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Skylight Sizing based on balancing Daylighting Performance and Visual Comfort in Atrium Buildings

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Abstract. As one of the most traditional and ubiquitous elements in architecture, atrium design has remained an imperative topic. With the growing concerns of energy conservation, carbon emission, comfort, and well-being recently, atrium design optimization to match the new crises and demands becomes a big challenge. This study investigated the impact of atrium shapes and building heights to daylighting performance. It was found that round atrium performs the best, next is square, and the worst one is the rectangle. And the higher the buildings are, the worse the daylight performance is. To further guide design work, generic atrium design criteria from a view of balancing daylight performance and visual comfort was proposed. The more reliable and valid annual dynamic simulation methods and climate-based daylighting modeling metrics are adopted.

Keywords: skylight sizing; atrium; daylighting; visual comfort; simulation

1. Introduction

Daylighting is a fundamental, primary and historic element in the architectural design. With the worldwide efforts in energy conservation and well-being nowadays, daylighting is brought to a new level. The benefits and advantages of daylighting have been examined and illustrated by a body of studies. Generally summarized is energy saving and health. The energy saving here is a broad-sense concept, could be expanded to economics, carbon emissions and global warming etc.[1-6]. For instance, Energy Center of Wisconsin indicated that a 22% annual lighting and HVAC cost savings were achieved by using daylighting in an experiment. A survey produced by Southern California Edison reported that the saving range of daylight was between 6% and 80% [1]. In the aspect of health, by hundreds of literature review, Edwards and Torcellini demonstrated that daylight could enhance learning efficiency, improve learning outputs, reduce patients' recovery time and increase turnover[5]. Evidence presented in studies that daylight plays a crucial role in vitamin D producing, which has a close relation to diseases like rickets, osteomalacia, depression and possible cancers[1, 6]. Besides, daylighting is also good to sleep quality and productivity.

Due to the prominent ability to draw daylight deep into the core of the building, atrium has become a ubiquitous architectural component in many building types [3, 7-9]. A number of investigations on atrium daylighting have been carried out in previous research, but most are focused on the office building, therefore, there is a strong demand on extending the study area to other types of building [10-12]. In other hands, along with the maximum of the glazing portion, unexpected discomfort glare is growing at the same time, so how to balancing these two ambivalent factors becomes a challenge. As a result, this study chooses commercial building type as object, to exam the relationship of atrium shape and glazing proportion to daylight performance, thereby further propose a skylight sizing criteria from a view of balancing daylighting illuminance level and discomfort glare for atrium design.



1.1. Daylighting assessment

Various daylighting performance investigating methods are developed in the past, which could be generalized into four types: Scale models, Mathematical models, Full-scale models, and Computer simulations [13-17]. Among all these methods, full-scale models are the most expensive, difficult and time-consuming one to implement because of full-size building construction while the results are always the most reliable and practical. By contrast, building of scale models is much easier in cost, but more technical issues raised up in a daylighting model along with the size scaling, like the geometry, material choice, furniture, etc. Previous research has shown that the data simulated from reliable software is highly in accord with the site measurement[15, 18], plus the economic, time effective and realistic visualization, etc. characteristics, computer daylight simulation has become a trend and popular tool currently [13]. Survey indicates that the total number of daylighting simulation program has reached to about 42 [4], which can be classified into two categories generally, static simulation and annual dynamic simulation. Ecotect and Radiance are two typical and frequently used static modeling tool, annual dynamic simulation tools are developed in recent decades, DAYSIM and DIVA for Rhino are good examples.

1.2. Daylighting Metrics

1.2.1. Illuminance. Along with the exploration on daylighting, two main kinds of daylighting evaluating metrics are formed, Static Daylight Modeling Metrics and Dynamic or Climate-Based Daylight Modeling Metrics. Daylight factor (DF) was first developed in the early of the 20th century by Moon and Spencer in 1942, is the most traditional and prevalent static metric to predict daylight in building regulations. It is defined as the ratio between the daylight illuminance level at a target indoor point and the outdoor illuminance on the ground in the International Commission on Lighting (CIE) overcast sky mode[1]. However, this simple and easy method exists many limitations, for instance, avoidance of seasonal variations, time variations, and different sky conditions etc.[3, 19]. An example is that clear sky usually rarely appears in many places, like Boston[19]. In last decades, a series of time and climate based metrics emerged, which remedy the limitations of static daylight modeling metrics appropriately, is called Dynamic or Climate-based Modeling Metrics. The calculation span over the entire year and take the solar radiation data of the building located in. A couple of these metrics are as below:

- Daylight autonomy (DA): the percentage of a given time frame of a year when a minimum illuminance on a workplace is met by daylight[3, 18].
- Spatial daylight autonomy (sDA): is based on the floor area percentage instead of time percentage, represents the ratio of the floor area that reach the certain illuminance level for a specified amount hours. One frequently used indicator is $sDA_{(300,50\%)}$, which means the space percentage with over 300lux illuminance level for more than 50% time in the schedule[3, 20, 21]. This method usually is used to evaluate the daylight availability of a daylight space.
- Maximum Daylight Autonomy (DA_{max}): presents the area with illuminance is ten times than the target illuminance level, usually 5% of time is used as the line, which means when the sensor receiving over ten times illuminance is greater than 5% of the annual schedule time, it counted as maximum daylight autonomy[21, 22]. This indicator could be a kind of benchmark for uncomfortable high illuminance or glare.
- Useful daylight illuminance (UDI): calculates the time percentage of the interior daylight illuminance which within a specific range, 100 lux to 2000 lux[3, 18, 21, 23, 24]. As the name states, this approach suggests the illuminance both lower than 100 lux and over 2000 lux is not merited to consideration due to the poor visibility and visual discomfort, which was also the first metric to take visual comfort into daylighting modeling considerations[1].

1.2.2. Glare. Glare is the concept to measure the physical discomfort for light. To quantify the glare, a number of indices are developed during the past years, such as Daylight Glare Index (DGI), CIE Glare Index (CGI), Visual Comfort Probability (VCP), Unified Glare Rating (UGR) and Daylight Glare

Probability (DGP). As these metrics is invented from diverse experimental conditions, in different methods, and for various intentions, select an appropriate metric is still difficult. According to Jakubiec and Reinhart (2012), DGP is the most recommended one among all the above indices after a detail theoretical analysis and a computer-based software simulation[19], however, one nonnegligible limitation is that the glare calculation should base on a certain point and one specific view direction, so it is actually hard to interpret that how about if the occupant changing a position or facing to another direction.

2. Methodology

Annual dynamic and climate-based computer simulation was utilized as the major method of this study. Program DIVA for Rhino was entirely used, which is a highly advanced annual daylighting modeling plug-in. Its daylight performance calculation is based on Radiance backward ray tracing techniques, while discomfort glare evaluation utilizes Evalglare to calculate glare indices. It was initially developed at Harvard University and has been trusted and validated by the industry[21, 25].

2.1. Model description

Generic shape, dimensional proportions, and fenestration system are three main determinants to an atrium. According to the taxonomy of rectilinear form developed in 1980s, atrium can be identified by four types: four-sided atrium, three-sided atrium, and two-sided or linear atrium. Four-sided enclosed atrium is chosen as the study object, three most common forms, Rectangle, Square and Round, are taken in account, as illustrated in Figure 1.

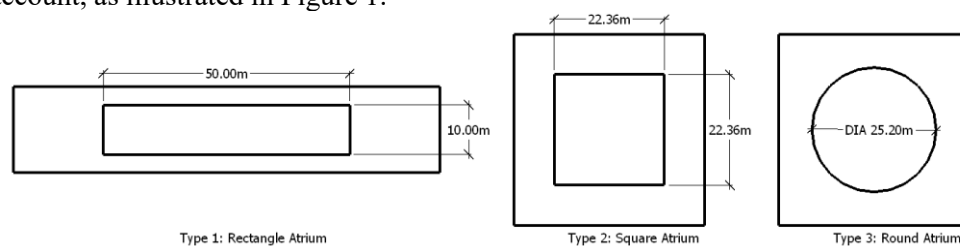


Figure 1. Plan of different type of atrium.

The variable is the percentage of skylight glazing area to atrium roof area. Meanwhile, five variations of building heights from 24m to 56m were set for each atrium type. Table 1 shows all the detail model information.

Table 1. Model variation of Rectangle, Square and Round atrium type.

