creates more spatial variety for the occupants and enables architects to design a dynamic interior space. We investigate the impact of the number of atriums and their spatial configuration on the energy consumption of building.

Researches on the energy consumption of atriums can be listed into three broad categories: studies on total energy consumption based on shape and geometry of atrium, ventilation and stack effect topics and performance in terms of daylight factor.

Regarding atrium geometry and energy consumption, Aldawoud [1] indicated that energy performance of square and rectangular shape of atria varies according to different climate, glazing type and ratio of its length to width. DOE-2.1 was implemented as a simulation tool. The results show that the total energy consumption of the rectangular atrium with the high ratio of length to width is significantly greater than the square shaped atrium. Nasrollahi et al. [8] indicated that by decreasing the ratio of atrium to the total building area, the annual energy consumption reduces.

About stack effect and ventilation, Liu et al. [9] investigated the performance of buoyancy driven ventilation in atrium buildings by using computational fluid dynamics (CFD) and scale model tests during the design stage. They showed that the dimension and position of the stack openings should be considered. Results indicate that placing the stack openings in proper position can provide ventilation paths which help to enhance thermal indoor conditions and the dimensions of the stack openings located in atrium roof affect the temperature distribution inside the atrium space. Also results showed that the effect of internal thermal loads on the temperature change, is not as remarkable as that one made by outside environment. Assadi et al. [10] analyzed the impact of dimension of a rectangular atrium on the passive heating and ventilating effect. They emphasized on the glass height and atrium diameter factor, which had significant effect on the total absorption area of solar radiation. They show that when glass height increases and diameter of the atrium reduces, the total absorption area of solar radiation; accordingly, the thermal and ventilation efficiency increases. Shafiei Fini et al. [11] implemented CFD models to compare case studies with different atrium's wall angularity. Results show that converging tilted walls in tall atrium only increases thermal comfort for stories that are located lower than neutral pressure level, and the thermal comfort for upper stories decreases.

Diverging walls in atrium show no advantage. Also results indicates that a combination of vertical walls for upper stories and tilted wall for lower stories, yield the best performance.

Regarding daylight factor of atrium, Erlendsson [12] investigates the effect of different physical factors on the atriums daylight factor by using Honeybee (an environmental plugin for Grasshopper). The efficiency is the best in the circular atrium. By changing the shape to square, and then triangle, the efficiency degrades; Besides, increasing the opaque surfaces in the upper floors extenuate the reflection from upper surfaces to the lower levels of the atrium; Therefore, the different percentages of glass surfaces in different levels increase the amount of daylight. Ghasemi et al. [13] predicted the ADFs (Average Daylight Factor) of different floors of an atrium building in tropical climate. By using IES-Radiance modeling software that are validated by scale model measurements, they indicated that variation rate of ADF (Average Daylight Factor) of different floors of atrium are not similar. By increasing the widths of the atrium (or in the square form atrium), ADF decreases in all floors except ground floor. Also results show that increasing the height of the clerestory windows (vertical windows at the top of the atrium) increases the amount of "average daylight factor" in the atrium and its adjacent spaces.

Table 1. Literature review

Classification on researches about energy performance of atria	Author (year)	Study field	methodology	results
shape	Abdelsalam Aldawoud (2013)	The proportion of length to width of the atrium	Four central atriums with different geometrical proportion (Length to width ratio) were compared. Models have equal areas, function, schedule, controls, occupancy, and construction. Energy simulation has been done using DOE-2.1E simulation program.	Atrium geometry affects the total energy consumption of buildings. Narrow, elongated atrium shapes, show poor results in all climates.
	Nasrollahi et al. (2016)	The ratio of atrium to the entire building.	The proportion of atriums in 9 office buildings that have the same area is altered. (Length to width ratio) Also, the average height of these buildings are examined by field studies, and the appropriateness is validated as well. DesignBuilder Software is used as a simulation tool.	-The annual energy consumption reduces by decreasing the ratio of atrium to the total building area from 1:2 to 1:10. -The most efficient ratio in terms of energy performance, daylighting and thermal comfort, is 1:4. -The amount of daylight in ratio 1:2 was significantly higher than other ratios.

Ventilation and stack effect	Khalaji Assadi et al. (2011)	Effect of glazing system type and its dimensions	To analyze the effect of an atrium in the building, a three-story building in Tehran is assumed to have an atrium. Heat balance equations are written for each of three elements of wall, glazing, and air. Temperature of each element has been obtained by substituting the temperature profile of the atrium in the set of temperature equations.	- In an atrium building, it is not possible to design the building fully heated and ventilated by buoyancy-driven flows and stack effect. -increasing the glass height and decreasing the diameter, enhance the thermal and ventilation efficiency.
	Doheim et al. [14] (2014)	effect of the atrium plan form on smoke ventilation from the atrium space	By the use of computational fire dynamics simulator (FDS), The smoke ventilation performance of three different configurations for the atrium (square, rectangular and triangular) with the same area, height, and volume were tested.	In terms of smoke filling time, the rectangular, square, and triangular configurations contribute better to smoke ventilation, respectively.
	Shafiei Fini et al. (2015)	Effect of wall angularity of atrium	The atrium's wall angularity is changed in different case studies to balance ventilation and thermal comfort in different levels of atrium with equal opening areas. CFD models were used to find the relations between atrium wall angularity and thermal performance.	Converging walls are worse cases for top stories when height of building increases; though, they are suitable for lower stories; therefore, using a combined case that comprises converging wall for lower stories and vertical wall for upper stories indicates the best thermal condition in comparison to other cases.
daylight	Mohsenin et al. [15] (2015)	effect of form and atrium proportions (WI)	Investigates daylight metrics in 3 types of atriums (central, attached and semi-enclosed atrium) which have different proportions and roof aperture designs, based on the Well Index (WI)[1]. Climate-Based Daylight Modeling (CBDM) is implemented as the assessment strategy. For the climatic setting, U.S Climate Zone 3 is selected. DIVA for Rhino as the simulation tool is applied for validation.	-Well Index is a reliable indicator to describe atrium proportion, and it is confirmed that Well Index works with (CBDM). -Atria with different dimensions, but with the same Well Index, shows approximately the same average dynamic daylight metric.
	Ghasemi et al. (2015)	effect of appropriate geometric dimensions, and the height of the vertical glazing of the atrium skylight	Study the effect of the width of the atrium and the height of its vertical windows on the "average daylight factor" and determine the appropriate geometric dimension for a four-sided four-story atrium to provide adequate daylight in the office space.	The lowest height ratio of vertical windows (clerestory opening) (h) to the height of the atrium (H) is realized 3 to 8; to provide the required "average daylight factor" in the adjacent spaces of the atrium.

[1]WI is used to describe the atrium proportions. $WI = H * \frac{(W+L)}{2*W*L}$.
H is the atrium height; w is the atrium Width; l is the atrium length. [16]

Erlendsson (2014)	impact of physical factors	Investigates the design of atria for daylighting in large scale buildings. A three-dimensional test building with a central atrium was constructed and various parameters of the atrium altered. The impact of these changes was studied through computer simulations of annual daylight distribution by Honeybee that is coupled with the graphical algorithm editor Grasshopper for Rhinoceros 3D, which allows for an efficient way of parametric modeling.	-Increasing the reflection coefficient from the atrium floor does not significantly affect daylight; However, increasing the reflection coefficient of the walls in the southern, eastern, and western views has a good effect. -The pyramidal and curve roof shape show a higher daylight factor in the upper floors due to the diffraction and effuse light in the surrounding spaces. In the lower floors, the effect of the

According to the above literature review, broaching the study on the role of positioning the atriums is worth mentioning. This can be realized through modelling different spatial configuration of atriums in a given building.

2. Methodology

Simulation of energy consumption is of great interest in architectural design according to various benefits it provides.

DesignBuilder, as the GUI (Graphical Usage Interface) for EnergyPlus, is the most comprehensive and easy-to-use interface for EnergyPlus available today. This enables the whole design team to use the same software to develop comfortable and energy-efficient building designs from the concept. DesignBuilder has been used to evaluate façade options, thermal simulation, daylight, total energy consumption, CO2 reduction, natural ventilation and HVAC[2] equipment and systems. [17] In this study, we evaluate total energy consumption of three case studies by this software.

Despite DesignBuilder provides a variety of country- or region-specific templates for selection of parameters (such as materials and constructions), the application of DesignBuilder material library for the city of Tehran, ended to an ideal simulation results- different from the real condition. In a comparison between the standards of ASHRAE[3] and the Iran National Building Regulations, we got that the former one suggests lower standards; so we decided to use the materials suggested in the Iran National Building Regulations.

The accuracy of the DesignBuilder software has been validated using the BESTest (Building Energy Simulation TEST) procedure, originally developed by the International Energy Agency. The BESTest is a comparative set of tests that has been regarded by the American Department of Energy and the international community as being a reputable basis for evaluating the capabilities of building energy simulation programs [18].

This research investigates the impact of spatial configuration and number of atriums on the energy consumption of buildings. In the first group, energy consumption of three buildings with single, twin and quadruple central atriums were analyzed and compared. All atriums have the same area and volume but different distances to the external walls of the building (Fig. 2).To gain more reliable results, we investigated two other buildings (with triple and sextuple central atriums). In this group, the distances to the external wall for all models were the same (Fig. 3 and Fig. 4).

To evaluate the effect of this distance on the energy consumption, three models with a single central atrium were simulated; they have

[2] Heating, ventilation, and Air-Conditioning

[3] The American Society of Heating, Refrigeration, and Air-Conditioning Engineers

the same shape, volume and area but different distances to the external walls (Fig. 5).

