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RESEARCH PAPER

Architectural Engineering

A Study of Optimal Area of Atrium for Daylight Utilization
(Case Study: Administrative Building in Qazvin, Iran)

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Abstract

Atrium has been used with various shapes and purposes in many different climates and buildings especially public ones. It is mainly used to take advantage of daylight in buildings. Therefore, achieving the optimal atrium dimensions is of great importance. This research employed computer simulation using Ecotect and Radiance for daylighting. The collected database is created using simulations for different atrium proportions in IRAN-Qazvin climate zone, where using atria could improve building performance based on the clear sky condition. The aim of present study is assessing the impact of atrium width and clerestory height on the amount of Average Daylight Factor (ADF) in different floors of horizontal top-lit atria and determining the appropriate geometrical sizes for the ten 5-storey, four-sided atriums to provide sufficient daylight in office spaces. Qazvin climatic conditions were simulated in Ecotect, Design Builder and Radiance. Ten 5-story administrative buildings with atrium ranging from 5%-50% area and one without atrium were modeled. The results showed that optimal samples were buildings with 10% and 15% atrium area in terms of daylight utilization.

Keywords: *Atrium, Daylight, Optimal atrium area, Radiance, Ecotect, Design builder.*

1. INTRODUCTION

The Architecture, Engineering, and Construction (AEC) and building sectors are major consumers of energy in all parts of the world. According to the 2014 report of the International Energy Agency (IEA), the building sector alone accounts for about 40% of energy use worldwide [1-2]. Due to changes in lifestyle and growing use of power-hungry appliances and home comfort systems, energy consumption in the Chinese building sector, for example, is set to reach 19-24×10^8 MJ by 2020 [3]. The efficient use of natural light (daylight) in combination with other sustainable lighting and thermal comfort solutions can greatly reduce the energy consumption of the building sector. But to allow in more daylight, architectural designs have to include larger natural lighting elements, which exacerbate heat gain and loss problems, thereby imposing greater heating and cooling loads [4]. Hence, dimensions, features, and orientation of natural lighting elements such as atriums should be carefully optimized for efficiency. Atriums are popular architectural elements with extensive use in residential, commercial, office, and educational buildings. By definition, an atrium should have at least one facade with enough transparency for the passage of daylight [5-6].

Daylight is a free and effective source of lighting. In places that direct daylighting is impossible, an atrium can be used to allow natural light into the interior [7]. Daylighting through atriums not only saves energy by reducing artificial lighting[8] but also offers the inhabitants significant psychological and ergonomic benefits [9-10]. Daylighting also improves the inhabitants' visual perception [11-12] and diurnal rhythms [13]. As a natural lighting element, atrium could be a viable solution not only for the architectural problems but also for the environmental problems caused by rising energy consumption in buildings [14]. The amount of daylight received through an atrium depends on its position, dimensions, and elevation and the distance of the measurement point from the transparent facade. In multi-story buildings with deep atriums (atriums with a low width or length to depth ratio), the upper floors receive too much light which may cause glare problems, but lower floors may still need artificial lighting for visual comfort

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[7, 15]. In reality, an atrium's contribution to energy saving depends on how much it actually reduces the use of artificial lighting in adjoining spaces [16]. The quality and quantity of daylight that an atrium provides to its adjoining spaces depend on the following factors [17]:

- The typical sky conditions (in terms of cloudiness) and the quantity of daylight that reaches the building
- The roof configuration, which affects the quantity and direction of daylight penetration. The intensity and distribution of daylight are also controlled by the atrium openings, the roof geometry and orientation and type of shading systems.
- The atrium type, geometry, and proportions (length, width, and height of the atrium)
- The atrium facade, the reflectance of its surfaces, the size and position of windows, and the use of innovative daylighting systems, which determine the quantity of light reflected into the adjacent and lower spaces.
- Properties of the adjoining spaces such as geometry, surface materials, furniture

One of the important applications of deep horizontal atriums is the daylighting of interior cores of multi-story buildings. But if poorly designed, these atriums can lead to excessive heat entrapment and thus an increased need for air conditioning [18]. As mentioned, one of the key parameters in the design of atriums is the atrium geometry Fig. 1. Hence, architects and researchers often try to optimize atrium geometry and dimensions for maximum energy saving in the building [19-21].

