



A Sunlight Duration Time Driven Multi-objective Optimization Method for the Layout of High-Rise Residential Quarters Based on NSGA2 Algorithm

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Abstract. Extending sunlight duration time by optimizing the layout of the high-rise residential quarters during the early design stage is one of the most effective approaches to reducing carbon emissions. This paper proposes a multi-objective optimization method for high-rise residential quarter layout based on the NSGA2 algorithm. The method is aimed to maximize the first floor's sunlight duration time and its uniformity both. A simulated plot in Xiamen is taken as an example for multi-objective optimization. After the optimization, the layouts are analyzed and the better one is selected. The results show that the proposed method can achieve higher overall sunlight duration and its uniformity rate and maximize floor area ratio in the early design phase. However, the proposed method has its drawbacks. This method requires the pre-design of the building plan. The algorithm generates a lot of invalid solutions during the optimization. The optimization time increases dramatically with the quantity increase of input parameters. According to the above, there is still room for improvement in the proposed method.

Keywords: Residential quarter · Sunlight duration time · Multi-objective optimization · WallaceiX

1 Introduction

The urbanization process has accelerated since the Reform and Opening, resulting in cities full of skyscrapers with a typical example of high-rise residential quarters. In the design of high-rise residential quarters, sunlight is a crucial factor that determines whether the project can continue. According to statistics, the nationwide building life-cycle carbon emissions in 2018 were 4.93 billion tons of CO₂, and that of the operation phase is 2.11 billion tons, accounting for 42.8% of building lifecycle carbon emissions [1]. Maximizing sunlight duration during the daytime by adjusting the layout in the early design stage to provide users with a good daylighting environment can effectively reduce the energy consumption and carbon emission of daytime lighting.

As shown in Fig. 1, the traditional workflow relies on designers' experience, but they can hardly obtain a plan that is optimal in multiple dimensions in a short time. Most of the designs just meet compulsory codes, while other criteria are neglected. Generative design research has become a trend in recent years to solve these problems. In this way, designers can improve the efficiency in the early design stage, and optimize building performance to reduce carbon emissions.

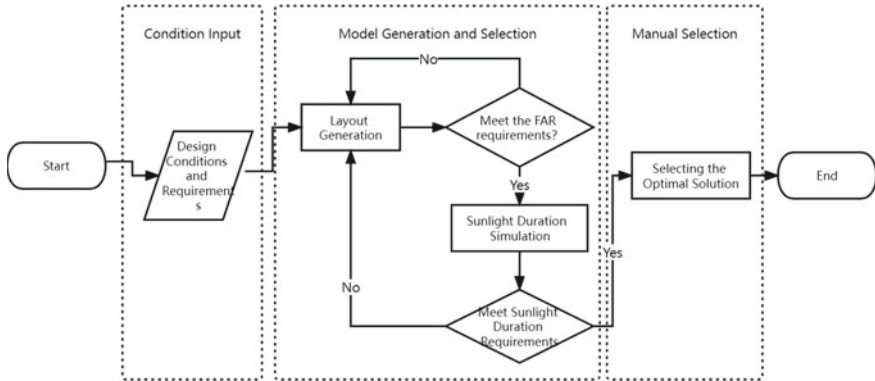


Fig. 1. Traditional design workflow

There is much research about building group layout optimization, and the methods can be classified into three categories: agent-based model (ABM), genetic/annealing algorithm and artificial intelligence (AI). ABM: JI Guohua et al. explored the optimization of residential quarters based on Netlogo [2]. LI Biao et al. used the highFAR to optimize the layout of a residential quarter and calculated the shadow area [3, 4]. YUAN Feng proposed an ABM based on Rhino, GH, and python to generate wind environment performance optimal building group layout [5]. Genetic/Annealing algorithm: GAO Fei optimized the layout driven by sunlight duration based on Geco and Galapagos [6]. LIU Ke et al. used genetic algorithm engine with Galapagos to perform energy efficiency optimization of residential quarter layout [7]. AI: Xcool Technology has made great strides in residential quarter master plan design relying on AI [8]. DENG Qiaoming et al. implemented the generative design of campus layout through generative adversarial networks (GAN) [9].