The analyses were conducted as follows:

- Modeling three groups of buildings: 1- single, twin and quadruple atriums with different distances to external walls 2- single, twin, triple, quadruple and sextuple atriums with equal distances to external walls, and 3- three single atriums with different distances to external walls.
- Collecting the information on physical parameters and operational parameters based on existing standards and conditions close to real conditions.
- Simulating the energy consumption of models based on physical and operational parameters in the DesignBuilder software.
- Comparing simulation results based on the discrepancy between the energy consumption of each individual building in groups.

The diagram of the methodology process is depicted in Fig. 1.

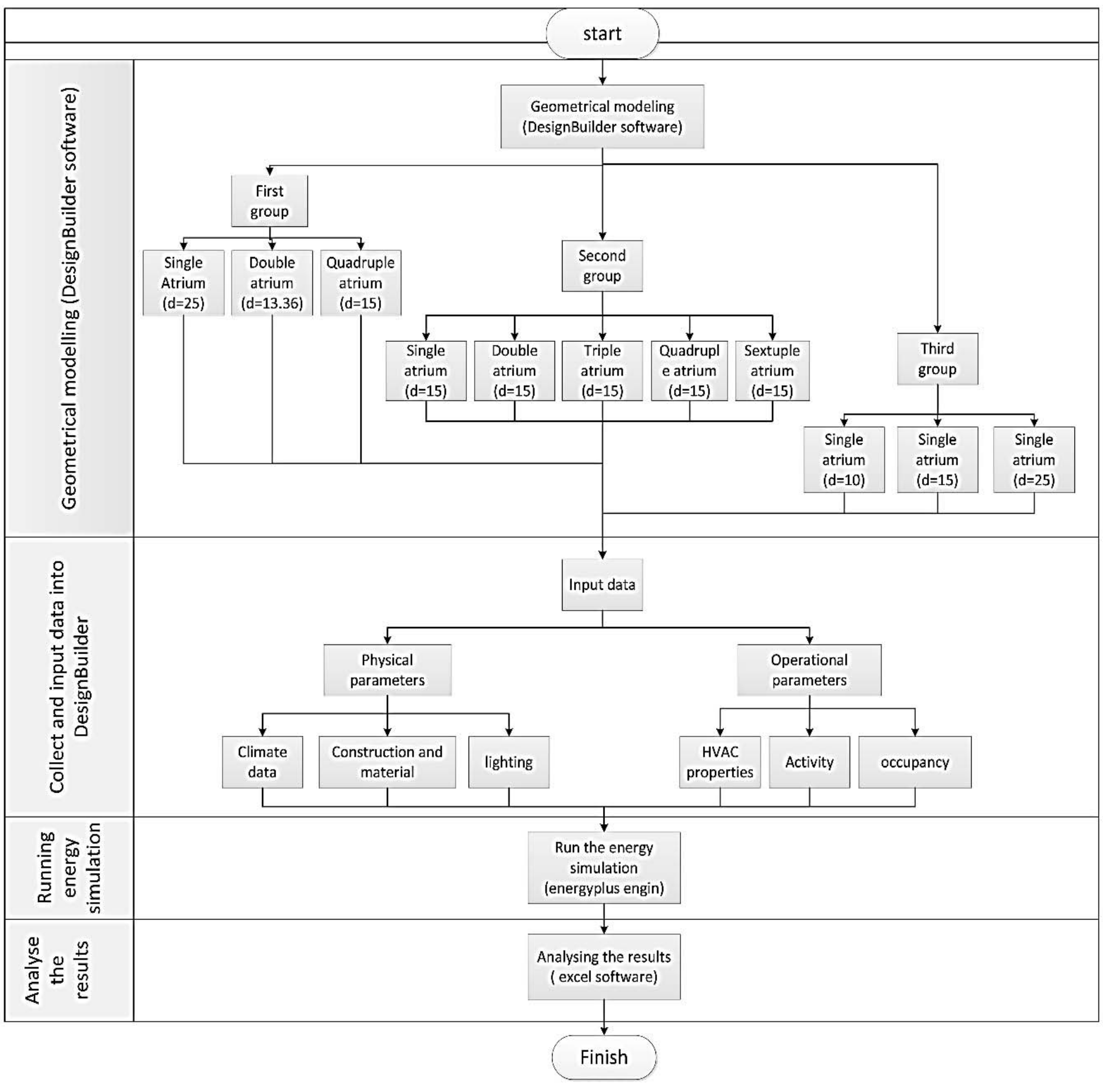


Fig. 1. Diagram of methodology process

2.1.Description of the case studies

The building is a 4-storey commercial-office with commercial function in ground floor and offices in other floors. The total volume and area of atriums in all case studies are the same. The geometrical dimensions of the parent building, occupancy [people/m²], number of floors, type of the building, glazing ratio, glazing characteristics and materials are under fixed conditions in all case studies. Distance to the external wall of the building is 15m in all models (Fig. 4).

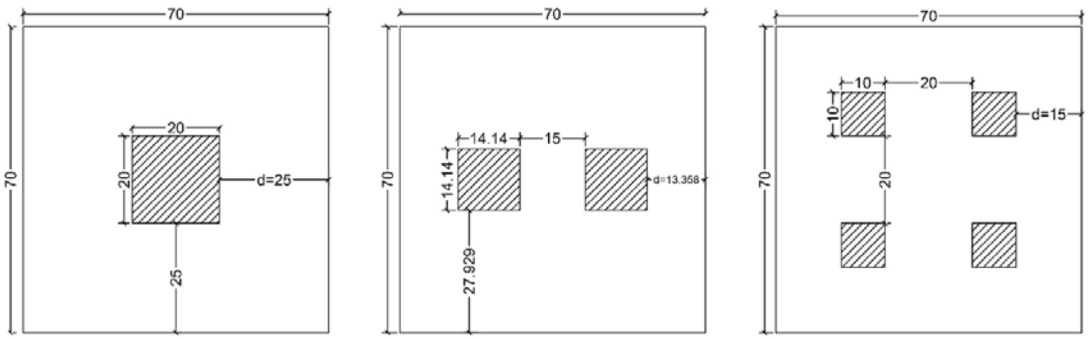


Fig. 2. plan of single, twin and quadruple atrium building with different distances to the external wall: first group of simulations

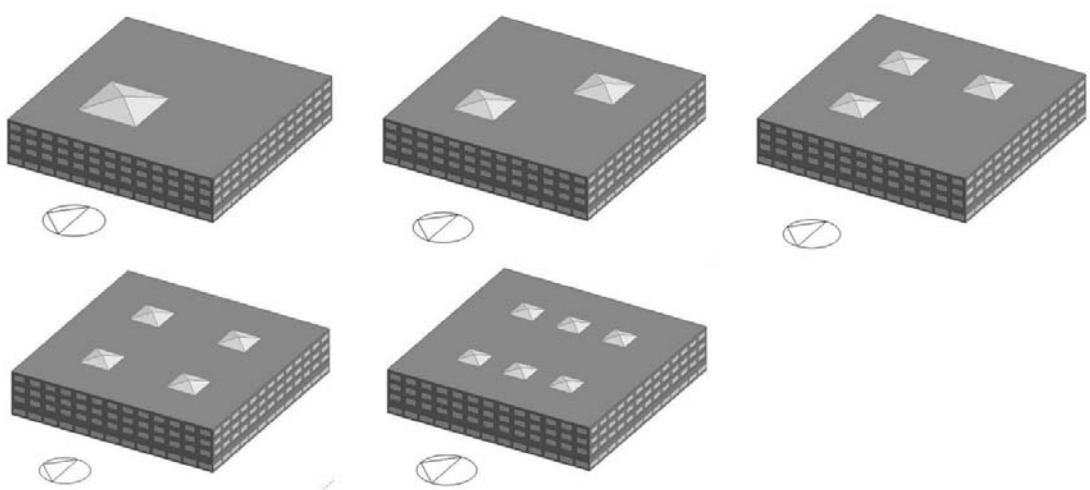


Fig. 3. Schematic of Single, twin, triple, quadruple and sextuple atrium building: the second group of simulations

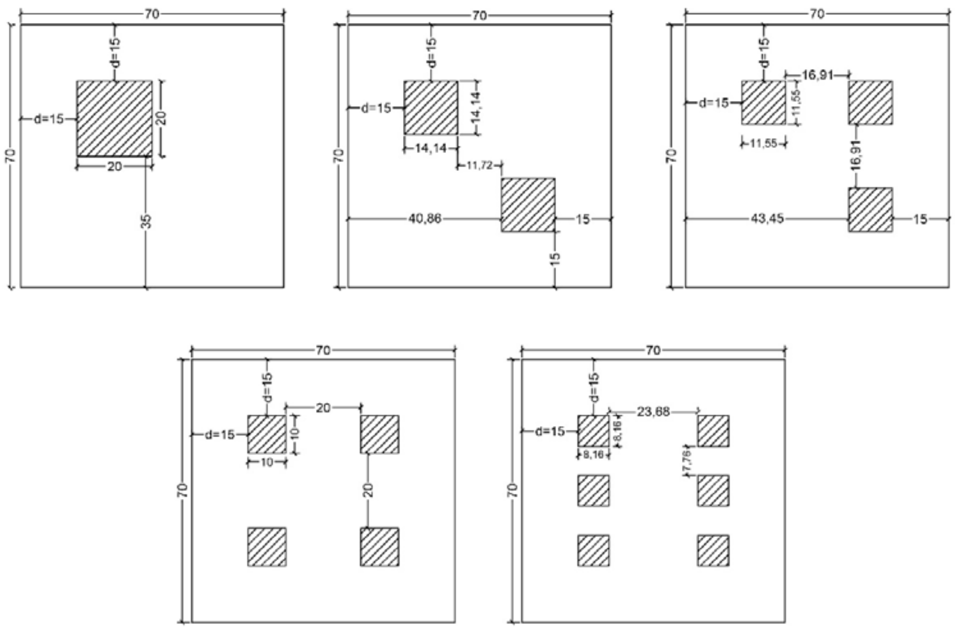


Fig. 4. plan of single, twin, triple, quadruple and sextuple atrium building with equal distances to the external wall: second group of simulations