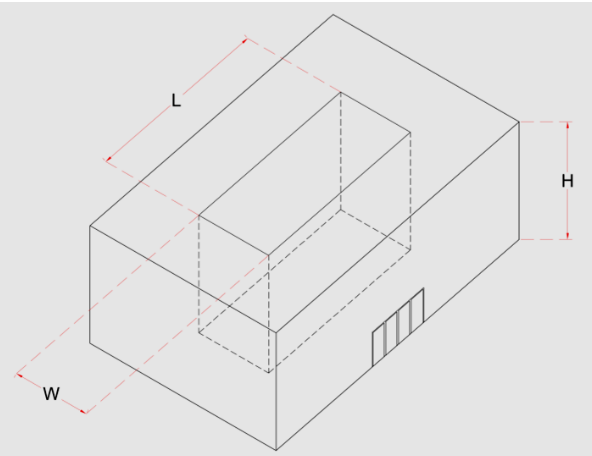


Fig. 1 Geometric parameters of an atrium

As mentioned earlier, geometry and proportions of an atrium play a key role in how it contributes to natural lighting within a building [22]. The quantity and quality of daylight provided by atriums have been the subject of several studies. These studies have shown that the upper parts of an atrium well (upper floors) often receive too much light to the point that glare becomes a common phenomenon, but the light received in lower floors is much more limited and strongly depends on the surface and floor reflectance [23-24]. It is notable that most of the studies on the daylighting performance of atriums are focused on the buildings located in temperate climates and northern latitudes. Regarding the atrium type, a research by Yunnes et al. (2010) has reported that horizontal atriums are the most frequently used variety of atriums in architectural designs [10]. In an investigation conducted in 2012, Daylight Factor (DF) was reported to be an excellent metric for the study of daylighting performance. This factor, which measures the diffusion of daylight, has been defined as follows [25].

$$\text{Daylight Factor (DF)} = \frac{\text{Indoor illuminance at a fixed point}}{\text{Outdoor illuminance under an overcast or uniform sky}} \times 100$$

Although the effect of atrium features and dimensions on the adjacent surfaces and indoor spaces has been extensively researched, too few studies have investigated these factors and their effects on the daylighting performance of atriums for buildings in Iran. Hence, the study of daylighting performance of atriums in typical climates of Iran can contribute to the more efficient use of this architectural element in Iranian buildings.

This study investigated the daylighting performance of horizontal atriums under overcast sky based on the 30-year climatic data pertaining to the city of Qazvin, Iran, in order to determine the optimal atrium area for office buildings in this city. For this purpose, the mean daylight factor in the atrium's adjoining spaces was estimated using the software packages of Ecotect, Design Builder, and Radiance.

According to the standards of Illuminating Engineering Society (IESNA RP-5-99), an average daylight factor of less than 2% means that the room is poorly lit and artificial lighting is necessary. In contrast, an average daylight factor of more than 5% means that the room is well lit [26]. According to the British standard of lighting for buildings (BS 8206 Part 2), the minimum acceptable value for daylight factor is 2%. If this factor is between 2% and 5%, the room requires artificial lighting. For artificial lighting not to be required during the day, the room has to have a daylight factor of more than 5% [27]. According to the guideline of Chartered Institution of Building Services Engineers (CIBSE), if average daylight factor is 5% or more, the room receives more than sufficient lighting during the day except around early morning and late afternoon. But if daylight factor is 2% or less, the room must be categorized as poorly lit and be given proper artificial lighting [28].

2. METHODOLOGY

Several computer simulations were performed based on the climatic conditions of Qazvin, Iran in order to measure the daylight factor of the buildings with horizontal atriums that are located in this area.

