Optimization design of heliostat field parameters based on gray Wolf algorithm

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Abstract. Tower solar thermal power generation is the most promising way of light energy utilization in China at present, and it is also an important program to achieve the strategic goal of "carbon neutrality" and "carbon peak". In order to obtain the best solar optical efficiency and maximize the use of solar energy, how to design the relevant parameters of the heliostats field, the core equipment of tower solar solar thermal power generation, is extremely important. In this paper, the objective function, constraint conditions and decision variables are established based on the premise that the average annual output thermal power per unit mirror area is maximum and the rated average annual output thermal power of heliostat field is 60MW. Five specific times on the 21st day of each month are used to solve the relevant values, and several calculation models, including the sun position model and the optical efficiency model of heliostat field, are established. Then the grey Wolf algorithm is selected to optimize the model, and the decision variables are substituted into the grey Wolf optimization algorithm. When the Wolf pack updated the data every time, the decision variables were substituted into the DELSOL3 empirical layout, and finally the accurate and reliable heliostat field related layout parameters were obtained.

Keywords: Gray Wolf algorithm, DELSOL3 empirical layout, excellent.

1. Introduction

The implementation of large-scale tower solar thermal power generation is one of the most promising measures to use light energy to achieve the goal of "carbon peak" and "carbon neutrality". In this paper, under the condition that the average annual output thermal power of the heliostat field is 60MW, the size and installation height of all heliostats are the same and the rated power of the heliostat field is reached, in order to maximize the average annual output thermal power per unit mirror area, the Grey Wolf algorithm optimization model of the heliostat field is designed to calculate the relevant parameters.

2. Research methods

This paper establishes our objective function, constraint conditions and decision variables by taking the maximum annual average output thermal power per unit mirror area and considering the premise that the rated annual average output thermal power of heliostat field is 60MW.Then the grey Wolf algorithm is selected to optimize the model, and the decision variables are substituted into the grey Wolf optimization algorithm. Each time the Wolf pack updates the data, the decision variables are substituted into the DELSOL3 empirical layout, and the coordinates of each heliostat and their number N are calculated. Finally, after the completion of iteration, the data of each group are compared to get the optimal solution.

2.1. Modeling preparation

2.1.1. A mathematical model of the sun's position

In the concentrated solar heat utilization system, it is necessary to track the position of the sun with high precision to obtain the maximum heat utilization efficiency. When calculating the position of the sun, it is mainly based on the celestial coordinate system such as the horizon coordinate system, the first and second equatorial coordinate system, and the ecliptic coordinate system to describe the

apparent position of the sun relative to the Earth (the height Angle and azimuth Angle of the sun that can be observed on the Earth, but not the real position of the sun), and then derived from the spherical triangle formula [1]. Style definition: Formula: Paragraph spacing Before paragraph :0.5 line, after paragraph :0.5 line, font alignment: Center set format: Font: 4 set format: Font: 4 set format: Font: not bold set format: font: not bold set format: font: 4 set format: superscript.

On the premise of ensuring reliable data and simple method, the position relationship between the sun and the earth can be expressed more directly. The due east direction of the observation point is set as the X-axis, the due north direction as the Y-axis, and the directly above the observation point as the Z-axis. The sun altitude Angle αs is the Angle between the incoming light of the Sun and the earth plane, and the sun azimuth Angle βs is the Angle between the incoming light of the Sun and the shadow on the earth plane and the due north direction. However, the solution of solar altitude Angle and solar azimuth Angle belongs to the category of astronomy. It is necessary to first calculate the sun declination Angle δ as the sum hour Angle ω. On this basis, the sun altitude Angle αs in the horizon coordinate system is calculated as the square azimuth Angle βs by using the spherical trigonometric geometry method [2].

$$\sin \alpha_s = \sin \varphi \sin \delta + \cos \varphi \cos \delta \cos \omega \tag{1}$$

$$\sin \beta_s = (\cos \delta \cos \omega) / \cos \varphi \tag{2}$$

$$\cos \beta_s = (\sin \alpha_s \sin \varphi - \sin \delta) / (\cos \alpha_s \cos \varphi) \tag{3}$$

Where φ is the local latitude and the north latitude is positive. According to astronomical data, the hour Angle ω and the sun declination Angle δ are calculated as follows:

$$\omega = \frac{\pi}{12}(ST - 12) \tag{4}$$

$$\sin \delta = \sin \frac{2\pi D}{365} \sin (\frac{2\pi}{365} 23.45) \tag{5}$$

Where ST is the local Beijing time, and D is the number of days counting from the 0th day of the vernal equinox, as shown in Figure.1.