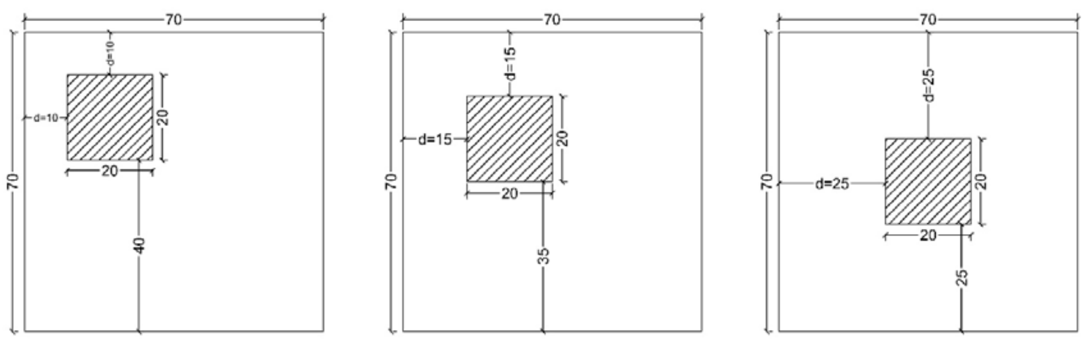


Fig. 5. plan of single atriums with different distances to the external wall: third group of simulations

2.2.Input parameters for DesignBuilder

All models have the characteristics of real commercial – office buildings. Design requirements including occupancy levels, lighting, equipment and HVAC were included in the simulation process. To evaluate the effect of atrium geometry on its energy performance, the atrium ceiling was the only point of access to the external environment.

The effective parameters in DesignBuilder can be grouped into two general categories: physical and operational.

2.2.1.Physical parameters:

- climate data

In this project, the climate data of Tehran (.epw format), which is available in the DesignBuilder library, is used for a one-year period. Tehran (51º 2' to 51º 36' E) is the administrative center of Iran and features a semi-arid, continental climate with hot and dry summers.

Table 2. description of case studies: the first group of simulations

Case studies	Number of atriums in the building	The dimension of each atrium(m)	Area of atriums (m^2)	The perimeter of atriums(m)	The ratio of perimeter to area of atriums	Distance to the external wall(m)
Single atrium	1	20*20	400	80	0.2	25
Twin atrium	2	14.14*14.14	400	113.12	0.28	13.358
Quadruple atrium	4	10*10	400	160	0.4	15

Table 3. description of case studies: the second group of simulations

Case studies	Number of atriums in the building	The dimension of each atrium(m)	Area of atriums(m^2)	The perimeter of atriums(m)	The ratio of perimeter to area of atriums	Distance to the external wall(m)
Single atrium	1	20*20	400	80	0.2	15
Twin atrium	2	14.14*14.14	400	113.12	0.28	15
Triple atrium	3	11.54*11.54	400	138.552	0.34	15
Quadruple atrium	4	10*10	400	160	0.4	15
Sextuple atrium	6	8.16*8.16	400	195.936	0.48	15

Table 4. description of case studies: the third group of simulations

Case studies	Number of atriums in the building	The dimension of each atrium(m)	Area of atriums (m^2)	The perimeter of atriums(m)	The ratio of perimeter to area of atriums	Distance to the external wall(m)
Single atrium	1	20*20	400	80	0.2	25
Single atrium	1	20*20	400	80	0.2	15
Single atrium	1	20*20	400	80	0.2	10

- Thermal characteristics of materials:

In this software, the most important thermal characteristics of the materials is their U-value.[4] For modeling process in this study, the U-value is extracted from Iran National Building Regulations. (Issue 19)

- Glazing systems characteristics

The thermal properties of the glazing systems are listed in Table 6.

The area of glazing to wall ratio is 25% for the eastern and western external walls and 30%[5] for the north and south external walls. The interior windows (between the atrium and its adjacent zones) type are Curtain walls with 85% glazing ratio.

[4] Thermal transmittance, also known as U-value, is the rate of transfer of heat through a structure (which can be a single material or a composite), divided by the difference in temperature across that structure [19].

[5] The glazing to wall ratio of an office room with maximum height of 3.5 meters, should be 30% [20].

Table 5. U value of used materials (W/m2.K)

	Flat roof	**Ground floor**	**Internal floors**	**External walls**	**Pitched roof**	**Internal walls**
U-value ($W/m^2.K$)	0.69	0.25	0.69	1.39	4.28	1.63

Table 6. Thermal properties of the glazing systems

	U	**SHGC**	**VT**
Internal glazing	2.9	0.24	0.88
External glazing	3.09	0.7	0.89
Skylight glazing	2.42	0.56	0.88

U: surface heat transfer coefficient
SHGC :Solar heat gain coefficient
VT :visible transmittance

- Glazing properties

Table 7. Glazing properties

	Atrium zone	Commercial floor	Office floors	Atrium roof
Glazing type	Double glazing	Single glazing	Single glazing	Double glazing low E
frame	Aluminum thermal break	Aluminum with no break	Aluminum with no break	Aluminum thermal break
Glazing to wall ratio of the eastern and western face	85	25	25	100
Glazing to wall ratio of southern and northern faces	85	30	30	100
shading	yes	no	no	yes

2.2.2.Operational parameters

- Window aperture pattern

Table 8. Window aperture pattern

Atrium roof	Atrium zone	Commercial floor	Office floors	Atrium roof
Operation schedule	Open from April to September Close from October to March	Open from April to September Close from October to March	Open from April to September Close from October to March	Open from April to September Close from October to March
Glazing area (open) (percentile)	15	5	5	10

- Occupancy

On the ground floor, due to the commercial use, all days of the week are considered to be working days and the presence of people is from 9:30 to 21:00. The density of people in this category is 0.1 people per square meter based on ASHRAE 90.1 standard. The presence of people in the atrium of the ground floor is possible from 9:30 to 21:00 every day.

In the first to third floors, with office functions, Saturdays to Wednesdays were considered as working days and the presence of people is from 7:30 to 16:30. The density of people in these floors was defined to be 0.05 person per square meter based on ASHRAE 90.1 standard.

Computers are working from Saturday to Wednesday at office hours and generate 4 watts of heat per square meter.

Other office equipment was not included in the calculation.

- HVAC

The heating-cooling system starts before the start of office hours, with a setback of 13 ℃ in the cooling seasons and 32 ℃ in the heating seasons, and the internal temperature reaches to 23℃ in the heating season and 26 ℃ in the cooling season.

Also, according to the schedule, the heating system switches off from April to September and switches on from March to October.

We switched off the heating and cooling system inside the atrium zone in order to estimate the natural ventilation. The time schedule for atrium openings covers the time from April to September; 15% of unshut states of the atrium openings serve to allow natural ventilation through the stack effect caused by the pressure difference. From March to October, the windows are closed, and the natural heating of the atrium takes place through the trap of high-wavelength sunlight (greenhouse effect).

3.Results and discussion

The energy simulations of office building alternatives show the amount of annual energy demands for heating and cooling of the building. Fig A.1 to Fig. A.3 show the annual energy consumption, as well as an overview of the building's energy needs for each month. (DesignBuilder outputs)

3.1.The first group of simulations:

Fig A.1 to Fig. A.3 indicates the results of the first group of simulations. Alternatives in this group do not have equal distances to the external walls of the building. According to the Fig. 6 and Fig. 7, the quadruple atrium demonstrates less heat consumption during the winter and the single central atrium shows less cooling energy consumption during the summer. As shown in Fig. 6 and Fig. 7, cooling energy demand is generally much higher than the required energy for heating. Therefore the effect of single atrium on reducing the total energy consumption of the building is more than the effect of quadruple one.