Daylight simulations were performed in Ecotect, Design Builder, and Radiance. Ecotect is able to model various buildings and simulate factors such as sunlight, daylight, energy, shading, thermal load, acoustic comfort and various costs for a certain building or a set of buildings. Using this software package, designers can evaluate the building performance at very early stages of design [28]. Compared to v4, Design Builder v5.5 enjoys a substantial set of additional features and improvements including significant productivity for LEED and ASHRAE 90.1 PRM work, Climate Based Daylight Modelling, graphical visualization of simulation results on the model and new Scripting tools for customizing Energy Plus simulations. Radiance is an accurate simulation engine operating based on Backward Retrace, which is capable of providing 3D interior images and calculating and displaying lighting conditions on a screen. It can also prepare the data for transferring the calculations to Ecotect [29]. Accuracy and validation of Radiance analyses have been verified in numerous studies, which have shown close correlations between the results of physical tests and the simulation results of this software [30].

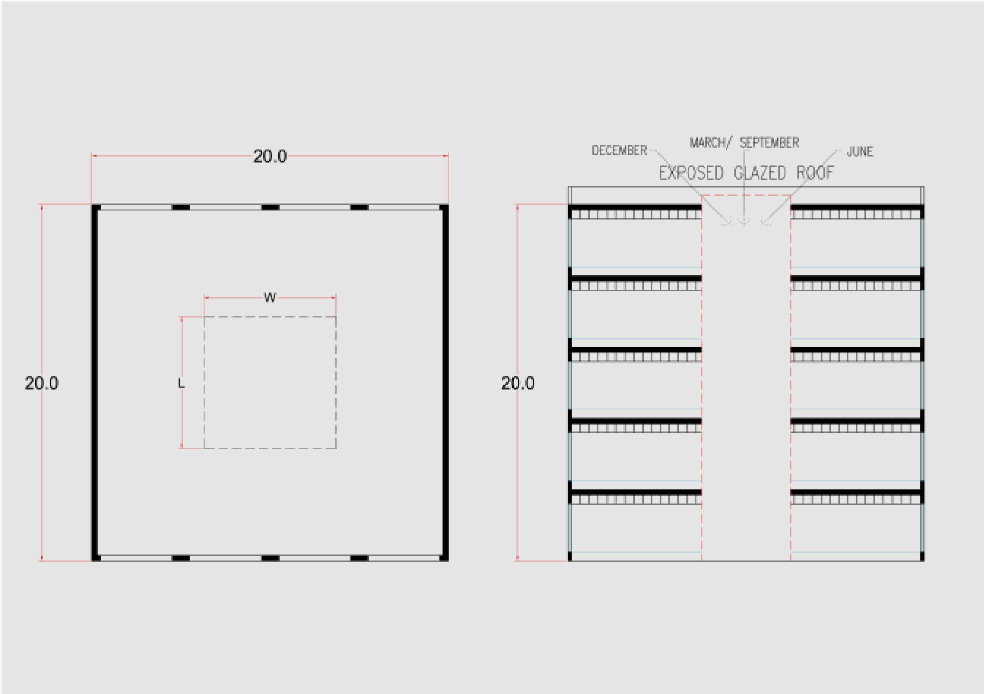


Fig. 2 Plan and cross-section of the atrium model

3. SIMULATED MODEL

For simulation, a 5-story building without atrium and ten 5-story buildings with atrium/floor area ratios of between 5% and 50% were modeled Fig. 2. The buildings were assumed to be exposed in north and south sides and enclosed in east and west sides. In the northern and southern facades, the ratio of the opening area (windows) to the total area was 42%. Window and floor heights were considered to be 90cm and 400cm, respectively. Overall, each building was 20 meters tall. All models were built with brick walls with a reflectance coefficient of 0.561 and double-glazed windows with aluminum frames and a light transmittance coefficient of 0.639. Climatic data of Qazvin were introduced in the WEA format. The sky setting was set to Overcast. The building was assumed to be dedicated to office use with open rooms. The height of the analysis grid was set equal to the desk height (70 cm) so that daylight factor would be calculated at this height. Daylight factor simulation was performed for each building separately so as to avoid interfering effects from other buildings. A total of 61 analyses were performed to compute daylight factor at floors and cross-sections. Tables 1 and 2 show the results of these analyses.