Atrium Type	Height (m)	Atrium Size (Length/Width, m)	Skylight Size (Length/Width, m)				
			20%	40%	60%	80%	100%
Rectangle	24	10/50	4.47/22.36	6.32/31.62	7.75/38.73	8.94/44.72	10/50
	32	10/50	4.47/22.36	6.32/31.62	7.75/38.73	8.94/44.72	10/50
	40	10/50	4.47/22.36	6.32/31.62	7.75/38.73	8.94/44.72	10/50
	48	10/50	4.47/22.36	6.32/31.62	7.75/38.73	8.94/44.72	10/50
	56	10/50	4.47/22.36	6.32/31.62	7.75/38.73	8.94/44.72	10/50
Square	24	22.36/22.36	10/10	14.14/14.14	17.32/17.32	20/20	22.36/22.36
	32	22.36/22.36	10/10	14.14/14.14	17.32/17.32	20/20	22.36/22.36
	40	22.36/22.36	10/10	14.14/14.14	17.32/17.32	20/20	22.36/22.36
	48	22.36/22.36	10/10	14.14/14.14	17.32/17.32	20/20	22.36/22.36
	56	22.36/22.36	10/10	14.14/14.14	17.32/17.32	20/20	22.36/22.36
Round	24	12.6	5.6	8	9.8	11.3	12.6
	32	12.6	5.6	8	9.8	11.3	12.6
	40	12.6	5.6	8	9.8	11.3	12.6
	48	12.6	5.6	8	9.8	11.3	12.6
	56	12.6	5.6	8	9.8	11.3	12.6

To keep the comparability among three types, assume atrium floor area of the three models the same, adjoining space area is in a fixed ratio with the atrium floor area, and the aperture type of skylight is horizontal. As the pedestrian corridor in the atrium is an essential element of a commercial building, a 4m wide corridor is set in the model as the import analysis area.

2.2. Metric

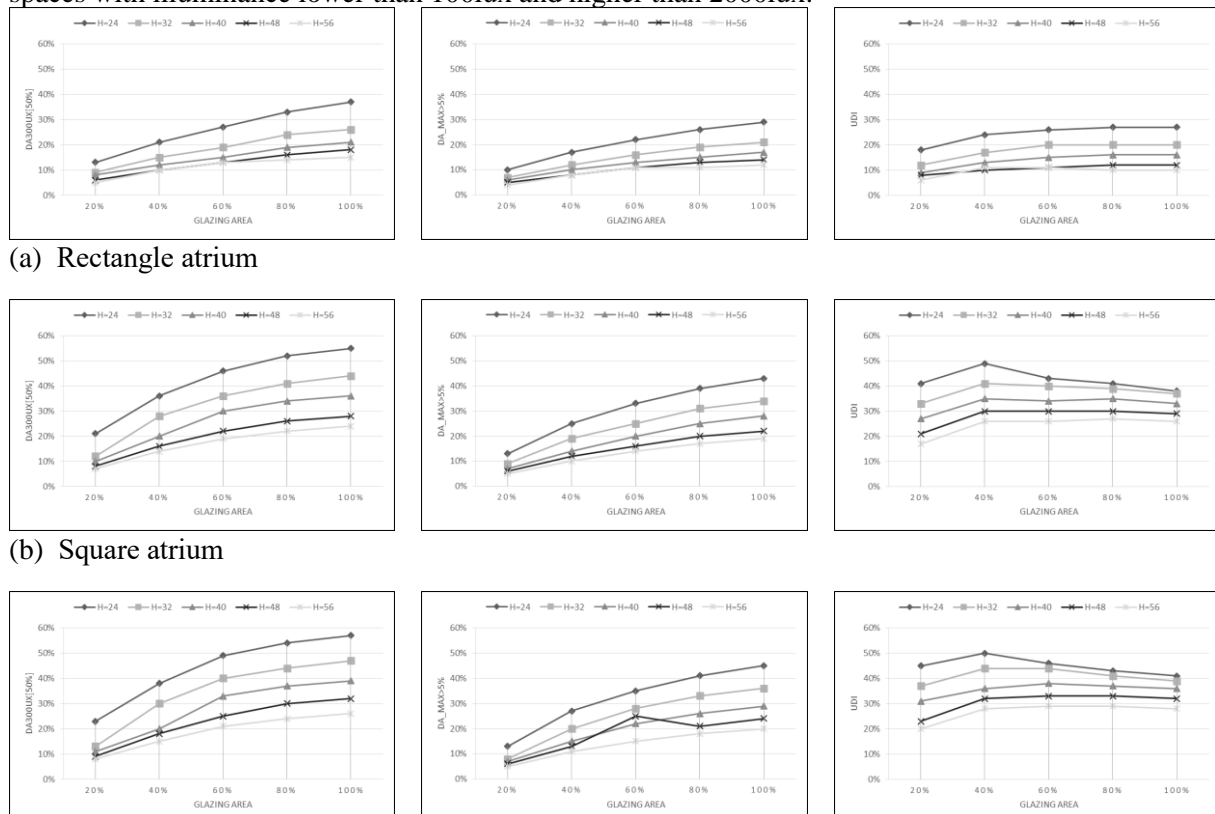
Three annual dynamic daylight metrics are chosen to analysis illuminance and glare. sDA and UDI are used to shown the daylight results, some comparison is carried to get a mutual validation. Since the above-discussed limitation of DGP and comparison demands in the subsequent analysis, DA_{max} is chosen to indicate the glare level.