Table 9. HVAC properties

	Atrium zone	Commercial floor	Office floors
Mechanical ventilation	-	-	-
Natural ventilation	yes	yes	yes
Cooling system	-	on from April to September	on from April to September
Heating system	-	on from October to March	on from October to March
infiltration	-	-	-
Air temperature distribution	mixed	mixed	mixed

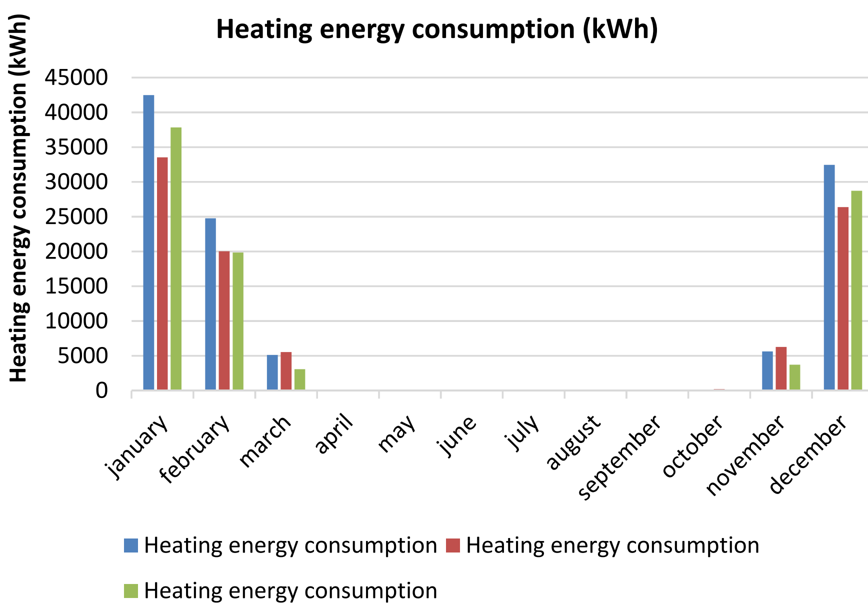


Fig. 6. Heating energy consumption of single, twin and quadruple atrium buildings in the first group of simulations

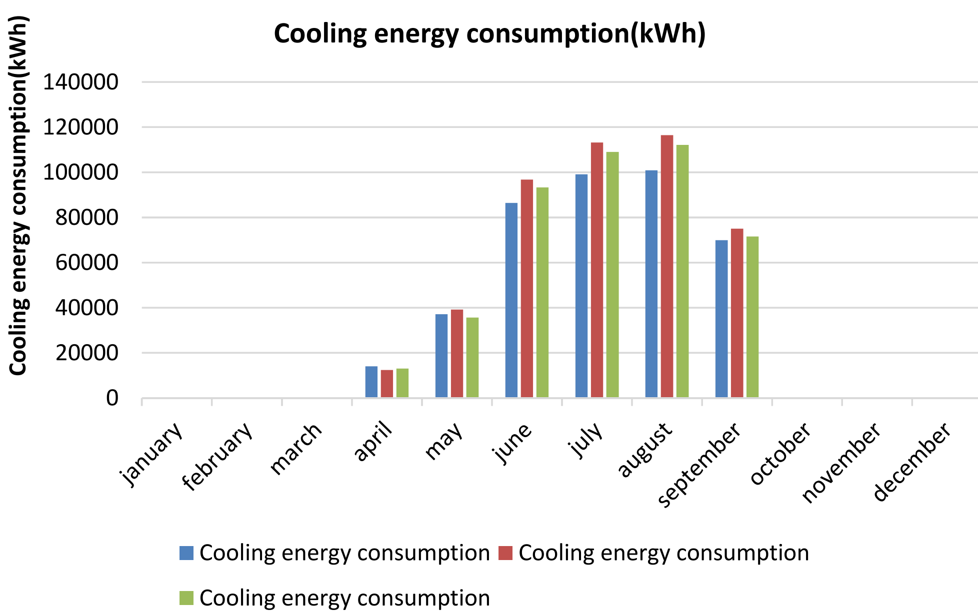


Fig. 7. Cooling energy consumption of single, twin and quadruple atrium buildings in the first group of simulations

According to Table 10 and Table 11, which shows the system electricity consumption (cooling energy consumed), and the system's gas consumption (consumable heating energy), it can be concluded that in comparison to single atrium , the twin one consumes energy 20 percent more, and the quadruple one, about 11 percent.

Table 10. Comparison of electricity and gas consumption between the single and twin atrium

Total electricity and gas consumed	Electricity consumption (kWh)	gas consumption (kWh)	Total electricity and gas consumed (kWh)
Single atrium	769981/77	110474/1	880445/8
Twin atrium	970963/01	91967/48	1062930/493
Difference (percentile)	26	-16	20

Table 11. Comparison of electricity and gas consumption between the single and quadruple atriums

Total electricity and gas consumed	Electricity consumption (kWh)	gas consumption (kWh)	Total electricity and gas consumed (kWh)
Single atrium	769981/77	110474/1	880445/8
quadruple atrium	884865/02	93201/86	978066/9
Difference (percentile)	15	-16	11

3.2. The second group of simulations:

The second group of simulations contains five alternatives (single, twin, triple, quadruple and sextuple atrium buildings) that have the same distance of 15 m to the external wall of the building (Fig B.1 to Fig B. 5).

- According to the Figs.8 and 9, the annual energy consumption is increased from single to triple atriums and then decreases in quadruple and sextuple ones.
- Sextuple atrium has the best energy performance in winter and the triple atrium has the best energy performance in summer.
- As shown in the Figs.8 and 9 with the same distance to external walls and equal area and volume for atriums, annual energy consumption of single to sextuple atrium buildings does not show significant difference. We can explain that the equal area, volume and distance of atriums to external walls almost result in equal outputs.

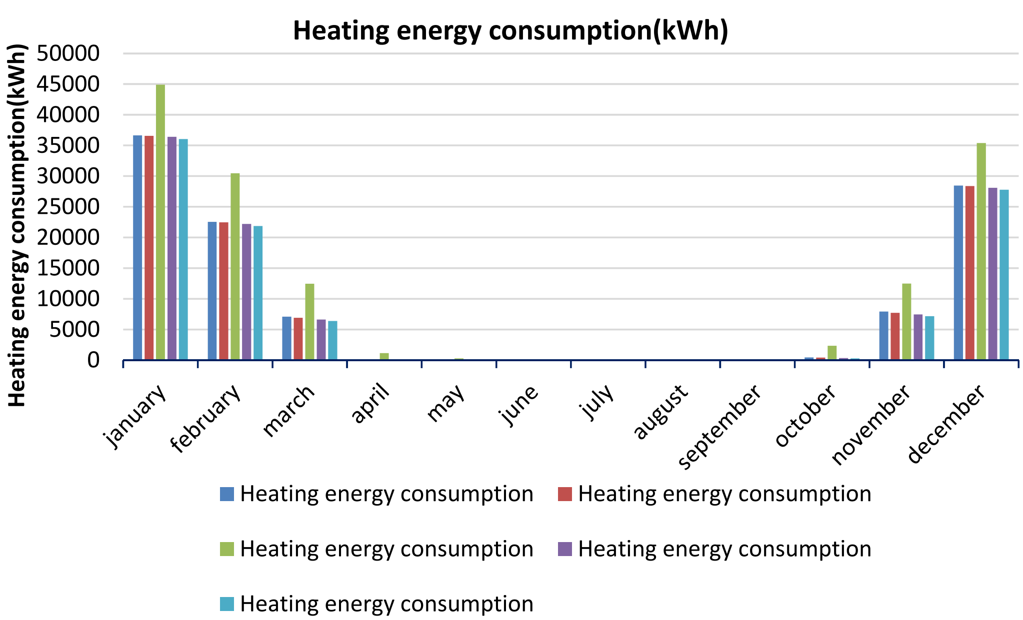


Fig. 8. Heating energy consumption of single, twin, triple, quadruple and sextuple atrium buildings in the second group of simulations

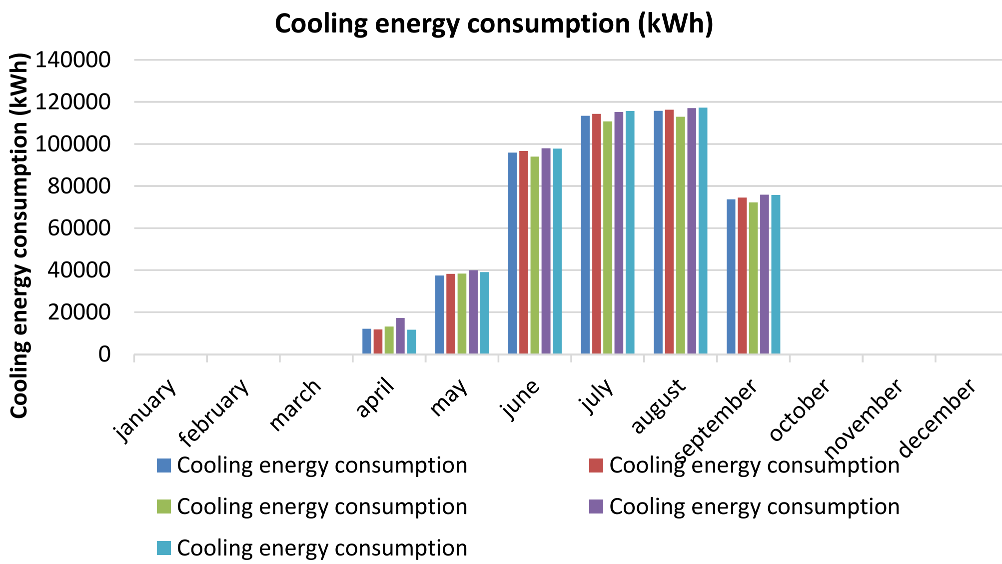


Fig. 9. Cooling energy consumption of single, twin, triple, quadruple and sextuple atrium buildings in the second group of simulations

- By increasing the ratio of perimeter (of all atriums in the building) to area (of all atriums in the building), the annual energy consumption increases from single to triple and then decreases in quadruple and sextuple atrium buildings (Fig. 10).

3.3.The third group of simulations:

Fig C. 1 to Fig C. 3 show the third group of simulation results. Figure 12 indicates the impact of the distance to the external walls in three single atriums; by increasing the distance, energy consumption is decreased. This can be explained that the distance between atriums and external walls play as isolations; in other words, the more the distance is, the thicker is the isolation and hence the less is the annual energy consumption. Of course the difference is not significant.