Diagram 1 illustrates the hourly historical weather data for Qazvin for the 30-year period from 1987 to 2017. In this diagram, the "mean daily maximum" (solid red line) represents the maximum temperature of an average day in every month. Likewise, the "mean daily minimum" (solid blue line) represents the average minimum temperature. Hot day and cold night temperatures (dashed red and blue lines) are the average temperatures of the hottest day and coldest night of each month over the 30-year period.

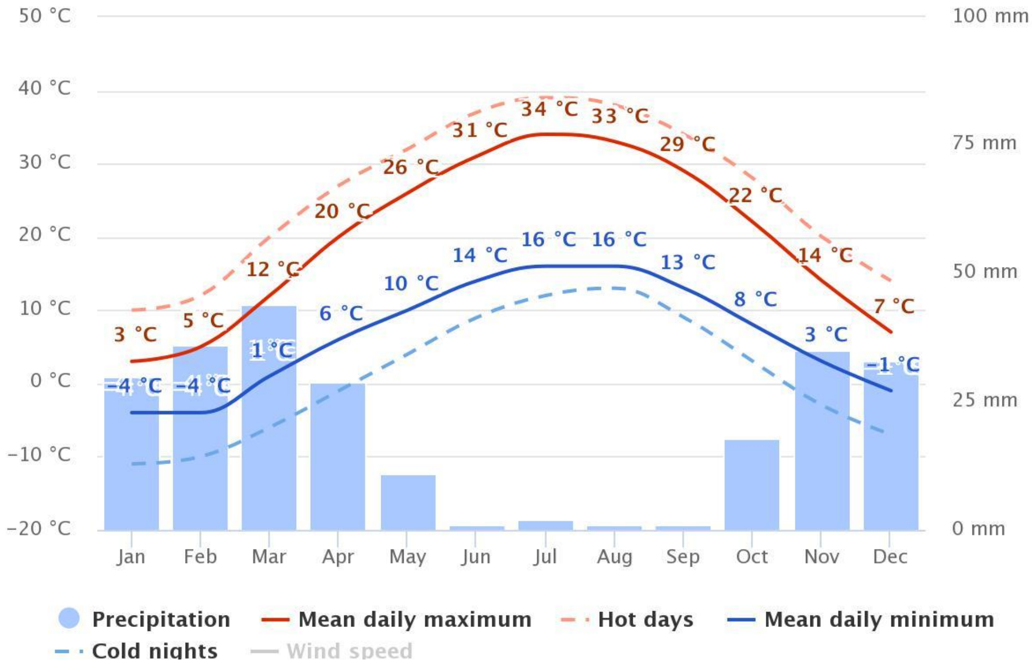


Diagram 1 30 years of hourly historical weather data for Qazvin-Iran (in WEA format)

4. DAYLIGHT SIMULATION AND ANALYSIS

As can be seen in Fig. 3 (left), because of the poor distribution of daylight in the ground floor of the building without atrium, the daylight factor in this floor reaches as low as 1.25 near the middle of the room; however, it is over 4.4% near the windows. On average, the daylight factor of this room is about 1.7%. Hence, it is clear that while areas around windows receive good daylight, the middle of the room is poorly lit and requires artificial lighting during the day. Next, we investigated the daylight conditions in the interior spaces of the buildings modeled with atriums with different atrium/floor area ratios.