The methods above are gradually moving to application. ABM and AI are difficult to shift to the industry in a short time due to their high coding demand and genetic/annealing algorithms are preferred due to their out-of-the-box feature. A lot of the research focuses on single-objective optimization, while in real design scenarios, the optimization objectives of design problems are often multiple conflicting indicators. Therefore, based on the Grasshopper platform, this study proposes a multi-objective optimization method for the layout of high-rise residential quarters based on sunlight duration time using the NSGA2 algorithm plugin WallaceX [10] and building simulation plugin Ladybug Tools [11], then conducts an analysis of the optimization results with inbuilt tools to test the optimization capability. With the help of such methods, designers can efficiently

complete the design of the residential quarter layout in the preliminary design phase and can add other building performance simulation tools for energy, ventilation, and microclimate simulation on this basis to further optimize the overall building layout, optimize building performance, and reduce carbon emissions.

2 Research Methodology

The problem can be translated into an optimization problem: within a given site, the layout of the residential quarter is generated by controlling the location, orientation, and the number of floors, to maximize the total sunlight duration, its uniformity, and FAR.

As shown in Fig. 2, the optimization process consists of five parts. The basic calculation and parametrize section calculates the plot area, building projection area, FAR, and building density and optimize the maximum number of each building type with Galapagos, as a reference for the optimization. In generating model section, the program generates residential models defined by building location, orientation, and the number of floors. In constraint calculation section, the building spacing is represented by no-entry zones according to the relevant codes of Xiamen City. In the sunlight duration calculation section, the sunlight duration of the test surface is analyzed by Ladybug Tools to generate corresponding values. Then determine whether the duration meets the needs. In the genetic algorithm & merit selection section, WallaceiX is used to start and stop optimization and control parameters, together with merit selection and breeding.

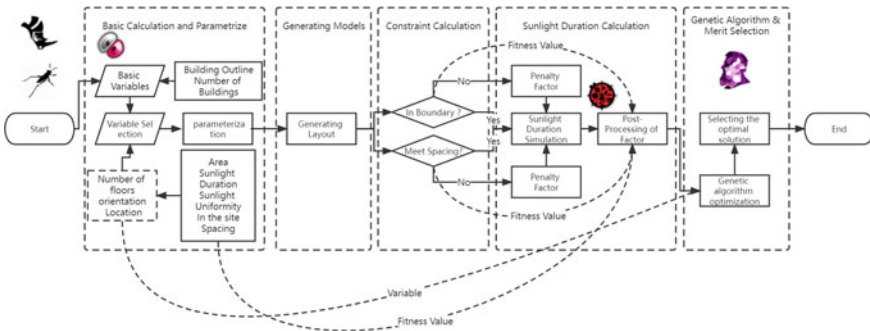


Fig. 2. Workflow of the proposed multi-objective optimization

2.1 Basic Calculation

The experiment simulates an L-shaped irregular plot in Xiamen. The site area is about 33,671.6 m². Outside the site in the northeast is an existing residential area, with three 6-story residential buildings, and the sunlight duration is up to standard. According to the regulations, the property line setback according to the upper limit of 18 m in the north–south direction and 15 m in the east–west direction (Fig. 3).