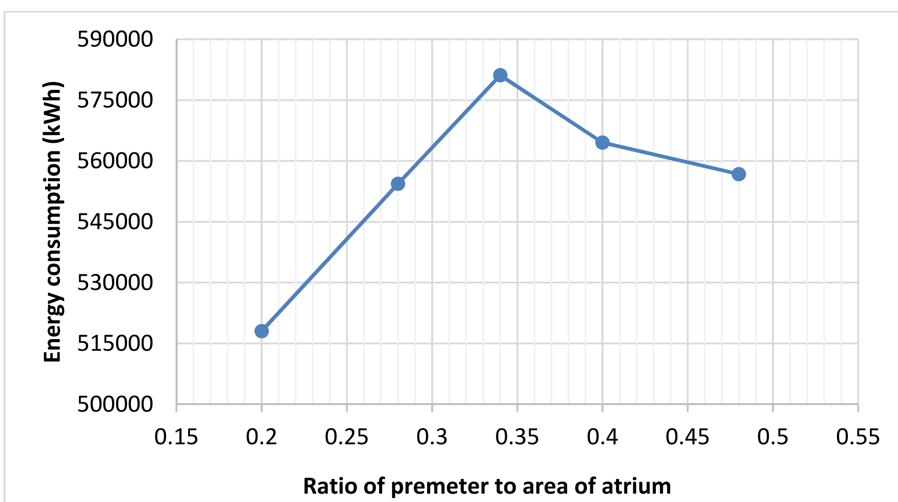


Fig. 10. Effect of perimeter to area ratio on the annual energy consumption: second group of simulations

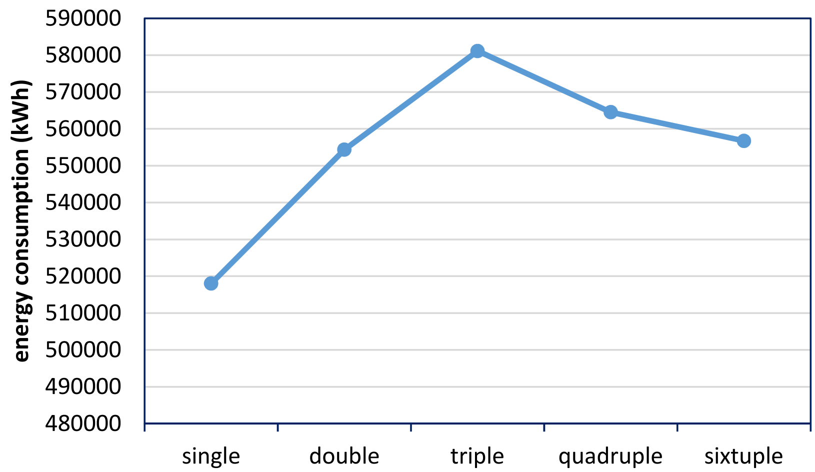


Fig.11. Total annual energy consumption: second group of simulations

According to Fig. 8 due to the unpredictable behavior of triple atrium in heating energy consumption, we sought for explaining this observation. The triple atriums are modeled in symmetrical and non-symmetrical configurations (Fig.13). The annual energy consumption of the first one has been less than that of the latter one. This demonstrates the impact of the distance to external walls on reduction of energy consumption.

4. Conclusion

In this study, we modelled a commercial-office building in DesignBuilder with single, twin, triple, quadruple and sextuple central atriums in different positions in the Tehran. The building and the atriums have equal volumes and areas. The focus of this study is on how different spatial configuration of atriums or the number of atriums in a building affect the energy consumption of building. The first group of simulation results (with different distances from atrium to external walls) show that a building with a single central atrium exhibits up to 11% less annual energy consumption than the quadruple one and 20% less than the twin central atriums.

The second group of simulations (equal distance from atrium to external wall) demonstrates that splitting the volume of one atrium into several atriums in a fixed distance from external walls, make the annual energy consumption increase from single to triple atriums and then decreases in quadruple and sextuple atrium buildings (Fig.11).

It could be concluded that with the same volume and area of atriums, the factors of distance between atriums, distance to the external walls and the ratio of perimeter to area have affected the energy consumption. In other words, the number of atriums and the spatial configuration of them affect the total energy consumption of buildings. As a matter of energy consumption, there is no significant limit for the number and spatial configuration of atriums with equal areas and volumes. According to this result, it is possible to decide whether to design a single or multiple atrium buildings with respect to important parameters of projects rather than the least energy consumption.

Building energy analysis with energy simulation software can help to make the right decisions at the early stages of design and then, plan the design process based on it. More detailed analyses can be done by field studies and the simulation results with real samples can be compared in future.

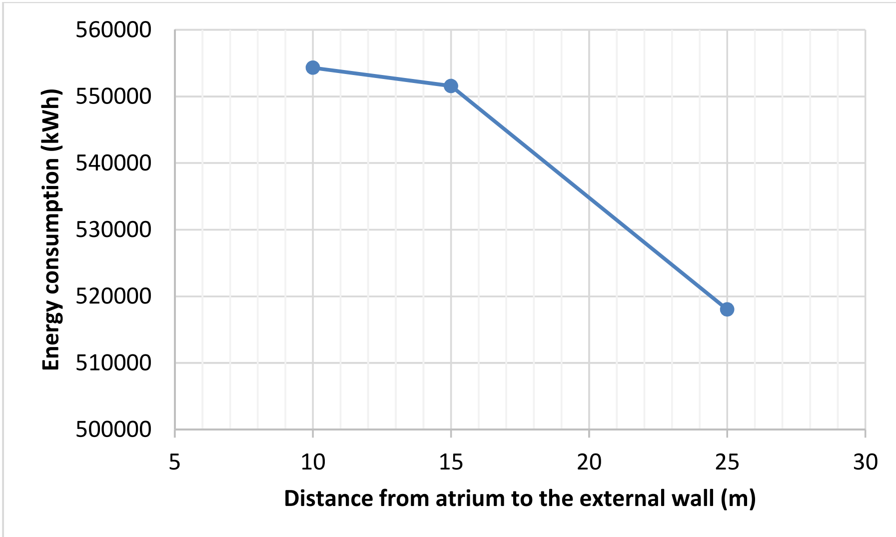


Fig. 12. Energy consumption in third group of simulations

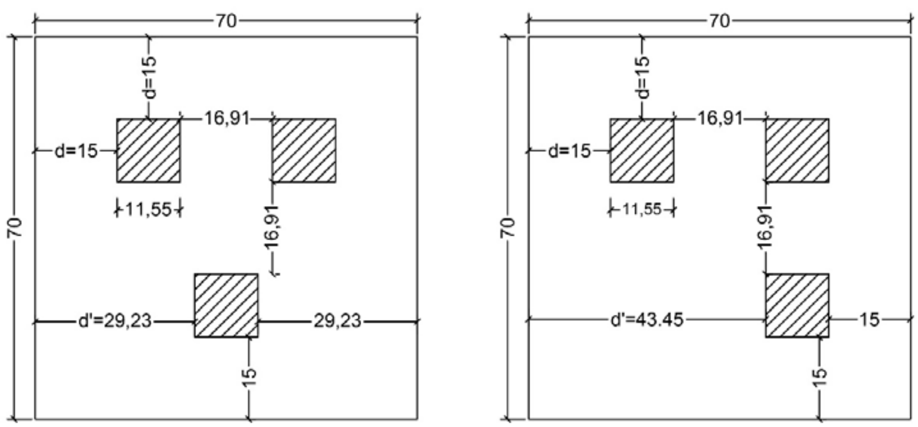


Fig 13. Symmetrical and non-symmetrical spatial configurations for triple atrium

References

[1] Aldawoud A., The influence of the atrium geometry on the building energy performance, Energy and Buildings (2013) 57: 1-5.

[2] Alzoubi H.H., Al-Zoubi A.H., Assessment of building façade performance in terms of daylighting and the associated energy consumption in architectural spaces: Vertical and horizontal shading devices for southern exposure facades, Energy Conversion and Management (2010) 51(8): 1592-1599.

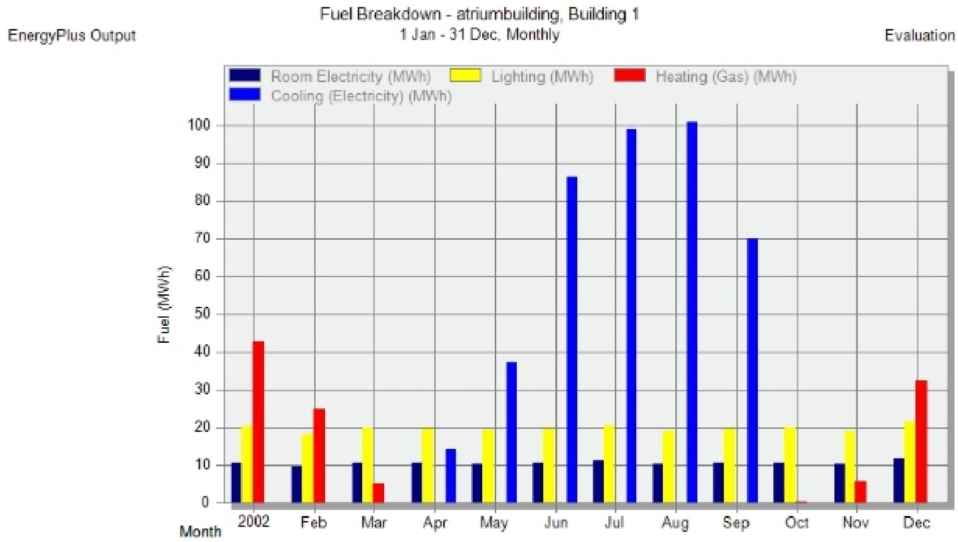
[3] Cantin F., Dubois M.-C., Daylighting metrics based on illuminance, distribution, glare and directivity, Lighting Research & Technology (2011) 43(3): 291-307.

