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Optimisation of heliostat layout based on BFS and genetic algorithm

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Abstract: *At present, the efficiency of power generation by a solar field with a radiation tower is not as good as that of a butterfly-shaped solar field. This paper aims to improve the conversion efficiency of solar thermal power generation by a radiation tower solar field. To this end, this paper proposes to use genetic algorithms and BFS to optimise the layout of the heliostat field, thereby improving the optical efficiency of solar thermal power generation by a radiation tower. The experimental results show that this method can effectively improve the average optical efficiency. This study provides a valuable reference for the design of solar thermal power generation systems.*

Keywords: *Genetic algorithm, optical efficiency, solar thermal power generation, breadth-first search*

1. Introduction

Recently, the development of new energy technology has led to the emergence of solar photothermal power generation technology as a pivotal developing project in various countries. Solar photovoltaic power generation technology is divided into four distinct power generation methods, namely, disc, tower, trough and linear Fresnel. In terms of photothermal power conversion efficiency, the order of these methods is disc, tower, trough and Fresnel, with the efficiency of trough and Fresnel being approximately equivalent. [1] Radiant towers have been employed for power generation purposes, although they are less efficient than discs in terms of photothermal power conversion. However, they have the advantage of a low level of pollution of the heat transfer medium, which has the effect of causing little damage to the environment. This is an important step towards achieving China's goals of ‘carbon peaking’ and ‘carbon neutrality’. [2]

Stephanie Forrest,in her genetic algorithm research, she employs a roulette wheel selection process to identify the most adapted individuals from the current population as the initial generation. This is followed by an iterative optimisation process, during which the strengths and weaknesses of the individuals are assessed by a fitness function to inform selection and elimination decisions.A combination of hierarchical search and breadth-first search (BFS) is employed to identify the heliostat coordinate points that are suitable for the genetic algorithm. These points are then clustered using hierarchical clustering, which enables the construction of an overall heliostat layout within the optimisation range. Subsequently, this paper employs the genetic algorithm to continuously modify the radial and circumferential spacing and offset angle of the heliostats in order to derive the optimal heliostat distribution coordinates for different time periods with the purpose is to maximize the average optical efficiency of the heliostat field. In comparison to the original data, the average optical efficiency has been found to be approximately 0.8, which represents a 30% improvement over the original average optical efficiency. Furthermore,it lead to a reasonable distribution of both the coordinates and the number of heliostats.

2. Optical efficiency calculation

The process of generating electricity by the heliostat will impacted by numerous parameters, among them, optical efficiency is representing a significant factor. This paper primarily considers the three primary factors that contribute to the calculation of optical efficiency: shadowing efficiency, cosine efficiency, and truncation efficiency. The mathematical formula used to determine optical efficiency is as follows:

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$$\boldsymbol{\eta = \eta_{sb}\eta_{cos}\eta_{trunc}} \tag{1}$$

The shading efficiency parameter ($\boldsymbol{\eta_{sb}}$) represents the fraction of light that is absorbed by the shading material. The cosine efficiency parameter ($\boldsymbol{\eta_{cos}}$) quantifies the fraction of light that is reflected by the shading material. The truncation efficiency parameter ($\boldsymbol{\eta_{trunc}}$) represents the fraction of light that is transmitted through the shading material. The following section will elucidate in detail how these parameters are calculated.

2.1. Calculate the shading efficiency

2.1.1. Shadow blocking

The phenomenon of shadowing is of significant importance in the design of solar systems. In a multi-mirror heliostat system, shadowing between adjacent mirrors can result in a reduction in optical efficiency. Two principal types of shadowing may be distinguished: incident shadowing and reflected shadowing.