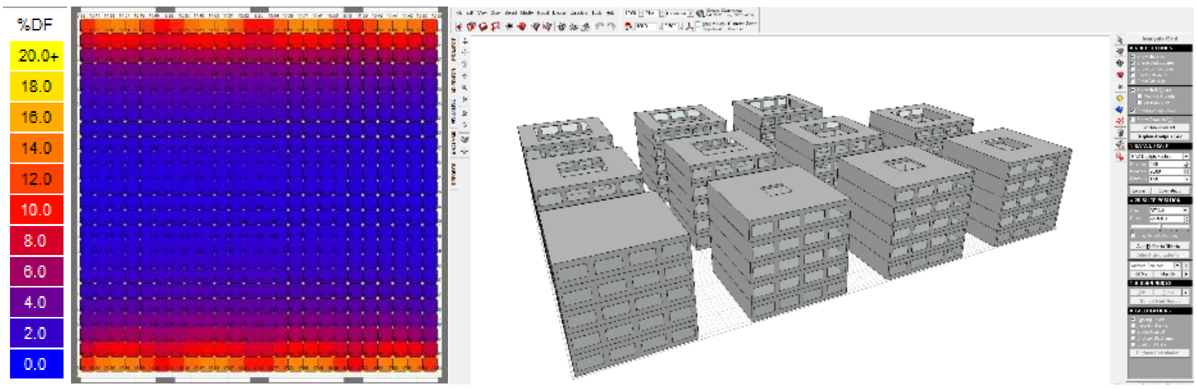
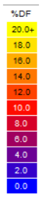
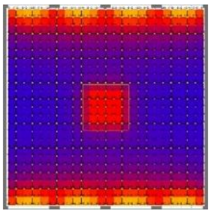
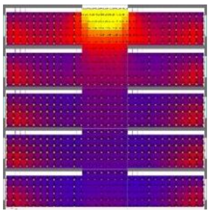
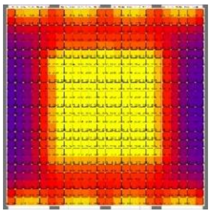
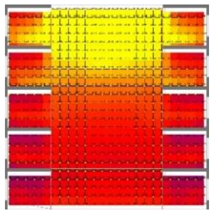
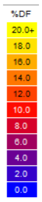
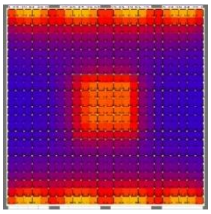
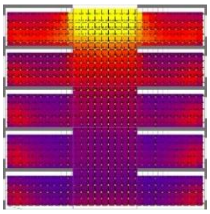
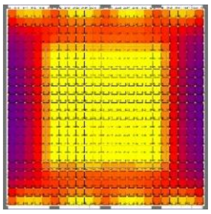
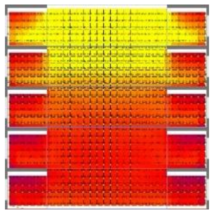
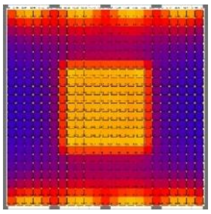
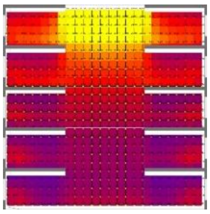
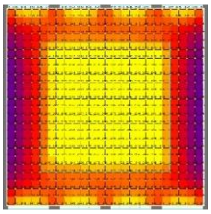
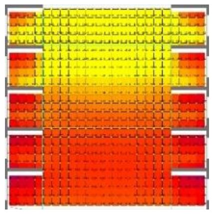
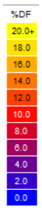
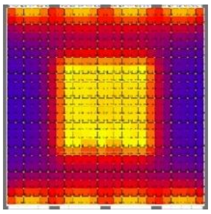
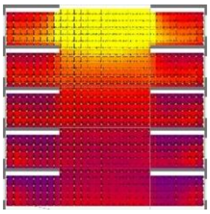
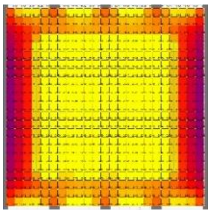
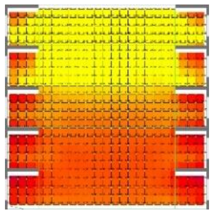
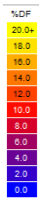
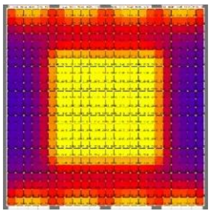
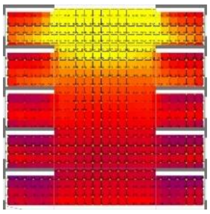
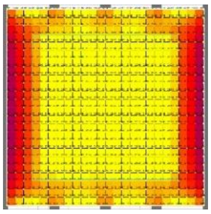
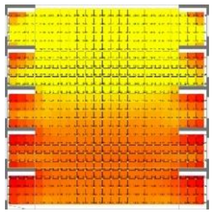