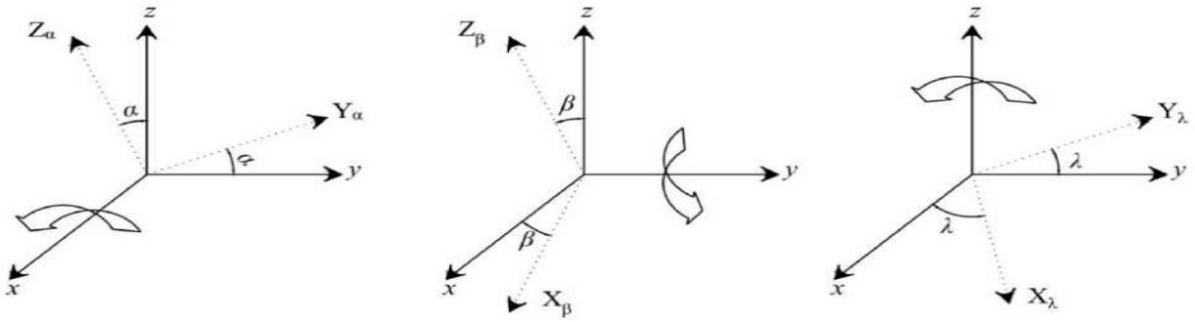


Figure 1. Definition of location-dependent parameters

2.1.2. DELSOL3 Experiential layout

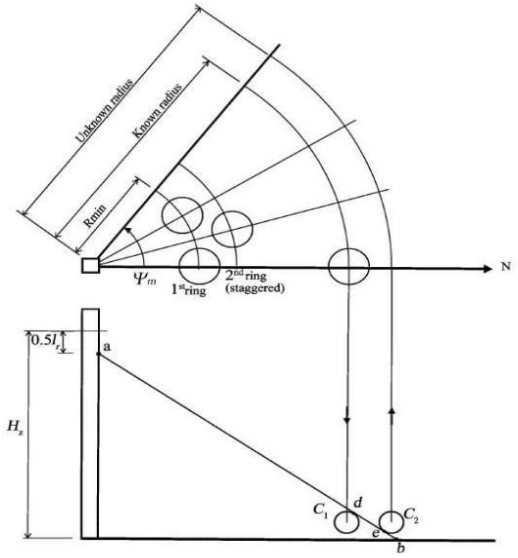


Figure 2. DELSOL3 experiential layout definition

Figure 2 shows a schematic diagram of the DELSOL3 layout. The original layout of the mirror field is defined by some basic parameters on the XOY plane, and the standard radial interleaving layout is adopted. In this layout, SW and SH are the width and height of heliostat, respectively.DM is the characteristic length of heliostat, $DM2=SW2+SH2$; $Rmax$ and $Rmin$ are the land boundaries of the mirror field. The basic ring is defined as the ring with heliostatic mirror on the positive north axis of the mirror field, and the staggered ring is the ring without heliostatic mirror [3].The mirror field is divided into n regions and defined ΔAz 1,1 is the azimuth spacing of the adjacent helioscopes on the first ring of the first region of the mirror field; similarly, ΔAzi,1 is the azimuth spacing of the adjacent helioscopes on the first ring of the i region of the mirror field, then the azimuth spacing of the adjacent helioscopes on the first ring of the first region of the mirror field can be expressed by the formula (6) [4].

$$\Delta A_{z1,1}=\Delta A_{z2,1}=\ldots=\Delta A_{zi,1}=(1.791+0.6396\theta)\,\mathrm{SW}+\frac{0.02873}{\theta_L-0.04902} \tag{6}$$

The number of heliostats on each ring in the same region of the mirror field is equal. Suppose that $N_{hel,i}$and i represent the number of heliostats on each ring in the i region, then:

$$N_{hel,i}=\frac{2\pi}{\Delta\alpha_{zi}} \tag{7}$$

Starting from the first ring of the first region of the mirror field, set ΔR=DM. When the ring radius increases to the i ring j ring, the radial distance $\Delta R_{i,j-1}$ =DM of the ring can no longer meet the requirement of no shadow and and occlusion loss, and the heliostatic mirror on the j ring begins to have shadow and and occlusion loss, so it is necessary to increase ΔR from the ring and recalculate ΔR value [4].

2.1.3. Wolf pack optimization algorithm model

The general model of Wolf optimization algorithm consists of four basic elements, which are: social hierarchy hierarchy, exploring prey, encircling prey, and attacking prey. It is inspired by the group predation behavior of gray wolves, and carries out the search and optimization process by simulating the process of wolves tracking, surrounding and hunting prey.