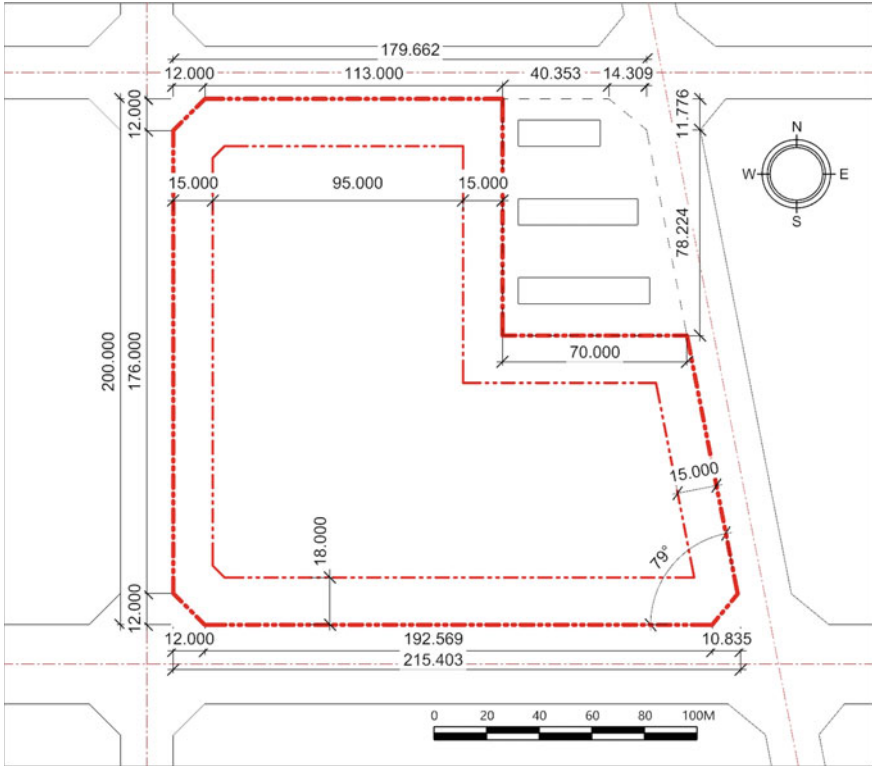


Fig. 3. Plan of the plot

Residents have higher requirements for living quality, reflected in the demand for housing width resources, therefore, Large-width, slab-type buildings are more popular. Two similar types of buildings are arranged within the setback Line: “long-slab type” 53 m*15 m, and “short-slab type” 26 m*15 m, both simplified into rectangles. According to the “Technical Regulations for Urban Planning and Management of Fujian Province”, high-rise residential quarters with a land area of more than 30,000 m², FAR shall under 2.9, and a building density of 20%, so the maximum building area is 97,647.7 m², and the maximum building projection area is 6734.3 m². Using Galapagos to optimize the number of two types of buildings mentioned. Getting a result of 5 short-slab buildings and 6 long-slab buildings. To reduce the building density, it is changed to 3 short-slab buildings and 4 long-slab buildings. In this step, the result generated by the algorithm is only for the designer’s reference.

2.2 Parameters of Model

In this optimization, the variables are designed according to the problem: building location, building orientation, and the number of floors. The center of building projection is the reference point to the building position. There are two ways to generate the reference point position: coordinate method and point grid method. As shown in Fig. 4, for

complex shaped site, method 2 has no points outside the site, saving computing power. Generating a total of 67,011 points in the site at an interval of 0.5 m. Rotation axis point is also the center of the projection, the default angle is 0° . Floor number of building is expressed as an integer.

In order to improve the efficiency of the program, the continuous variables are discretized to reduce the search space. The step of position is 0.5 m. The rotation angle of the building is -45° to 45° , with a step of 1° . The number of floors varies from 8 to 27 floors, with the same step of 1, and the story height is 2.9 m.

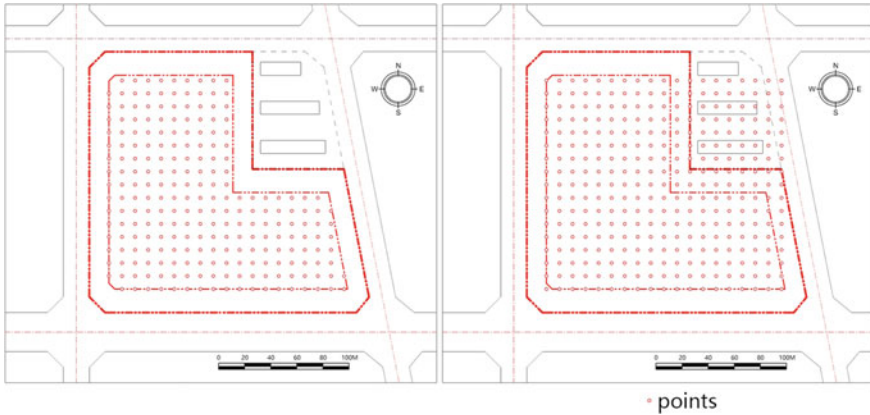


Fig. 4. Two ways generating points

2.3 Constraint Design

The generated plans have building overlap and mass intersection problems, so it is necessary to construct a constraint mechanism that generates penalty coefficients to clarify the optimization direction of the program and improve the computing efficiency. There are two constraints in this optimization: boundary line constraint and spacing constraint.

1. Setback line constraint. The generated buildings need to be in the setback lines. Set the area of the setback line as S . The area that represents merged surfaces of the setback line and building projections is set as S_1 . If $S_1 - S = 0$, which means all the buildings are in the setback lines, the program proceeds with the actual value. If $S_1 - S > 0$, then there is at least a part of buildings out of the setback line, output the penalty coefficient to all the fitness values.
2. The spacing constraint is based on the Codes of Xiamen City Urban Planning Management. According to the height of the building on the south side of each building, or, its own height (if there is no building on the south side), offsetting 14–24 m forward and backward, and offsetting the hill wall 6.5–8 m. (as Fig. 5) The area of a single no-entry zone is set as S_i . The sum of them is set as $\sum_{i=1}^7 S_i$. The area of

merged no-entry zones is set as S . If $\sum_{i=1}^7 S_i - S = 0$, then there is no overlapping of no-entry zones and the layout is valid, proceeding with the actual value. If $\sum_{i=1}^7 S_i - S > 0$, it means that there is overlapping of no-entry zones, output the penalty coefficient to each fitness value.