(1) Incident occlusion refers to the phenomenon whereby the sun's rays are blocked by other heliostats when they enter the heliostat, resulting in some of the light being unable to enter the system. This occlusion phenomenon is primarily influenced by the position of the sun and the configuration of the heliostats.[5] In a multi-heliostat system, occlusion between the heliostats may result in some of the light being unable to be concentrated on the receiver, thus affecting the optical efficiency of the system. As illustrated in Figure 1 below:

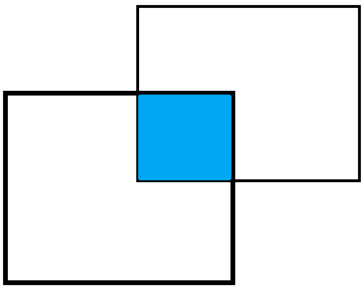

Figure 1: This caption has one line so it is centered

(2) Reflective blocking may result from the reflection of solar rays by heliostats, whereby some of the rays are blocked by adjacent heliostats, resulting in a reduction of light reaching a receiver. The position of the sun in the sky, and the configuration of heliostats, can affect the occurrence of reflective blocking. Reflective occlusion can reduce the amount of reflected light from a heliostat system, and thus the overall optical efficiency of that system.

2.1.2. Calculation method

The effectiveness of shadowing can be quantified by calculating the solar altitude angle, azimuth angle, and the position and orientation of the heliostat. The elevation angle and orientation of the heliostat are determined according to the laws of optical reflection and the coordinates of the heliostat. Finally, the shadowing of the heliostat can be calculated using the coordinate transformation equation for shadowing in literature [6] and the incident shadowing calculation method in literature [7]. The formula for the efficiency of shadowing is as follows:

$$\eta_{\text{shadow}} = \frac{\text{d}\tan\alpha_s}{\text{w}\cos\alpha_{\text{h}}(\tan\alpha_s+\tan\alpha_{\text{h}})} \tag{2}$$

2.1.3. Calculate solar altitude angle and solar azimuth angle

The solar altitude angle is the angle between the sun's rays and the earth's plane. The solar azimuth angle is the orientation of the sun in the horizontal direction, from which the heliostat model is constructed. This is illustrated in Figure 2:

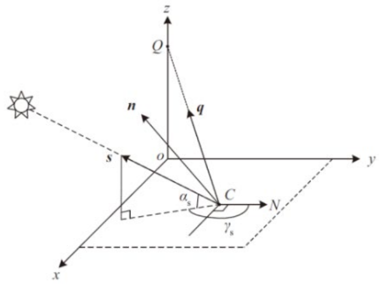

Figure 2: Fixed-mirror reflection model

In accordance with the heliostat model, the center of a heliostat is designated as C. Similarly, a heat-absorbing tower is designated as the center of the Q. The vector $\vec{q}$ represents the unit vector of the center of a heliostat, which in this case points towards the center of a heat-absorbing tower. This vector can be considered the reflection vector, as it reflects the vector of sunlight, designated as the vector $\vec{S}$ which points towards the center of the heliostat from the Sun. This vector is designated as the incidence vector. Finally, the orientation vector, $\vec{n}$, represents the heliostat's vector after being subject to the superposition of $\vec{q}$ and$\vec{S}$. This leads to the following equation:

$$\vec{q} = \left[\frac{-x_c}{\sqrt{x_c^2+y_c^2+z_q^2}}, \frac{-y_c}{\sqrt{x_c^2+y_c^2+z_q^2}} \frac{z_q}{\sqrt{x^2+y_c^2+z_q^2}}\right] \tag{3}$$

$$\vec{s} = (\cos\alpha_s sin\gamma_s, \cos\alpha_s \cos\gamma_s, \sin\alpha_s) \tag{4}$$

The angle α_s between the sun's unit vector $\vec{s}$ and the plane on which the heliostat is placed is the sun's elevation angle, and the angle γ_s on the horizontal plane of the heliostat is the sun's direction angle, as shown in the following formula:

$$sin\alpha_s = cos\omega cos\varphi cos\delta + sin\varphi sin\delta \tag{5}$$

$$cos\gamma_s = \frac{\sin\alpha_s \sin\varphi - sin\delta}{\cos\alpha_s \cos\varphi} \tag{6}$$

2.2. Cosine efficiency

Cosine efficiencies are important parameters in solar installations, used to evaluate how light angle affects installation performance. Cosine efficiency plays an important role in the optical efficiency of the system and describes the cosine between the angle of incidence of light and the normal to the light.