[4] Lim Y.-W., et al., Empirical validation of daylight simulation tool with physical model measurement, American Journal of Applied Sciences (2010) 7(10): 1426.

[5] Rundle C., et al., Validation of computational fluid dynamics simulations

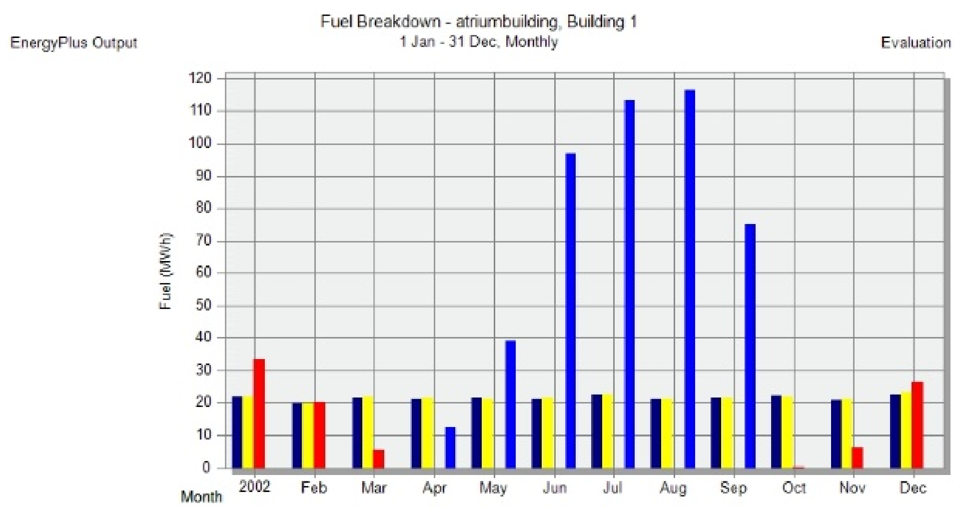
for atria geometries, Building and Environment (2011) 46(7): 1343-1353.
[6] Göçer Ö., et al., Thermal performance simulation of an atrium building, in Proceedings of eSim building performance simulation conference, Faculty of architecture, landscape, and design, University of Toronto, Canada (2006).
[7] Hussain S., et al., Evaluation of various turbulence models for the prediction of the airflow and temperature distributions in atria,Energy, and Buildings (2012) 48: 18-28.
[8] Nasrollahi N., et al., Appropriate Geometrical Ratio Modeling of Atrium for Energy Efficiency in Office Buildings, Journal of Building Performance (2015) 6(1).
[9] Liu P., et al., Evaluation of buoyancy-driven ventilation in atrium buildings using computational fluid dynamics and reduced-scale air model, Building and Environment (2009) 44(9): 1970-1979.
[10] Assadi M.K., et al., Analytical model of atrium for heating and ventilating an institutional building naturally, Energy and Buildings (2011) 43(10): 2595-2601.
[11] Fini A.S., Moosavi A., Effects of “wall angularity of atrium” on “buildings natural ventilation and thermal performance” and CFD model, Energy and Buildings (2016) 121: 265-283.
[12] Erlendsson Ö., Daylight optimization: A parametric study of atrium design, Y. Lisans Tezi. School of Architecture and the Built Environment, Stockholm (2014).
[13] Ghasemi M., et al., The influence of well geometry on the daylight performance of atrium adjoining spaces: A parametric study, Journal of Building Engineering (2015) 3: 39-47.
[14] Doheim R., et al., The impact of atrium shape on natural smoke ventilation, Fire safety journal (2014) 63: 9-16.
[15] Mohsenin M., Hu J., Assessing daylight performance in atrium buildings by using Climate Based Daylight Modeling, Solar Energy (2015) 119: 553-560.
[16] Du J., Sharples S., Daylight in atrium buildings: Geometric shape and vertical sky components, Lighting Research & Technology (2010) 42(4): 385-397.
[17] Tabesh T., Sertyesilisik B., An investigation into energy performance with the integrated usage of a courtyard and atrium, Buildings (2016) 6(2): 21.
[18] Radhi H., On the optimal selection of wall cladding system to reduce direct and indirect CO_2 emissions, Energy (2010) 35(3): 1412-1424.
[19] Lymath, A. (2015, February 01). What is a U-value? Heat loss, thermal mass and online calculators explained. Retrieved from https://www.thenbs.com/knowledge/what-is-a-u-value-heat-loss-thermal-mass-and-online-calculators-explained
[20] Ghiabaklou, Z, Fundamentals of building physics 5: Daylighting (2013) 88, ISBN 978-964-210-167-2, Jihad Amirkabir University.

Appendix A. First group of simulation results for annual energy consumption



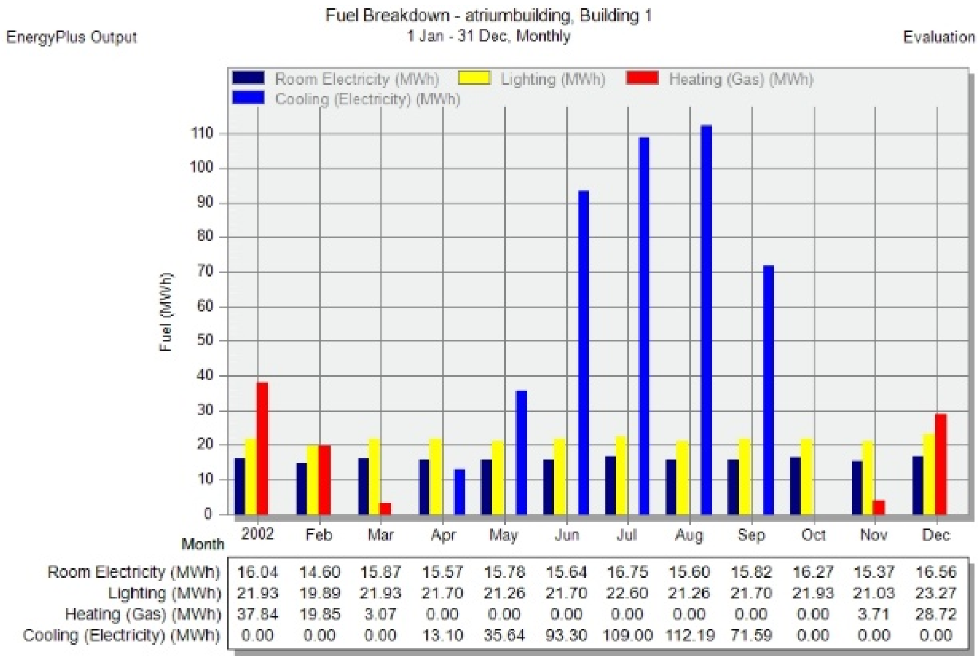
Month	2002	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Room Electricity (MWh)	10.62	9.65	10.62	10.62	10.13	10.62	11.10	10.13	10.62	10.62	10.13	11.58
Lighting (MWh)	20.19	18.13	19.88	19.65	19.15	19.50	20.38	19.10	19.52	19.90	19.11	21.49
Heating (Gas) (MWh)	42.49	24.77	5.13	0.00	0.00	0.00	0.00	0.00	0.00	0.02	5.62	32.44
Cooling (Electricity) (MWh)	0.00	0.00	0.00	14.10	37.11	86.46	99.12	100.87	69.89	0.00	0.00	0.00

Fig A.1. Single atrium



Month	2002	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Room Electricity (MWh)	21.77	19.82	21.53	21.12	21.45	21.21	22.75	21.19	21.47	22.10	20.87	22.44
Lighting (MWh)	21.93	19.89	21.93	21.70	21.26	21.70	22.60	21.26	21.70	21.93	21.03	23.27
Heating (Gas) (MWh)	33.53	20.03	5.54	0.00	0.00	0.00	0.00	0.00	0.00	0.19	6.28	26.39
Cooling (Electricity) (MWh)	0.00	0.00	0.00	12.43	39.18	96.74	113.24	116.42	75.07	0.00	0.00	0.00

