Research on Multi-objective Optimisation Algorithm for Light and Heat Environment in Underground Atrium Buildings

Lufeng Nie [1,2*], Xiang Ji [1,2†], and *Heng* Liu[3]

[1] School of Mechanics and Civil Engineering, China University of Mining and Technology, Xuzhou 21116, China
[2] Jiangsu Collaborative Innovation Center for Building Energy Saving and Construction Technology, Jiangsu Vocational Institute of Architectural Technology, Xuzhou 221116, China
[3] School of Architecture and Design, China University of Mining and Technology, Xuzhou 221116, China

Abstract. This paper firstly defines the concepts of underground atrium body shape, climate adaptability and parametric design, analyses the climatic characteristics of cold regions to extract their climatic factors, and responds to the climate with the light and heat environment, extracts the influence factors of the light and heat environment of the underground atrium and the body shape factors of the underground atrium, and constructs the underground atrium body shape design parameter system according to the classification of the body shape factors. Secondly using Ladybug+Honeybee software, a parametric underground atrium performance simulation system is constructed to simulate the light and heat performance of the underground atrium under the non-air-conditioned state by controlling the design parameters of the underground atrium's body shape, and to explore the role of each body shape parameter in relation to the light and heat environment of the underground atrium respectively. Then, using Ladybug+Honeybee+Wallacei software, we construct a multi-objective optimisation system for under-ground atrium shapes under non-air-conditioned condition with differentiation of light and heat performance, and explore underground atrium shapes suitable for cold regions.

Keywords: Underground atrium, Optimization design, Light and Heat Environment.

1 Introduction

This paper focuses on the relationship between the shape of underground atriums and climate in cold regions, which involves many morphological variables, such as the proportion of underground atriums, azimuth, height-to-width ratio, length-to-shortness ratio, mouth-to-bottom ratio, depth ratio, proportion of underground area, proportion of skylight, and concavity-to-convexity ratio of the top, etc. The process of simulation is very complicated

* Corresponding author: nielufeng@cumt.edu.cn
† Corresponding author: jixiang2023@yeah.net

and the number of variables is huge[1]. The many complex variables combined with each other to form the underground atrium body shape is very different and huge in number, which not only leads to the increase of operation difficulty and exponential growth of workload, but also consumes a lot of time and manpower for repeated simulation and correction. And the conventional method of using computer simulation software, in the early stage of programme de-sign through software simulation to assist the design, follow the "find problems, solve problems" repeated simulation optimization. Firstly, it will consume a lot of time and manpower, and secondly, it is impossible to exhaust all the combinations of solutions, and can only be optimised continuously, but cannot arrive at the optimal solution under the existing conditions[2]. This study requires a high level of comprehensiveness of computer simulation software and integration of various output results, such as this study needs to obtain the results of multiple optimisation targets for light and thermal environments at the same time. Some conventional software can only output one or two results, but not all the results required in this study. Considering that the modelling workload of conventional software is large, the error of results is difficult to guarantee, the operation consumes more time and manpower, the optimal solution cannot be sought, and the integration is insufficient, it is not suitable for this study. This study requires a computational and simulation software that can satisfy all the above requirements[3].

Parametric design is a design process based on algorithmic thinking defined by a combination of parameters and rules, i.e., objective physical reality expressed through mathematical knowledge. The parametric design software Grasshopper is widely used in architectural design. Through continuous development, parametric design has been efficiently combined with simulation in two forms: port plug-ins and stand-alone tool systems. Port plug-in is the regular and iterative form of analysis and optimisation work. The independent tool system is the secondary development of Grasshopper software as a platform, which integrates Grasshopper with the computational kernel of conventional simulation tools to form an independent design operating system.

The stand-alone tool system integrates morphology generation, performance simulation, and logic algorithms. Its morphology generation can use parametric modelling to control the shape of the building with data parameters, and the complex building shape can be changed by simple adjustment of the data, which is highly convenient and operable. In the performance simulation aspect, it also reacts to the required building performance with data, and can visualise the results, which is highly accurate and scientific. It is equipped with a variety of logic algorithms, such as genetic algorithms, to achieve automatic optimisation of the building form with the building form parameters as control variables, making the design and simulation process more integrated and automated[4].

2 Methodology

2.1 Setting up of a multi-objective optimisation procedure

Wallacei program setting is mainly divided into three parts, firstly, input gene pool, i.e. genes at the input of Wallacei operator. secondly, input optimisation objectives and data import, i.e. objectives and data at the input. thirdly, the setting of parameters related to Wallacei multi-objective genetic algorithm(see Fig. 1).