Cosine efficiency can be evaluated by calculating the cosine of the angle of incidence of the light. In solar systems, the angle of incidence of the light depends on the position of the sun and the orientation of the heliostat. The cosine efficiency can be maximised and the optical efficiency of the system increased by optimising the position and orientation of the heliostat. As shown in Figure 3:

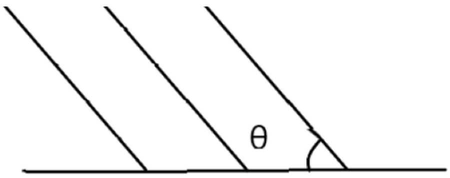

Figure 3: Cosine efficiency diagram

The relationship between the amount of sunlight received by the heliostat and the cosine of the angle of incidence of the sunlight on the heliostat's reflective surface is satisfied. As shown in Figure 2, the cosine value is as follows:

$$\cos(2\theta) = \frac{\vec{q}\cdot\vec{s}}{|\vec{q}||\vec{s}|} = \vec{q}\cdot\vec{s} \tag{7}$$

Using trigonometric transformations, the cosine efficiency can be expressed as follows:

$$\eta_{\cos} = \sqrt{\frac{\cos(2\theta)+1}{2}} \tag{8}$$

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2.3. Truncation efficiency

The truncation efficiency describes the percentage of solar energy absorbed by the top absorber of the solar tower compared to the energy reflected by the mirror. The incident solar radiation forms a cone of light, which undergoes reflection. As the absorber absorbs light within this cone area, it is considered truncation loss. This is illustrated in Figure 4:

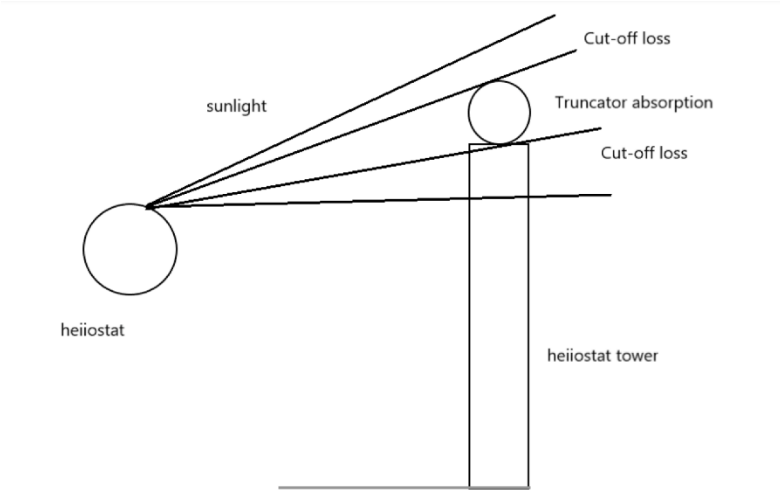

Figure 4: Truncation efficiency generation chart

Truncation efficiency may be evaluated through the calculation of the ratio between the absorbed energy by the absorber and that reflected by the mirror. The absorbed energy by the absorber may be established through calorimetric or temperature measurement techniques, whereas the energy reflected by the mirror may be quantified through spectral analysis or light power measurements. By optimizing the design and layout of the absorber, the cut-off efficiency may be optimized, thus improving the optical efficiency of the system. The formula for calculating the half-angle of the sun necessary for the cut-off efficiency is as follows:

$$\theta = \arcsin\left(\frac{R}{D(t)}\right) \tag{9}$$

The equation for the elliptic spot on the collector tower, as given in Formula (10) of this study, can be derived using the three cosines theorem as follows:

$$\frac{\cos^2(h_t)x^2}{{R_r}^2} f \frac{\cos^2(h_t)y^2}{{R_r}^2\cos^2(\alpha_r-\alpha_t)\cos^2(h_r-h_t)} = 1 \tag{10}$$

Using the collector, the double integral within the projection boundary is obtained:

$$\eta_t = \frac{1}{2\pi\sigma_{lot}^2}\int_x\int_y \exp\left(-\frac{x^2+y^2}{26^2 lot}\right)dxdy \tag{11}$$

In conclusion, the optical efficiency of the heliostat is primarily contingent upon the number and distribution of the heliostats. The objective of this paper is to demonstrate how the BFS and genetic algorithms may be employed to optimise the configuration of heliostats, thereby maximising the average optical efficiency of the entire heliostat field.