2.3. Simulation settings

Essential assumptions are set for the model. As is well known, surface reflectance is the key factor to affect the daylight distribution in spaces, generic materials surface reflectance is adopted in the simulation, with floor at 20%, outdoor wall at 35%, ceiling at 80% and skylight at 65% transmittance double glazing pane low-E. The atrium partition between atrium and adjoining is typically transparent glazing in commercial, so it is assumed as 88% transmittance single glazing pane. The schedule is set from 10 am to 8 pm every day, totally 3650 hours are calculated for each case of a year. Shanghai is utilized as the weather location, weather data is downloaded from EnergyPlus weather source in TMY3 format[26].

3. Results

The overall computed results are shown in Figure 2. It is obvious that DA_{300lux} [50%] and $DA_{MAX>5\%}$ is rising with the growth of skylight glazing proportion, while the increase rate decreases from low building to high building. And both DA_{300lux} [50%] and $DA_{MAX>5\%}$ are the highest in 24m height and reduce with the growth of the height. $UDI_{100-2000lux}$ rises distinct at the beginning then become gentle, it portends that there will be a critical point, at which even the glazing area becomes larger, the useful daylight will stop increase, which is caused by the exclusion of the spaces with illuminance lower than 100lux and higher than 2000lux.



(c) Round atrium

Figure 2. Daylight metrics of various building heights.

To show the impact atrium shapes to daylighting, averages of five building heights are calculated, as offered in Figure 3. It can be seen seemingly that round atrium performs the best, square is a little weaker than round but quite close, rectangle is the worst one.

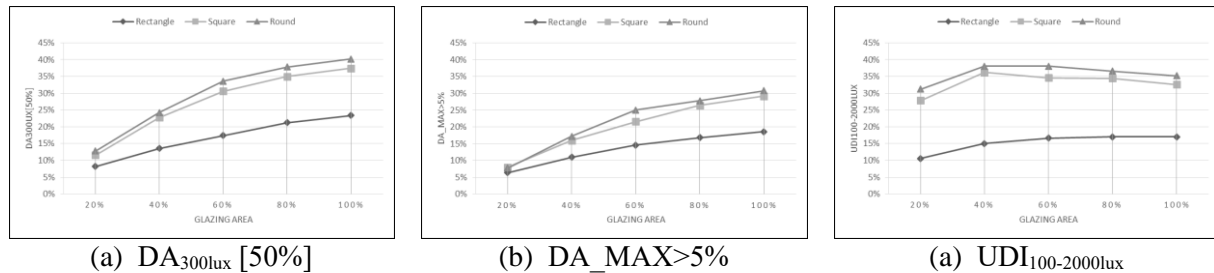


Figure 3. Daylight performance comparison of atrium types.

To find out the relationship between the two increases, the growth rate is introduced. The principles are when the growth rate of illuminance is higher than glare, we deem that the increase is positive and advantageous, and when it is contrary, the growth is negative and not suggested, thus the intersection point is the critical point of the design glazing proportion. By calculating and analyzing the growth rates of the two selected metrics, design criteria of skylight is summarized in table 2. One significant point should be highlighted is that the design criteria doesn't mean the glare will be completely avoided, thus shading or other effective strategies should still be taken into consideration in actual design process.

Table 2. Skylight design criteria.

	H=24m	H=32m	H=40m	H=48m	H=56m
Rectangle	100%	100%	100%	100%	100%
Square	80%	75%	78%	80%	80%
Round	78%	75%	80%	98%	80%

4. Discussion and Conclusion

Overall, this paper reveals the relationship between skylight glazing proportion and daylight performance, the influence of building height to daylight level and the contribution of atrium geometry to daylight illuminance, and proposes a skylight design criteria from a view of both maximizing daylight illuminance and minimizing discomfort glare of indoor environment, intend to provide designers a guideline on skylight area sizing. In conclusion, the findings of this study are as following:

- Atrium geometry is a significant effect factor to the daylight performance, by contrast, round atrium shows best, square atrium comes second, and rectangle takes the last.
- With the increase of building height, both illuminance and glare are reducing, and the impact of glazing area to daylight performance becomes smaller and smaller at the same time.
- The skylight design criteria based on the purpose both maximizing daylight illuminance and minimizing discomfort glare in design stage is proposed for three types of atrium geometry.