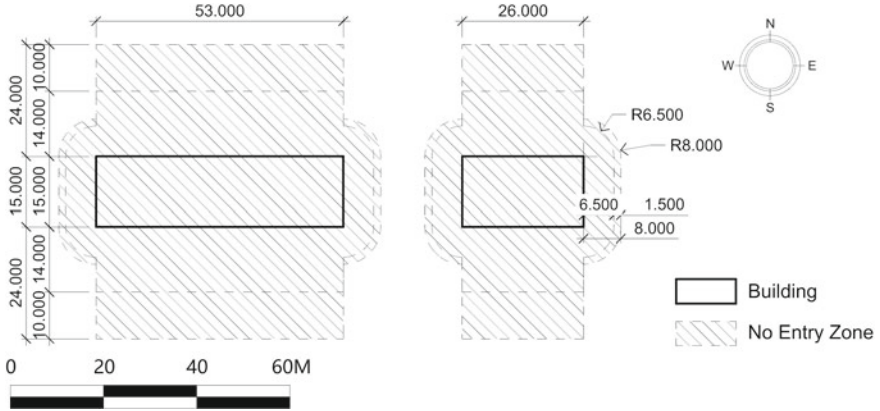


Fig. 5. No entry zone map

Only when layouts satisfy both the setback line and spacing constraints can the algorithm output actual values. If not, the fitness values are multiplied by penalty coefficients to make them higher, thus prompting the engine to optimize to the smallest value.

2.4 Sunlight Duration Calculation

According to the requirements of the Standard for Urban Residential Area Planning Design. GB 50,180–2018, the sunlight duration of the first-floor windows is at least 2 h on January 20th [12]. A test surface was generated at 1.35 m height of the south elevation and divided into multiple sampling points. There are three existing residential buildings in the northeast corner, so there will be shading influence between proposed buildings and existing buildings. The sunlight duration of each sampling point on the test surfaces on that day can be measured. Whether each measurement point meets the duration requirement, the overall sunlight duration, the uniformity of sunlight duration, and the total sunlight duration of existing buildings can also be measured. The effective sunlight time on January 20th is 8:00–16:00, a total of 8 h.

2.5 Fitness Value Design and Multi-objective Optimization

In the optimization, 7 objectives are set, which are: whether each sampling point meets the duration requirement, total sunlight duration, sun-light duration uniformity, total floor area, sunlight loss of existing buildings, whether any building exceeds the setback line, and whether any buildings’ no-entry zones overlapped. The objectives are converted

into fitness values that suit the engine feature of the WallaceiX. Then WallaceiX will optimize the fitness to the minimum.

“Whether each measurement point meets the duration requirement” is translated into the number of measuring points with sunlight hours less than 2 h. “Sunlight uniformity” is transformed into the value of 1 minus the ratio of the minimum value to the mean value. “Total sunlight duration” is transformed into the reciprocal of the sum of sunlight duration at sampling points of planned buildings. “Total floor area” is transformed into the difference between the maximum floor area and the floor area of planned buildings. “Sun-light duration loss of existing buildings” is transferred to the number of measuring points with sunlight hours less than 2 h on existing buildings. Whether there is a building crossing the setback line and whether there is a building not meet the building spacing requirements have been described in the previous section.

The location, rotation angle, and the number of floors of each building are input into the WallaceiX as variables and the above 7 fitness values to the optimization objectives. Then set up the genetic algorithm config: the optimization last 500 generations, with 50 results per generation, and the rest of the settings follow the default. When optimization starts, the WallaceiX automatically changes parameters in the gene pools and forms the building layout, and will output the fitness values, recording the relevant results and data in the memory for retrieval in the subsequent analysis. The optimization will stop automatically after reaching the number of iterations. Afterward, select the optimal layout with the help of GH definition and built-in tools.