Fig. 3 Models simulated in Ecotect (right), daylight factor in the ground floor of the building without atrium (left)

Table 1 shows the daylight factor in the ground floor and cross-sections of the buildings. As can be seen, the lowest daylight factor at desk height (1.8%) is observed in the ground floor of the model with the atrium/floor ratio of 5%. While still being unacceptable, these factors signifies better lighting conditions compared to the building without atrium. In the buildings with the atrium/floor ratio of 10% and 15%, the minimum daylight factor was computed to be 2.1% and 2.2%, respectively. In the building with the atrium/floor ratio of 50%, the minimum daylight factor reached as high as 5.4%. As the light analysis of cross-sections indicates, the interior daylight increases as we move toward the upper floors.

Table 1 Average daylight factor in floors and cross-sections of the buildings with atrium

Guideline	Atrium/floor Area Ratio	Distribution of daylight factor in ground floor	Distribution of daylight factor in cross-section	Atrium/floor area ratio	Distribution of daylight factor in ground floor	Distribution of daylight factor in cross-section
	5%			30%		
	10%			35%		
	15%			40%		
	20%			45%		
	25%			50%		

In Diagrams 2 and 3, a quantitative comparison is made between the lighting conditions and daylight factor of different floors. These diagrams show the average daylight factor obtained for different floors from Ecotect and Design Builder analyses. As can be seen, the average daylight factor is over 5%, which satisfies the IES and BS standards for good lighting. As stated earlier, in atrium/floor ratios of less than 5%, daylight factor of some areas reaches as low as 1.8%, which means the room needs artificial lighting. Given the adverse effects of having too much daylight in the interior spaces, the atrium/floor ratios of between 20% and 50%, which produce excessively large daylight factors, cannot be considered desirable.

As can be seen by comparing Diagrams 2 and 3, there is not much difference between the computer analyses of Ecotect and Design Builder.