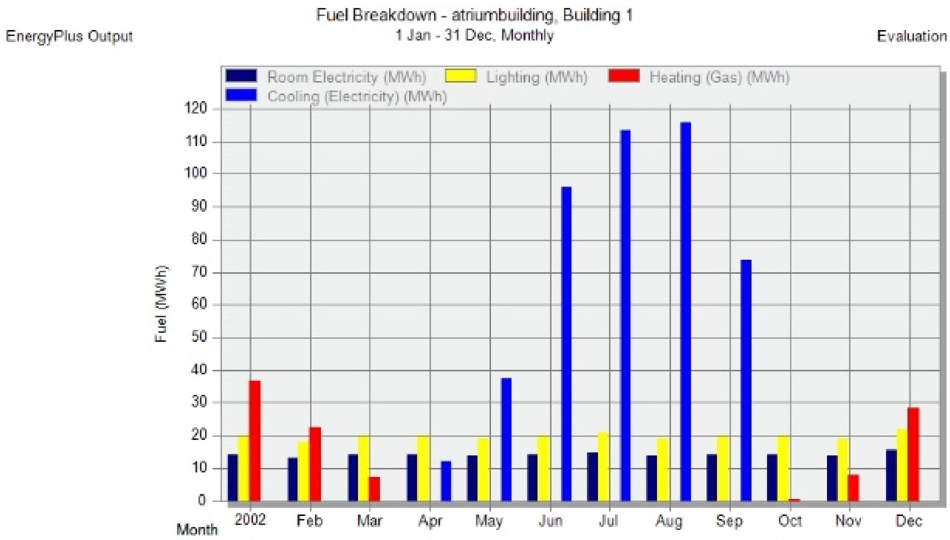
Fig A.2. Twin atrium



	2002	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Room Electricity (MWh)	16.04	14.60	15.87	15.57	15.78	15.64	16.75	15.60	15.82	16.27	15.37	16.56
Lighting (MWh)	21.93	19.89	21.93	21.70	21.26	21.70	22.60	21.26	21.70	21.93	21.03	23.27
Heating (Gas) (MWh)	37.84	19.85	3.07	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.71	28.72
Cooling (Electricity) (MWh)	0.00	0.00	0.00	13.10	35.64	93.30	109.00	112.19	71.59	0.00	0.00	0.00

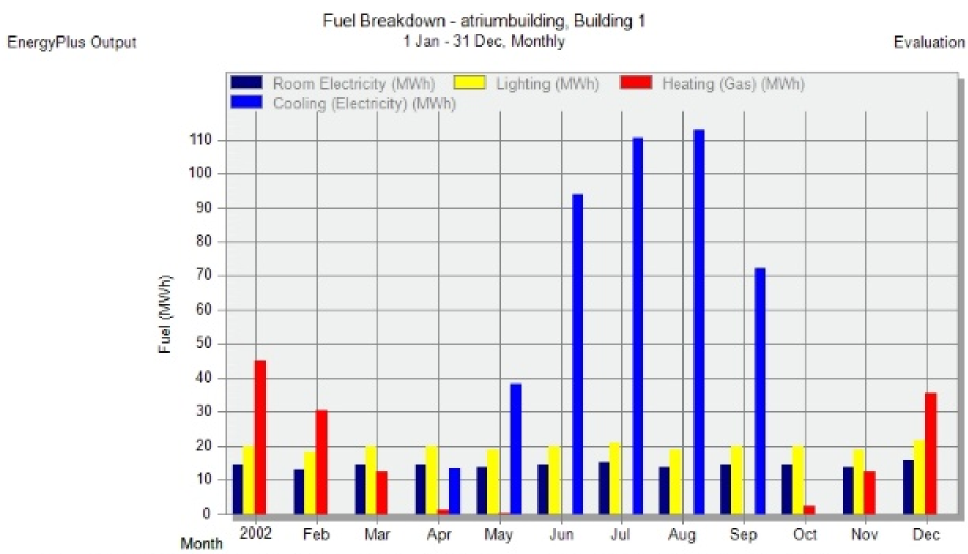
Fig. A.3. Quadruple atrium

Appendix B. Second group of simulation results for annual energy consumptions



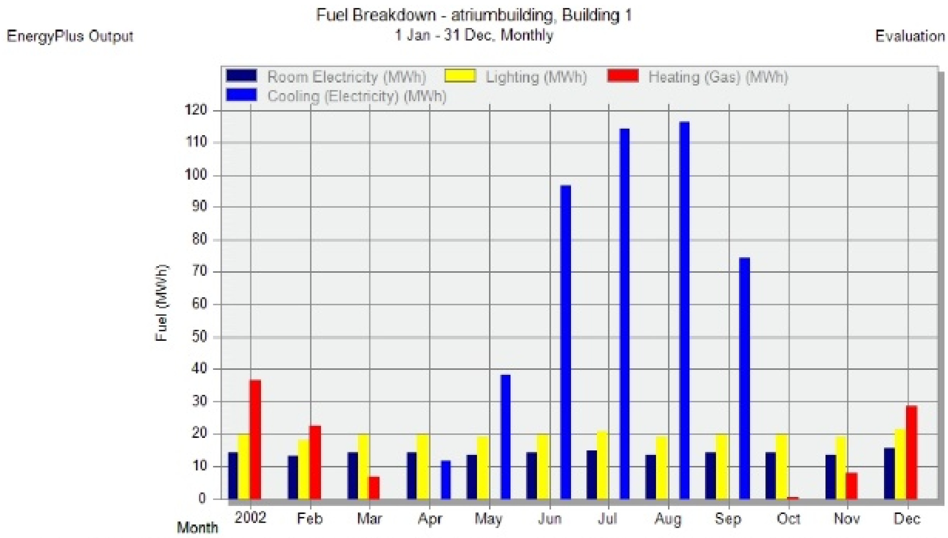
Month	2002	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Room Electricity (MWh)	14.26	12.96	14.26	14.26	13.61	14.26	14.90	13.61	14.26	14.26	13.61	15.55
Lighting (MWh)	19.83	18.03	19.83	19.83	18.93	19.83	20.73	18.93	19.83	19.83	18.93	21.64
Heating (Gas) (MWh)	36.65	22.56	7.07	0.00	0.00	0.00	0.00	0.00	0.00	0.44	7.91	28.47
Cooling (Electricity) (MWh)	0.00	0.00	0.00	12.17	37.49	95.87	113.39	115.81	73.72	0.00	0.00	0.00

Fig B.1. Single atrium



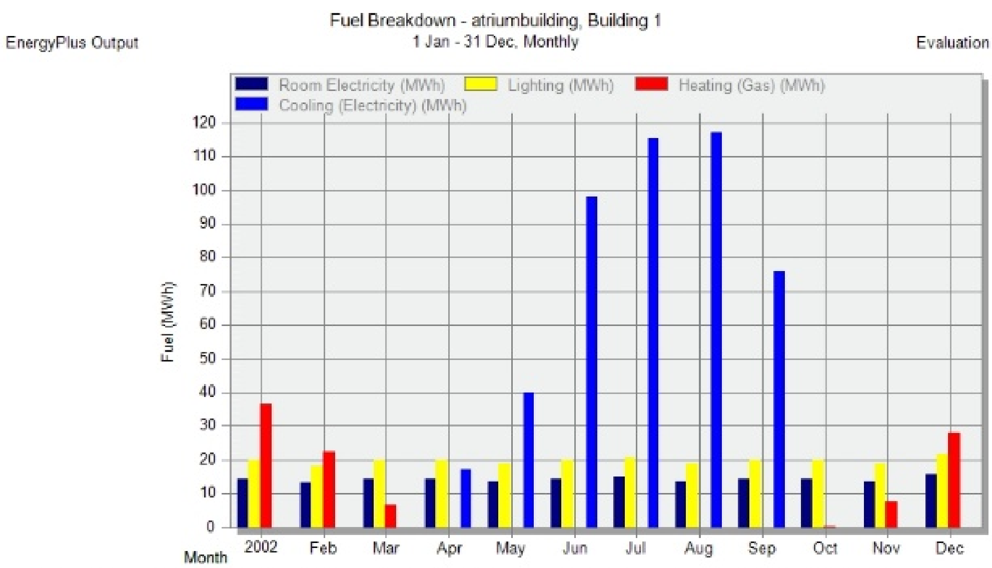
Month	2002	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Room Electricity (MWh)	14.57	13.25	14.57	14.57	13.91	14.57	15.24	13.91	14.57	14.57	13.91	15.90
Lighting (MWh)	19.83	18.03	19.83	19.83	18.93	19.83	20.73	18.93	19.83	19.83	18.93	21.64
Heating (Gas) (MWh)	44.91	30.48	12.46	1.15	0.28	0.00	0.00	0.00	0.00	2.34	12.48	35.41
Cooling (Electricity) (MWh)	0.00	0.00	0.00	13.25	38.37	94.06	110.72	112.91	72.30	0.00	0.00	0.00

Fig B.2. Twin atrium



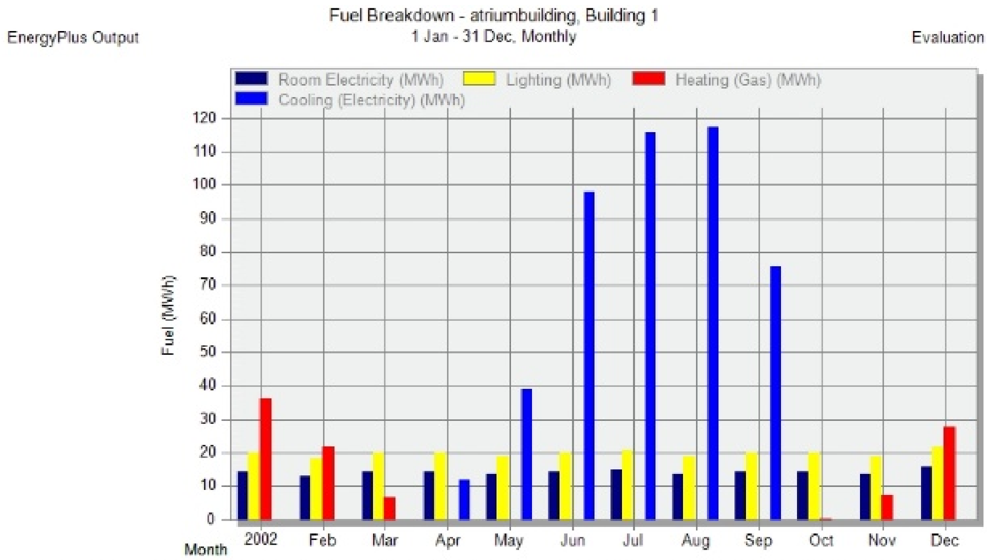
	2002	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Room Electricity (MWh)	14.26	12.96	14.26	14.26	13.61	14.26	14.90	13.61	14.26	14.26	13.61	15.55
Lighting (MWh)	19.83	18.03	19.83	19.83	18.93	19.83	20.73	18.93	19.83	19.83	18.93	21.64
Heating (Gas) (MWh)	36.57	22.47	6.90	0.00	0.00	0.00	0.00	0.00	0.00	0.40	7.72	28.39
Cooling (Electricity) (MWh)	0.00	0.00	0.00	11.88	38.21	96.68	114.27	116.33	74.51	0.00	0.00	0.00