3 Result and the Optimal Layout

The optimization shows convergence overall. The optimization runs for about 5 h, generating a total of 25,000 phenotypes. As shown in Fig. 6, the overall change curve of each fitness value shows a fluctuating decreasing trend, and the standard deviation value also tends to be a low value. For most of the fitness values from the beginning to 500 generations of the optimization process, its standard deviation decreases rapidly and enters a stable state. The standard deviation curve of most fitness values shows a narrow peak and the peak of the blue curve is shifted to the left compared with the peak of the red curve, indicating better mean performance. The overall trend of FO5 (out of the building plot red line) is different from that of the other fitness values, which oscillates in the process of optimization. In summary, after 500 generations of iterations, the optimization shows a trend of convergence and stability, and better layouts can be obtained by selection.

Using the Pareto frontier function to find the set of layouts where the optimal layout lies, there exists a certain number of Pareto optimal layouts in such multi-objective optimization problems. The layout on the Pareto front is selected as the better layout. Since the weights of all the fitness values in the optimization are the same, it is necessary to perform a secondary selection of these layouts according to the priority of each value in the designer’s mind. A total of 50 layouts are output using this method. They are all 500th generation, as shown in Fig. 7.

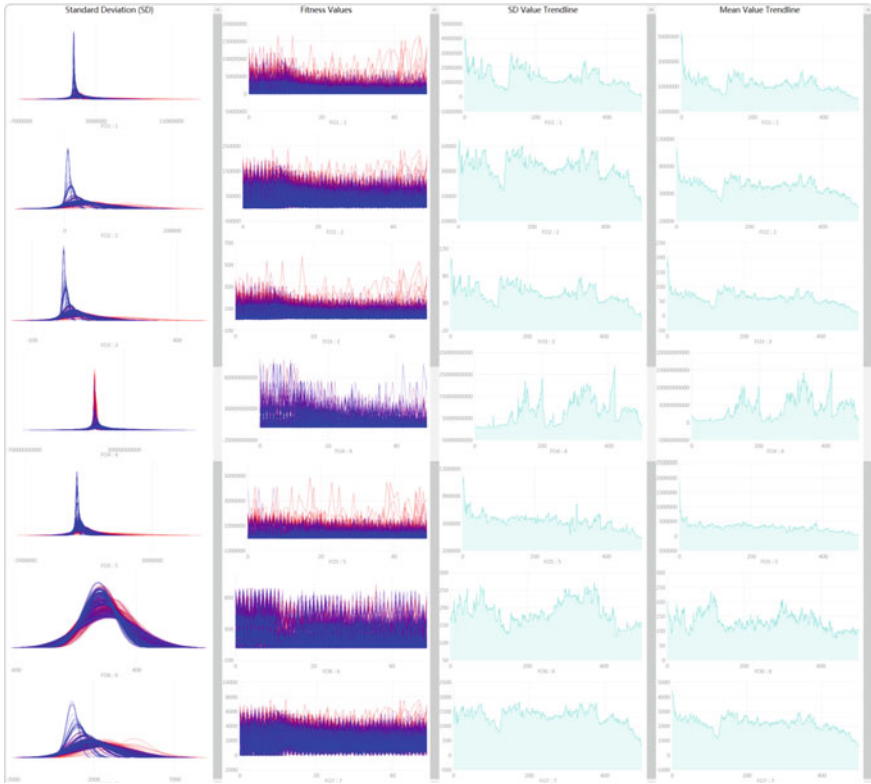


Fig. 6. Built in optimization analysis chart

Corresponding fitness values are extracted from the selected results for comparison, and further optimization is carried out. The layouts that meet the two constraints at the same time with optimal sunlight duration are selected. These layouts are analysed with the diamond diagram analysis tool. The diamond diagram reflects the fitness rank of the layout. The closer to the center point, the lower the fitness rank is, and the better the layout is. Through the comprehensive comparison of the 7 objectives, the optimal layout is selected from the layout set. As shown in Fig. 8, the layout numbered Gen499 Ind29 has the best comprehensive fitness values, and the number of points for insufficient sunlight duration is 0; The sunlight duration uniformity is 0.33; the sum of the sunlight duration is 846 h; the building area is 100,815 m² (the maximum is 97,648 m², so it needs to be adjusted); 5 test points of existing buildings cannot meet the sunlight duration requirement. The area out of the setback line is 166.8 m², and the overlapping area of the no-entry area is 318 m². In conclusion, this layout is the optimal layout for this optimization, but it still needs to be further optimized. Adjusting the No. 4 building plan to the short slab type and rotating No. 3 and No. 7 buildings to 0°. The adjusted layout basically meets all the constraints and maximizes the floor area and total sunlight