3. Analysis of the optical efficiency of the fixed-mirror field

3.1. Optical efficiency model construction

This paper presents a model for optimising the average optical efficiency of the heliostat field. Starting from the heliostat tower, the coordinates of each heliostat point are determined within a certain range to achieve the optimal average optical efficiency of the heliostat field.

3.1.1. Decision variables

In the heliostat array, the radial and circumferential spacing of the heliostats and the offset angle will affect the position and arrangement of the heliostats, which in turn will lead to changes in the optical efficiency. Therefore, the decision variables are radial spacing, circumferential spacing and offset angle.

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3.1.2. Objective function

$$\overline{\mathbf{W}}_{\mathbf{max}} = \frac{\sum_{i=1}^{12}\sum_{j=8}^{17} \mathbf{w(i,j)}}{\mathbf{12\times10}} \tag{12}$$

The variable W represents the average monthly optical efficiency of the heliostat field. The variable i represents the month from January to December. The variable j represents the time point from 8:00 to 17:00. Finally, the variable is the optical efficiency of a random day in month i at time point j (from 8:00 to 17:00).

3.1.3. Constraint condition

(1) The tower is 80 metres high; the circular heliostat field is 350 metres in diameter.

(2) The heliostats are rectangular with a length and width of 6 metres and a height of 6 metres.

(3) The weather is sunny all year round and the efficiency of the heliostats is not affected by the weather.

(4) The reflective surface of the heliostats is absolutely smooth and clean and the reflection of the heliostats is not affected by pollution; the heliostat field is located at 37 degrees longitude and 120 degrees latitude.

3.2. Breadth-first search settings layout

The Breadth-first search algorithm represents a graph search method that begins with the initial point and sets conditions for traversing the hierarchy in order to identify other points. This approach has proven to be particularly effective in solving path selection problems froms the initial point to the target point. In the optimisation of the heliostat layout, BFS is employed to identify an initial layout from the initial point to nearby points.

When initiating the configuration of the heliostat array, the possibility of collisions between the individual heliostats is considered. This is addressed by defining a relative distance as a BFS search condition. In accordance with the stipulated constraints, the distance between the centres of the adjacent heliostat bases must be at least five metres greater than the mirror surface. The formula is as follows:

$$\mathrm{DM} = \sqrt{\mathrm{l_m^2} + \mathrm{w_m}^2} + \mathrm{dS} \tag{13}$$

Among them, DM represents the relative distance, whereis the safety factor, which is set to 0.2m in this paper. l_m is the length of the heliostat, and w_m is the width of the heliostat.

In addition to the relative distance between the heliostats as a BFS search condition, this paper also selects the strategy of staggered arrangement [8]. The initial coordinate point is used as the centre to find the coordinate points of the staggered arrangement in a ring and the adjacent and continuous arrangement of the coordinate points in the same ring. The spacing between adjacent rings, that is, the radial spacing, and the circumferential angle between two heliostats in the same ring, that is, the circumferential spacing. By adjusting the radial spacing and circumferential spacing to lay out the mirrors, the spacing between each heliostat can be made closer and the layout more even.

In summary, the initial layout achieved by breadth-first search is shown in Figure 5:

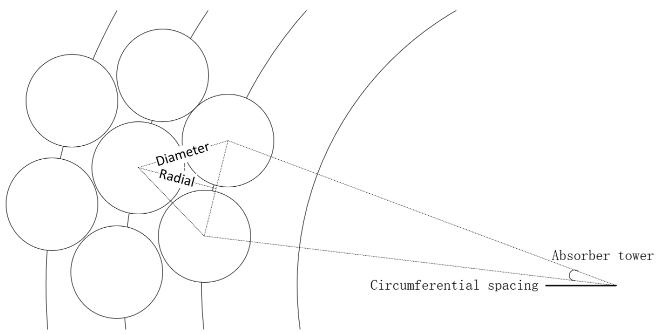

Figure 5: Staggered layout

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3.3. Layout optimisation based on genetic algorithms

Genetic algorithms (GAs) are a type of heuristic algorithm that, in contrast to traditional optimization techniques, employs an intuitive, random approach to draw general conclusions from a large amount of data. Rather than solving a local optimum to achieve a global optimum, GAs utilize a process of selection, crossover, and mutation to optimize the search space.