Fig B.3. Triple atrium



	2002	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Room Electricity (MWh)	14.37	13.06	14.36	14.36	13.72	14.36	15.02	13.72	14.36	14.37	13.72	15.65
Lighting (MWh)	19.83	18.03	19.83	19.83	18.93	19.83	20.73	18.93	19.83	19.83	18.93	21.64
Heating (Gas) (MWh)	36.42	22.21	6.62	0.00	0.00	0.00	0.00	0.00	0.00	0.34	7.44	28.09
Cooling (Electricity) (MWh)	0.00	0.00	0.00	17.24	40.00	97.98	115.25	117.06	75.87	0.00	0.00	0.00

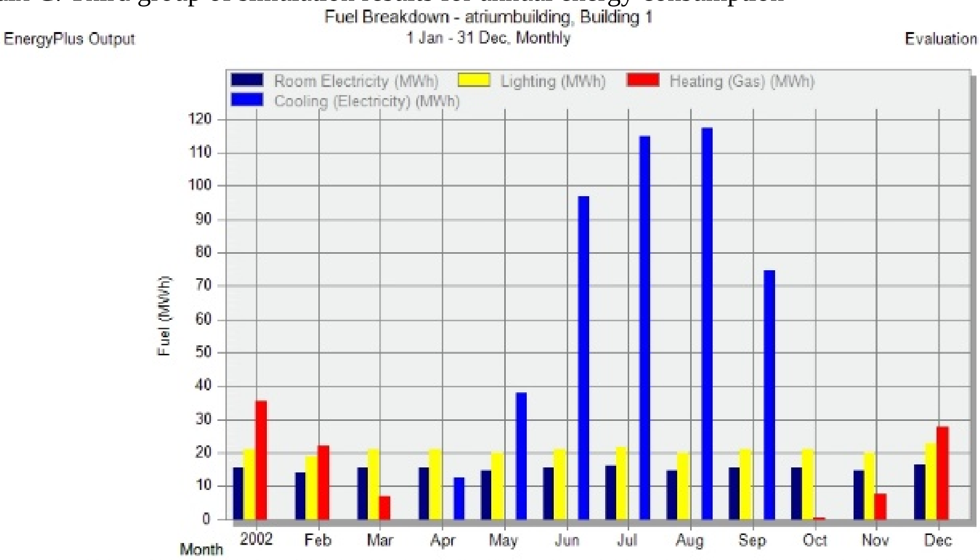
Fig B.4. Quadruple atrium



Room Electricity (MWh)	14.26	12.96	14.26	14.26	13.61	14.26	14.90	13.61	14.26	14.26	13.61	15.55
Lighting (MWh)	19.83	18.03	19.83	19.83	18.93	19.83	20.73	18.93	19.83	19.83	18.93	21.64
Heating (Gas) (MWh)	36.05	21.86	6.40	0.00	0.00	0.00	0.00	0.00	0.00	0.30	7.18	27.77
Cooling (Electricity) (MWh)	0.00	0.00	0.00	11.65	39.04	97.85	115.63	117.32	75.69	0.00	0.00	0.00

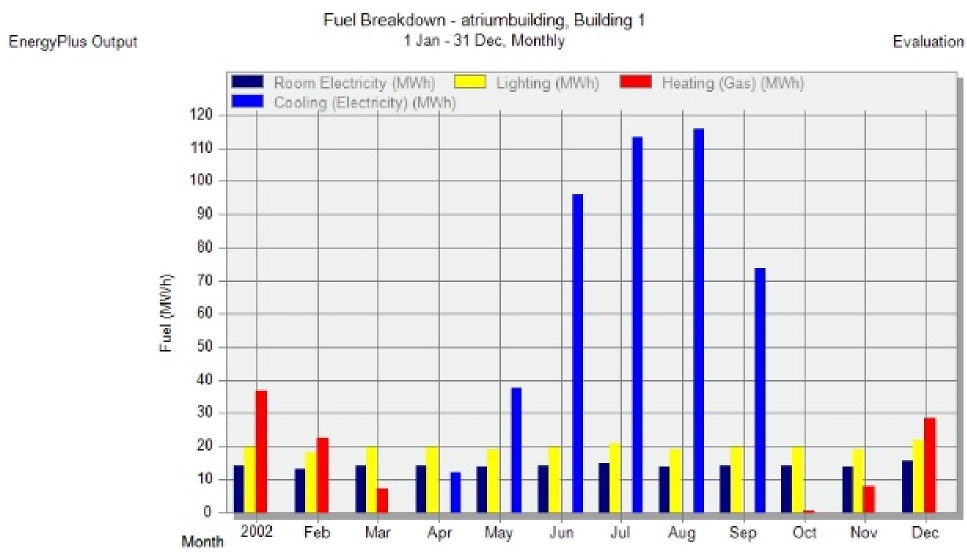
Fig B. 5. Sextuple atrium

Appendix C. Third group of simulation results for annual energy consumption



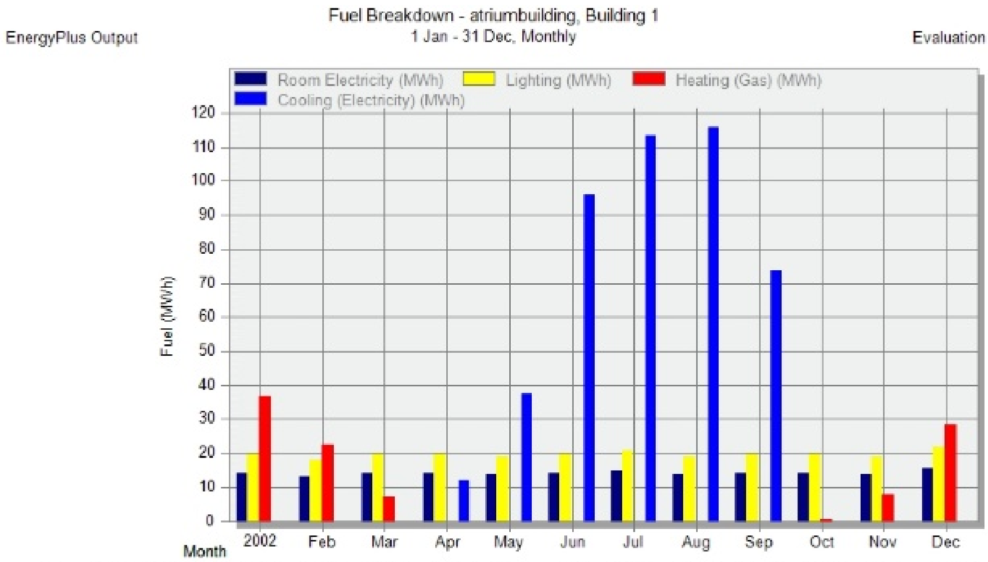
Month	2002	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Room Electricity (MWh)	15.21	13.82	15.21	15.21	14.52	15.21	15.90	14.52	15.21	15.21	14.52	16.59
Lighting (MWh)	20.89	18.99	20.89	20.89	19.94	20.89	21.84	19.94	20.89	20.89	19.94	22.79
Heating (Gas) (MWh)	35.60	22.03	6.89	0.00	0.00	0.00	0.00	0.00	0.00	0.41	7.70	27.63
Cooling (Electricity) (MWh)	0.00	0.00	0.00	12.41	37.94	96.98	114.80	117.35	74.57	0.00	0.00	0.00

Fig C. 1. Single atrium: d=10



Month	2002	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Room Electricity (MWh)	14.26	12.96	14.26	14.26	13.61	14.26	14.90	13.61	14.26	14.26	13.61	15.55
Lighting (MWh)	19.83	18.03	19.83	19.83	18.93	19.83	20.73	18.93	19.83	19.83	18.93	21.64
Heating (Gas) (MWh)	36.65	22.56	7.07	0.00	0.00	0.00	0.00	0.00	0.00	0.44	7.91	28.47
Cooling (Electricity) (MWh)	0.00	0.00	0.00	12.17	37.49	95.87	113.39	115.81	73.72	0.00	0.00	0.00

Fig C. 2. Single atrium: d=15



	2002	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Room Electricity (MWh)	14.26	12.96	14.26	14.26	13.61	14.26	14.90	13.61	14.26	14.26	13.61	15.55
Lighting (MWh)	19.83	18.03	19.83	19.83	18.93	19.83	20.73	18.93	19.83	19.83	18.93	21.64
Heating (Gas) (MWh)	36.64	22.56	7.07	0.00	0.00	0.00	0.00	0.00	0.00	0.44	7.91	28.46
Cooling (Electricity) (MWh)	0.00	0.00	0.00	12.19	37.50	95.85	113.36	115.78	73.71	0.00	0.00	0.00

Fig C. 3. Single atrium: d=25