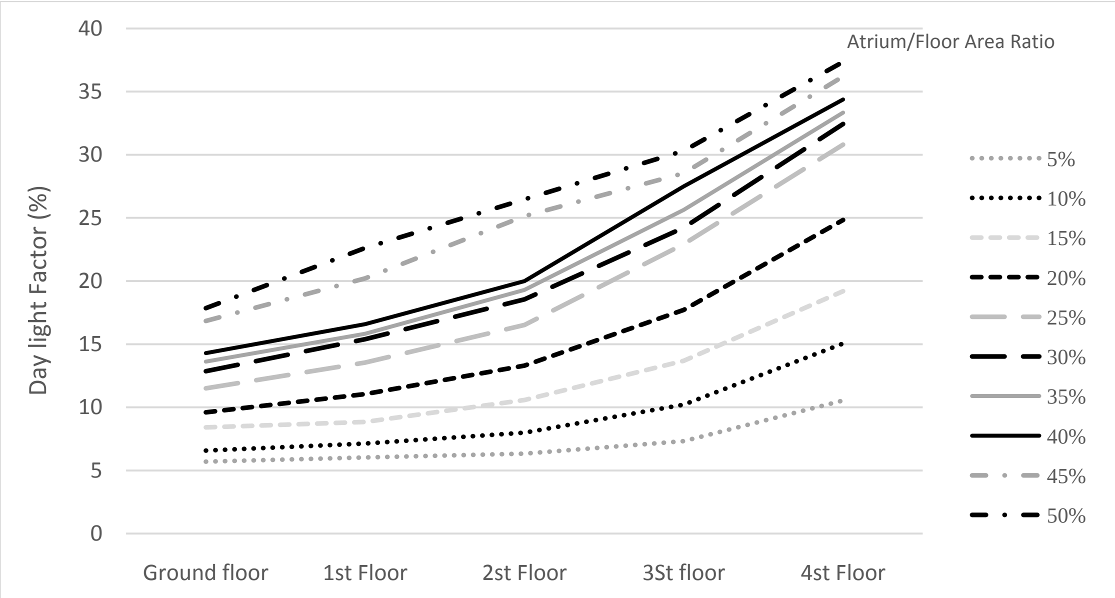


Diagram 2 Average daylight factor at the height of 70cm from the room floor in the buildings with different atrium/floor ratios (in the Ecotect analysis)

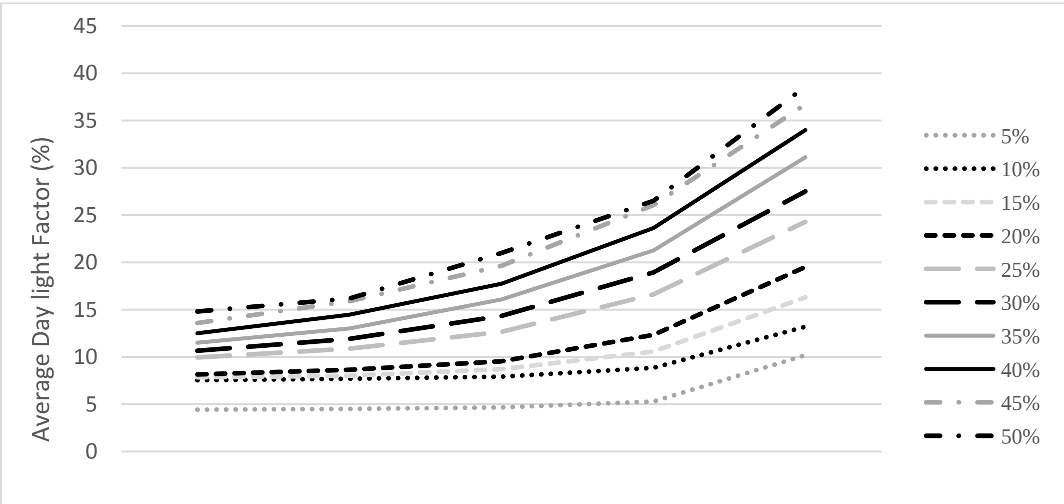


Diagram 3 Average daylight factor at the height of 70cm from the room floor in the buildings with different atrium/floor ratios (in the Design Builder analysis)

5. CONCLUSION

The results of this study showed that increasing the atrium dimensions without changing the ratio of atrium area to floor area leads to a sharper increase in the daylight factor of upper floors than that of lower floors. On the other hand, constructing larger atriums can lead to excessive daylighting of the interior spaces, especially on the upper floors. This excessive light may result in glare problem and visual discomfort and exacerbate heat gain by solar radiation, thus imposing an extra cooling load on the building. The simulation results obtained from Ecotect, Design Builder and Radiance based on the climatic data of Qazvin showed little difference in their estimations of average daylight factor. In fact, there was more than 90% accordance between the simulation results obtained from these software packages. The results showed that the daylighting performance in an atrium's adjoining spaces is non-uniform and varies with the floor. Also, increasing the ratio of atrium/floor area increased the visible sky angle, and consequently the amount of the received daylight. According to the results of this study, in order to provide enough daylight without imposing an extra cooling load, horizontal atrium should constitute 15-20 percent of the total floor area. Since it is not feasible to construct a real model of this research in the country at present, we have been focusing on software analytics; but as a research in the future, the present study could be studied in the form of a laboratory model comparing its results with the present study.

CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

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