The optimization of the genetic algorithm in this paper is centered on the initial point. The BFS algorithm is employed to identify nearby coordinate points, which are then utilised in an iterative optimisation process involving selection, crossover and mutation operations. This process is applied to the radial spacing, circumferential spacing and offset angle in order to identify the optimal position. The optimal coordinate points are then set as the new initial point, and the iterative optimisation process is repeated until the optimal heliostat layout is identified.

The genetic algorithm in this paper is designed according to the diversity factor [9], which is defined as the proportion of individuals in the population that are different from one another. The greater the diversity factor, the greater the population diversity. The values of other parameters are continuously optimised in accordance with the specified criteria, as illustrated by the following formula:

$$s = \frac{k_k(f_{max} - f_{av})}{f_{av}} \tag{14}$$

Where k_k is a coefficient that controls the convergence speed of the result; $f_{max}$is the fitness of the optimal individual in the population; f_{av} is the average fitness of the population.

This paper requires an optimal layout of 2000 heliostats. According to the formula, the population can be set to 200, the number of iterations to 20, the mutation rate to 0.05, and the crossover rate to 0.8. The set of data with the highest optical efficiency is recorded as the result after all iterations. The optimal heliostat distribution varies over time, as illustrated in Figures 6, 7, 8, and 9, which depict the optimal heliostat distribution for specific time periods:

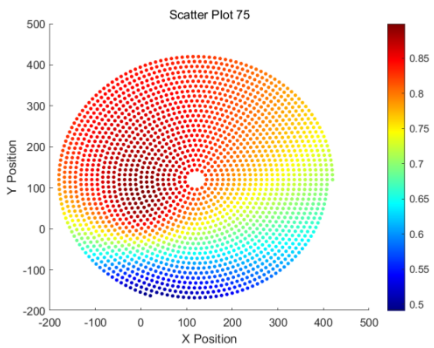

Figure 6: optical efficiency diagram 1

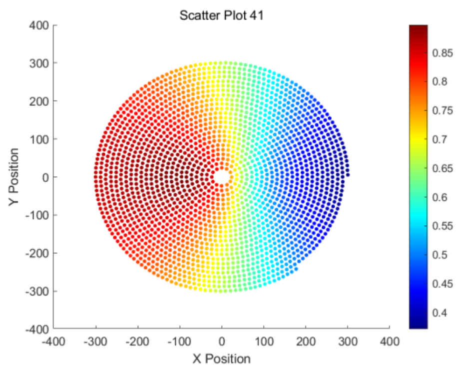

Figure 7: optical efficiency diagram 2

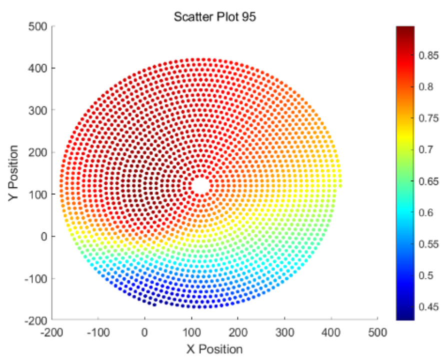

Figure 8: optical efficiency diagram 3

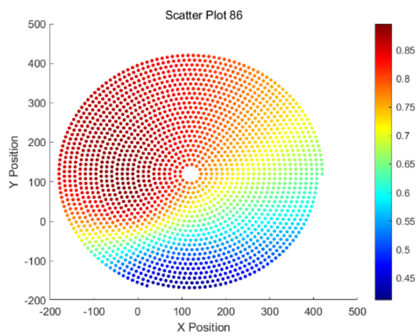

Figure 9: optical efficiency diagram 4

In comparison with the original data, the average monthly optical efficiency has also improved significantly, as shown in the figure 10s below:

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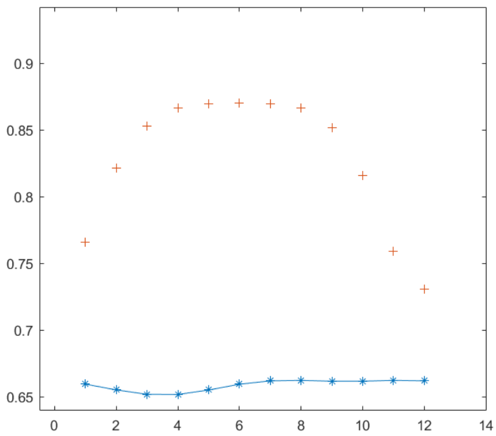

Figure 10: Average monthly optical efficiency comparison

Through analysis, the genetic algorithm used in this paper can effectively solve the problem of the distribution of heliostats and the optimisation of the radial and circumferential spacing. Compared with the traditional distribution method, it not only significantly improves the average optical efficiency of the heliostats, but also saves a lot of space for the arrangement of the heliostats.

3.4. Optimised operating speed

In the initial experiments, the time complexity of the BFS combined with GA optimisation was high, the running speed was slow, and the system would freeze when the data volume was large. In order to improve the running speed of the algorithm, the following optimisations were made in this paper:

(1) Parallel Computing: The BFS introduces a dynamic load balancing strategy, which combines both fine-grained and coarse-grained parallel strategies [10], in order to parallelize the BFS search process. As a consequence, this approach speeds up the node expansion process.

(2) Cache strategy: A cache strategy is introduced into the genetic algorithm to store intermediate results and avoid repeated calculations.

(3) Rapid evaluation of fitness: The fitness calculation process is simplified, and the fitness value of individuals is rapidly evaluated through pre-calculation and interpolation methods.

(4) The results of the experimental trials demonstrate that the optimisations described above result in a significant reduction in the time required to calculate the coordinates of 2000 heliostats. Furthermore, the running speed of the algorithm is significantly improved, and the time required for the optimisation process is reduced by approximately 30%.

4. Conclusion

This paper presents a new approach to optimising the layout of a heliostat field. The approach involves constructing an optical efficiency model for the heliostat field and using a new optimisation method that combines breadth-first search and genetic algorithms. The model takes into account the influence of decision variables such as radial spacing, circumferential spacing and offset angle on the optical efficiency. By defining the objective function and constraints, the model can accurately reflect the actual situation of the heliostat field. The initial layout of the heliostat field is generated using the breadth-first search algorithm, with the relative distance between the heliostats and the staggered arrangement strategy set to effectively solve the problem of collisions between the heliostats and ensure the uniformity and compactness of the layout. Finally, the initial layout is optimised further using a genetic algorithm. Through the application of selection, crossover and mutation operations, the radial spacing, circumferential spacing and offset angle are iteratively optimised, and the global optimum of the heliostat field layout is finally achieved, thereby achieving the optimal optical efficiency.

Although the layout of the heliostat field has been optimised in this paper, there are still some limitations: It should be noted that the simulation experiment presented in this paper does not take into account a number of practical environmental factors, including weather changes, mirror reflection losses,

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and heliostat ageing. It is therefore possible that the results may not be entirely accurate in real-world applications.

Furthermore, although parallel computing and caching strategies are employed, the computational complexity of the breadth-first search and genetic algorithm remains high, particularly when dealing with large-scale heliostat fields. This may result in bottlenecks in computing resources. Although a rapid evaluation method is introduced, the calculation of fitness still requires further simplification and optimisation to enhance the efficiency of the overall algorithm.

In conclusion,it is expected that the method for optimising the optical efficiency of heliostatic fields proposed in this paper will be more comprehensive and efficient to behold, so as to providing more robust support for the design and optimisation of solar heliostatic fields.

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