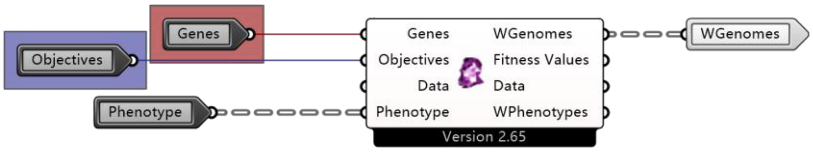

Fig. 1. Wallacei Calculator Diagram.

In the multi-objective optimisation system of the underground atrium constructed in this paper, the gene pool refers to the design parameters of each body shape. In the previous section, in order to carry out the initial typical model for performance simulation, as well as to carry out separate simulation for each body shape parameter of the underground atrium in consideration of the representativeness and operability of the parameter, the relevant parameters of each body shape factor of the underground atrium are set, and the step size of the parameter is relatively large, and the number of values taken is relatively small. Multi-objective optimisation is a multi-objective genetic algorithm, which no longer uses the exhaustive calculation method, greatly reducing the calculation time. Considering the scientific and quasi-academic nature of the optimisation results the underground atrium body shape design parameters are subdivided. In the parametric modelling process, "faces" are selected to give different materials and different external contact factors, such as the external climate environment or soil, so that the building has to be set up with different numbers of floors to divide the faces. The depth ratio is affected by the number of floors and its value cannot be subdivided. It is related to the number of surfaces of the rectangular ground floor atrium that are exposed to the outside world and therefore can only take a specific value[5].

In the parametric modelling process, due to the program set up by the material, external contact factors programming logic, the same building height not be changed at will. At this time to keep the area of the underground atrium unchanged, change the underground atrium length and short axis ratio, the width has produced changes, the height is unchanged, the aspect ratio has produced changes, so the length and short axis ratio changes, the same will make the aspect ratio changes, a parameter (length and short axis ratio) control the value of two parameters (length and short axis ratio, aspect ratio). In the multi-objective optimisation phase, the focus is on establishing the optimisation system and finding the optimal body shape without the need to control the variables. Therefore, there is no specific step for the values of aspect ratio, and different proportions of the length-short axis ratio correspond to different values of the aspect ratio[6].

As this study comprehensively researches the body shape of underground atrium from multiple dimensions of orientation factor, body shape factor, interface factor, and volume factor, the parameters of body shape factor of underground atrium form a more complex system, and the number of parameters is more considerable. However, when the following text for multi-objective optimisation, the need for synergistic control between the parameters, so it is necessary to carry out parameter screening to avoid mutual conflict between the parameters. And in the building design stage azimuth, depth ratio and other easy to control, body shape coefficient, underground atrium volume ratio is difficult to control directly, its corresponding value is only for reference and testing after completion. Combining the above two points, the under-ground atrium shape parameters are divided into design parameters and reference parameters. The design parameters do not conflict with other parameters and are easy to control in the architectural design stage[7]. The simulated azimuth angle, depth ratio, length/shortness ratio, height/width ratio, mouth/bottom ratio, skylight ratio, and concavity/convexity ratio meet the requirements after testing. The reference parameters

generally conflict with other parameters and are not easy to control, including the proportion of underground part, body shape coefficient, and the proportion of under-ground atrium volume. The reference parameters are used as output items so that the range of screening parameters corresponding to the optimal solution set can be ana-lysed. Set the two parameters of body shape coefficient and height-to-width ratio as output values, so as to analyse the range of its parameters corresponding to the model formed by the optimal solution set, so as to allow the designer to make reference (see Tab. 1).

Table 1. Setting of parameters for the shape of the underground atrium.

Parameter category	Body shape factor	Body type parameters	Step size	Parameter range	Parameter quantity
Design parameters	Azimuth factor	Azimuth	5°	-60°to 60°	24
		Depth ratio	25%	25%ti100%	4
		Extent ratio	25%	0%to75%	4
	Physique factor	Aspect ratio	0.5	1to4	8
		Bottom to mouth ratio	0.5	-3to3	12
	Interface factor	Skylight proportion	10%	0to100%	11
		Sunroof tilt angle	5°	0°to45°	10
		Sunroof protrusion value	1	-2to2	5
	volume factor	Proportion of underground atrium volume	2%	4%to20%	9
Reference parameters	Azimuth factor	Proportion of underground volume	Output value embodiment		
	Physique factor	Shape coefficient of underground atrium	Output value embodiment		

In this study, the parametric model of underground atrium and the simulation pro-gram of light and heat performance have been established by Ladybug and Honeybee, and the output of the simulation program will be numerically processed by PMV thermal comfort time percentage, summer and winter heat radiation difference, and the average of all-natural lighting time percentage sDA300, and then fed back to the input of Wallacei module's OBJECTS, in order to complete the multi-objective optimisation operation.