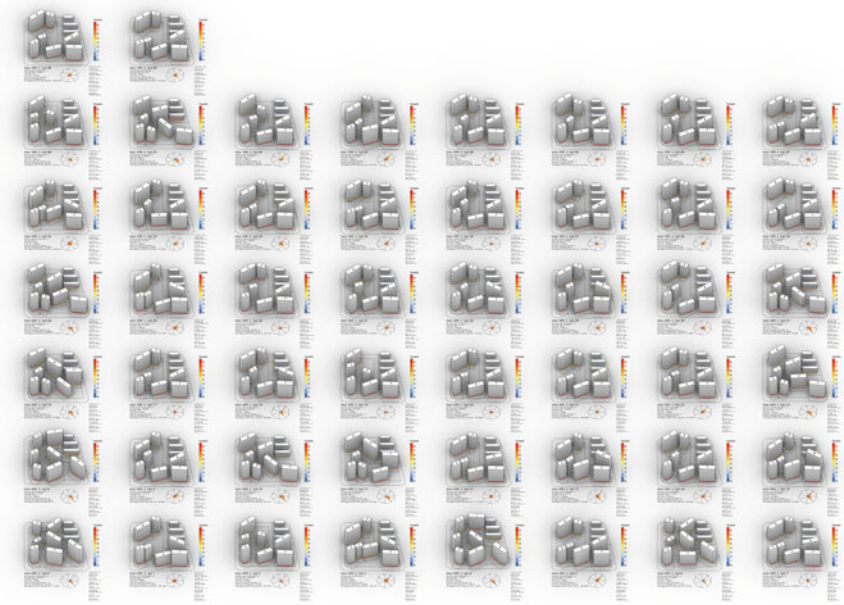


Fig. 7. Output better layouts

duration on the first floor. After adjustment, the objectives are more reasonable, and in this layout, buildings have different rotation angles and floors. Such a layout is difficult to derive from traditional means.



Fig. 8. Optimal layout diagram

4 Conclusion

The optimization results show that this method can significantly optimize all aspects of the sunlight duration and other indicators, thus obtaining better effects during the preliminary design of the residential quarter, which is more efficient than the traditional approach.

4.1 Advantages of Multi-objective Optimization

In traditional design workflow, architects can only consider the minimum requirements of sunlight duration while considering the building layout, ignoring other subtle objectives such as the uniformity of sunlight duration, etc. The experiment demonstrates the overall improvement of multiple indicators. The algorithm can break through the limits of human brainpower and experience to find optimal solutions. This type of design process is only limited by the constraints set, without the limitations of human cognition, and can even find a global optimum layout that humans can't.

The optimization shows strong potential for sunlight duration-driven objective optimization in residential quarter layout design. In this paper, three variables are selected and optimized roughly due to time and computing power limitations, and also achieve better results for the sunlight duration. In the future, designers can add more variables (CFD, noise, view, microclimate) for the automatic generation and optimization of the residential quarter according to the design requirements, and assist them with building energy simulation, which can achieve a more significant energy-saving effect.

4.2 Shortcomings of This Algorithm at this Stage

In this experiment, there are about 4.9×10^6 possible solutions in the search space. Although this method is designer-friendly, simple, and effective, it is still time-consuming. When the number of objectives is greater than 3, the selection pressure of the NSGA2 algorithm in this plug-in decreases, thus the optimization outcome becomes unsatisfying. This problem is solved in the NSGA3 algorithm, so the NSGA3 algorithm should be used in the subsequent multi-objective optimization.

Due to the combinations of multiple genetic pools of different values, there will be a large number of invalid layouts. The more parameters applied, the more buildings generated, and the greater the probability of such cases, resulting in the computing power waste on such layouts. When the designer is not clear about the design problem, it could be even worse. Some records show that when the number of buildings increases, the time consumed rises from 1.5 to 60 h, and there is no guarantee of an optimal solution [13]. In this experiment, there are about 4.9×10^6 possible solutions in the search space. Although this method is designer-friendly, simple, and effective, it is still time-consuming. When the number of objectives is greater than 3, the selection pressure of the NSGA2 algorithm in this plug-in decreases, thus the optimization outcome becomes unsatisfying. This problem is solved in the NSGA3 algorithm, so the NSGA3 algorithm should be used in the subsequent multi-objective optimization.

This experiment provides a prototype of the residential layout design workflow for practitioners. The energy conservation and carbon emission reduction of new housing needs to be paid attention to, and it is very important to optimize the layout of the residential quarter in the early stage of design. Maximizing the use of solar energy by design is still the first choice for energy saving. If such a workflow can be generalized, a huge amount of carbon emissions can be saved.

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