The annual and climate-based method makes the conclusions more reliable and valid, but the deficiencies of glazing area interval problem, limited geometry types, and integrating energy use etc. are existing as well, therefore, there are further and extensional work could be done in the future, we would welcome replication and extension.

5. References

- [1] B, M., *Daylighting Design: Planning Strategies and Best Practice Solution*. 2014, Basel: Birkhauser Verlag GmbH.

- [2] W, I.L., *A review of daylighting design and implementation in buildings*. Renewable and Sustainable Energy Reviews, 2017(74): p. 959-968.
- [3] H, M.M.a.J., *Assessing daylight performance in atrium buildings by using Climate Based Daylight Modeling*. Solar Energy, 2015(119): p. 553-560.
- [4] W, W., *The Key Research Points of International Daylighting*. Zhaoming Gongcheng Xuebao, 2016. **27**(4): p. 95-104.
- [5] Torcellini, L.E.a.P., *A Literature Review of the Effects of Natural Light on Building Occupants*. 2002, National Renewable Energy Laboratory: Colorado.
- [6] Council, U.S.G.B., *LEED Reference Guide for Building Design and Construction v4*. 2013.
- [7] Yang, S.S.a.F., *daylighting in atria: The effect of atrium geometry and reflectance distribution*. Lighting Res. Technol, 2007. **39**(2): p. 147-157.
- [8] Ran Y, L.S., Yuehong S and Saffa R, *Daylighting performance of atriums in subtropical climate*. International Journal of Low-Carbon Technologies, 2009(4): p. 230-237.
- [9] S, S., *A critical review of articles published on atrium geometry and surface reflectances on daylighting in an atrium and its adjoining spaces*. Architectural Science Review, 2010(53): p. 145-156.
- [10] R, B.P. *Lighting quality: the unanswered questions in First CIE Symposium on Lighting Quality CIE*. 1998. Vienna: CIE Central Bureau.
- [11] A, G.A.D.a.V.J., *Occupant preferences and satisfaction with the luminous environment and control systems in daylight offices: a literature review*. Energy and Buildings, 2006. **7**(38): p. 728-742.
- [12] P, B., *Lighting quality for all, in Session 3 Keynote Speaking, CIBSE & SLL International Lighting Conference Dublin 2013*. 2013: Ireland.
- [13] CIBSE, *Lighting guide 10: daylighting - a guide for designers*. 2014: London.
- [14] Aghemo C, P.A.L.V., *The approach to daylighting by scale models and sun and sky simulators: a case study for different shading systems*. Build Environ, 2008(43): p. 917-27.
- [15] Chen YY, L.J., Pei JJ, Cao XD, Chen QY and Jiang Y., *Experimental and simulation study on the performance of daylighting in an industrial building and its energy saving potential*. Energy Build, 2014(73): p. 184-91.
- [16] Li DHW, C.A., Chow SKH and Lee EWM. , *Study of daylight data and lighting energy savings for atrium corridors with lighting dimming controls*. Energy Build, (72): p. 457-64.
- [17] T, K., *Fuzzy logic model to classify effectiveness of daylighting in an office with a movable blind system*. Build Environ, 2013(69): p. 22-23.
- [18] A, R.C.a.F., *Findings from a survey on the current use of daylight simulations in building design*. Energy Build, 2006(38): p. 824-35.
- [19] Reinhart, J.J.a.C., *The 'adaptive zone' - A concept for assessing discomfort glare throughout daylight spaces*. Lighting Res. Technol, 2012(44): p. 149-170.
- [20] Society, I.E., *IES LM-83-12 - Approved Method: IES Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE)*. 2012.
- [21] *Rhino Training*. [cited 2018 5.23]; Available from: <http://solemma.net/TrainingRhino.html>.
- [22] Y, P., *Lighting Environment Simulation of Building*. 2010, Beijing: China Building Industry Press.
- [23] Nabil, A., J. Mardaljevic, *Useful Daylight Illuminance: A Replacement for Daylight Factors*. Energy and Buildings, 2006. **38**(7): p. 905-913.
- [24] Dubois, F.C.a.M.-C., *Daylighting metrics based on illuminance, distribution, glare and directivity*. Lighting Res. Technol, 2011(43): p. 291-307.
- [25] *DIVA User Guide*. [cited 2018 5.23]; Available from: <http://diva4rhino.com/user-guide>.
- [26] *weather data*. [cited 2018 0525]; Available from: <https://energyplus.net/weather>.