The data import of Wallacei refers to the data type of the initial population, i.e., the three reference parameters of the underground atrium body shape coefficient and the underground atrium height-to-width ratio can be entered, and the reference parameters corresponding to the optimised underground atrium body shape will be output at the output end[6].

Wallacei includes algorithm parameters, the setting of algorithm parameters will affect the scientific and accuracy of the optimisation results and the speed of calculation, Mutation Probability represents the probability of downward mutation of each parameter, which has an impact on the speed of convergence of the calculation and the depth of exploration of the optimal solution, this item only supports the minimization and maximization, in order to improve the simulation accuracy set to maximize the Mutation Rate. The degree of gene mutation Mutation Rate is maximised to enhance the simulation accuracy, Crossover Probability is the probability of exchanging parameters between the two generations of solutions, set to the default value of 0.9. Generation Count is set to 50 generations, the larger the number of generations, the closer to the optimal solution in theory. Generation Size represents the number of populations in each generation, because each generation will carry out the calculation of twice the value of Generation Size, so this item will greatly increase the computing time, this item is set to 50.

2.2 Underground atrium light performance simulation

Underground atrium light performance simulation is divided into two parts, one is its regional grid setting corresponds to the measured location of the measurement point arrangement 4m * 4m, to analyse its illuminance value and lighting coefficient trend, and the second is its regional grid setting the same as the above performance simulation grid setting, grid cell size of 0.5m * 0.5m, to analyse the percentage of its all-natural daylighting sDA300.
In the simulation results, the trend of illuminance value and lighting coefficient is similar to the measured results, with the average illuminance value ranging from 126 to 739lx and the lighting coefficient from 7.42% to 14.44%. All of them are within a reasonable range. The average illuminance value of the previous measurement is 300 to 721lx, and the average lighting coefficient ranges from 6.5% to 11.5%. Due to the different weather conditions, the illuminance value not be compared, but the overall data of the lighting coefficient is slightly higher due to the atrium skylight of Suning Plaza with a circular shading facility on the ground floor, and the overall error is within the acceptable range (see Fig. 2&3).

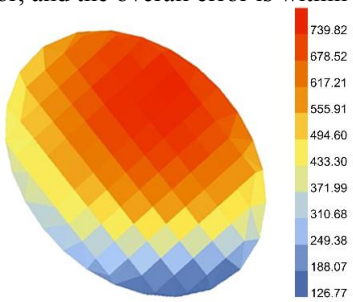

Fig. 2. The distribution map of the illumination area of the underground atrium.

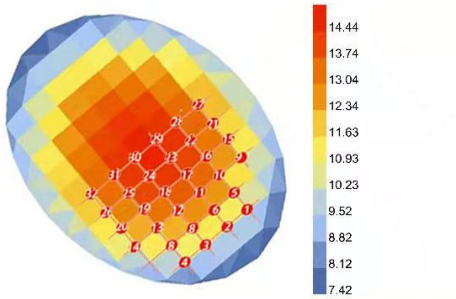

Fig. 3. Regional distribution of daylighting coefficients in the underground atrium.

From the distribution of sDA300, the average value of the percentage of all natural lighting time in the ground floor space of the underground atrium, it can be seen that the lighting performance of the ground floor space is distributed in a ring shape, with the middle area decreasing to the peripheral area; compared to the south side, the north side of the ground floor space has a slightly higher value of sDA300, i.e., the north side of the lighting performance is slightly superior to that of the south side; compared to the east side, the west side of the ground floor space has a slightly high-er value of sDA300, i.e., the west side has a better performance of lighting than the east side. Compared with the east side, the west side of the ground floor space has a slightly higher sDA300 value, i.e., the west side has a better lighting performance than the east side. The main reason is that the sunlight comes in from the east, south and west sides, which results in the middle and north side areas receiving sufficient sunlight and less regulation by the building, so the lighting performance of the middle side is better than the surrounding area, and the north side is better than the south side.

The west side is better than the east side, which means that the light from the east side is slightly higher than the light from the west side, but the difference is small.

From the results, it can be seen that the average value of the percentage of natural lighting is 63.01%, which is greater than 50%, and it can be considered that the light environment basically meets the requirements, but there is still room for optimisation, and it is necessary to ensure that the quality of the light environment will not be reduced while the quality of the thermal environment is subsequently improved (see Fig. 4).

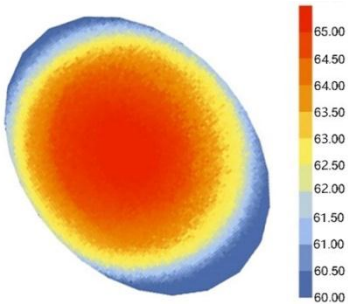

Fig. 4. Area distribution area of total natural lighting percentage.

2.3 Underground Atrium Thermal Performance Simulation

From the regional grid plot of the average thermal radiation difference in winter and summer, it can be seen that the subterranean atrium ground floor is "warm in winter and cool in summer", and the lower the RAD difference is, the better it is. As can be seen from the figure, compared with the north side region, the south side RAD difference is lower, which means that the south side region is better than the north side region; and compared with the east side region, the west side region has a relatively low RAD difference, which means that the west side region is slightly better than the east side; as a whole, it can be seen that the middle part of the atrium ground floor has a lower RAD difference than the east side region. Compared with the middle area of the ground floor of the underground atrium, the RAD difference of the peripheral area is lower, indicating that the peripheral area is better than the centre area. In summary the distribution law of the average thermal radiation difference in winter and summer is roughly the same as the distribution law of the annual average thermal comfort of the ground floor of the initial typical model of the underground atrium, i.e., the lower the RAD difference, the better the thermal comfort (see Fig. 5).

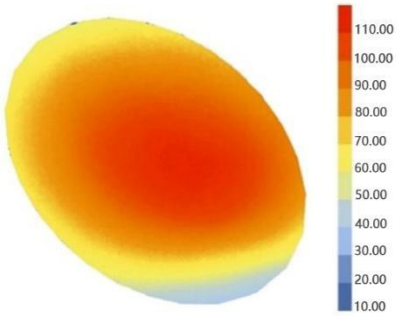

Fig. 5. Regional distribution of heat radiation difference between summer and winter.

3 Results

Since all three optimisation performance simulation results converged, the last generation of simulation results was selected for analysis, and the objective space plots of all non-dominated solutions. The optimisation objective space plot represents the relative position of each optimisation solution to the origin in three-dimensional space, and the closer to the origin, the higher the optimisation objective value. The objective space diagram contains three coordinates, F01Minimise RAD, F02Maximse PMV%, and F03Maximse sDA corresponding to summer and winter thermal radiation difference RAD summer-winter, year-round PMV comfort time percentage, and all-natural lighting time percentage sDA300, respectively. due to the default convergence coordinates of the Wallacei operator when searching for the optimal operation origin, which is the minimum of the three optimisation objectives. The three performance optimisation objectives involved in this study, only the summer and winter thermal radiation difference RAD summer-winter is the smaller the better, the annual percentage of PMV comfort time, the all-natural lighting time percentage sDA300 is the larger the better, so in the input Wallacei operator the annual percentage of PMV comfort time, the all-natural lighting time percentage sDA300 are taken as a negative number. The optimisation results are optimal when the summer-winter thermal radiation difference RAD summer-winter value is minimum, and the absolute value of the year-round PMV comfort time percentage[8], all-natural lighting time percentage sDA300 is maximum.(see Fig. 6).

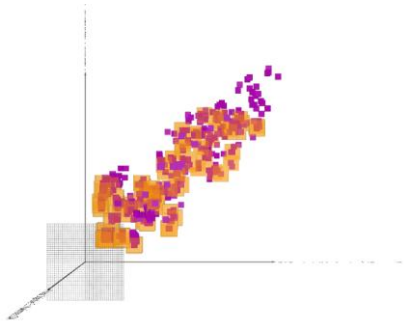

Fig. 6. Object space graph for all algebraic non-dominated solutions.

Under the condition that the climatic conditions, the number of underground atrium floors, and the number of building floors, height, and shape remain unchanged, by adjusting each body shape parameter of the underground atrium body shape, the difference of thermal radiation RAD summer-winter and the percentage of PMV comfort time for the whole year are positively correlated, the percentage of time of all-natural lighting sDA300 and the percentage of time of all-natural lighting sDA300 and the percentage of time of all-natural lighting comfort for the whole year are negatively correlated, and the difference of thermal radiation RAD summer-winter and the per-centage of time of all-natural lighting sDA300 are negatively correlated in the winter.

This research was funded by Jiangsu Collaborative Innovation Center for Building Energy Saving and Construct Technology, grant number SJXTBS2111; National Natural Science Foundation of China, grant number 51778611; National Key Re-search and Development Program of China, grant number 2018YFC0704900.

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