The general model of Wolf pack optimization algorithm consists of three basic elements:

(1): The gray Wolf algorithm controls the enclosure of the gray Wolf by the coefficient vector A. It is a random value between [-a, a]. When A>0, the gray Wolf enclosure is expanded, and the current optimal solution is jumped out, so as to find the global optimal solution. When 0>A, narrow the gray Wolf pack circle and prepare to attack the hunting target.

(2): The position signal is determined by random perturbations and direction vectors.
(3): The role of position update function: real-time data tracking of Wolf pack position

$$A = 2ar_1 - a \tag{8}$$

$$D_\alpha = |C_1.X_\alpha(t) - X(t) \tag{9}$$

$$X(t+1) = \frac{X_1+X_2+X_3}{3} \tag{10}$$

Grey Wolf optimization algorithm has more concise operation steps, more simplified setting parameters and stronger robustness. Compared with traditional artificial intelligence algorithms, Grey Wolf algorithm has faster convergence speed, higher solving accuracy and better performance, which is the reason why this paper chooses Grey Wolf optimization algorithm as optimization tool.

2.2. Model building

2.2.1. Solution of DNI for normal direct radiation irradiance

Solar normal direct irradiance DNI (DirectNormalIncidence) refers to the solar radiation energy received per unit area and per unit time on the horizontal plane of the earth, and its expression is as follows:

$$\text{DNI} = G_0\ [a + b\exp(-c\sin\alpha s)] \tag{11}$$

$$a = 0.4237 - 0.00821(6 - H)\ 2 \tag{12}$$

$$b = 0.5055 + 0.00595(6.5 - H)\ 2 \tag{13}$$

$$c = 0.2711 + 0.01858(2.5 - H)\ 2 \tag{14}$$

Where $G0$ is the solar constant, whose value is 1.366kW/m2, and H is the altitude (unit: km).

2.2.2. Mathematical model of optical efficiency of heliostat field

The optical efficiency model of mirror field is based on the solar position model. The optical efficiency distribution of mirror field represents the optical efficiency distribution of each heliostat in the mirror field at a certain time, which belongs to the microscopic characteristics. The formula is calculated by optical efficiency.

$$\eta = \eta_{\text{sb}} + \eta_{\cos} + \eta_{at} + \eta_{trunc} + \eta_{ref} \tag{15}$$

Type, η_{sb} is Yin and screening efficiency, $\eta_{\cos}$ is cosine efficiency, η_{at} is atmospheric transmittance, η_{trunc} is cutting collector efficiency, η_{ref} is mirror reflection rate, this paper to solve the problem of mirror reflection rate take constant 0.92 [5].

2.2.3. Shadow occlusion efficiency mathematical model

Shading and shielding efficiency is the ratio between the mirror area without shading and shielding and the total mirror area of the mirror field.

The figure shows the schematic diagram of shade and occlusion loss of a heliostat. Shade and occlusion loss refers to the loss caused by the incoming light of a heliostat and the occlusion of one or more surrounding heliostat. Occlusion loss refers to the loss caused by the reflection of a heliostat and the occlusion of one or more surrounding heliostat. Considering that the calculation accuracy of Monte Carlo light and tracking method depends on the size of the tracking light and number, the higher the accuracy, the longer the calculation time, so this paper adopts the shadow and shadow method to calculate the shadow and blocking efficiency. The calculation diagram is shown in Figure 3 below [6]:

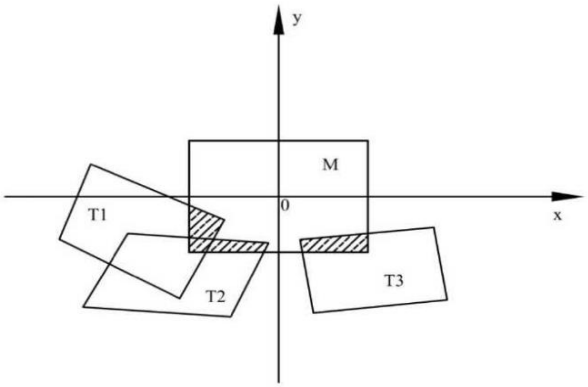


Figure 3. Shading and shading efficiency diagram

It is assumed that the sunlight is parallel, the adjacent heliostat is located in a parallel plane, and the shadow and occlusion area is rectangular, ignoring the overlap of the shadow and occlusion in the calculation process.

The solution process is as follows:

Each heliostat A is assigned a group of heliostat that may have shade and occlusion, and the heliostat B that is marked with possible interference.

Calculate the vector $\boldsymbol{i_B}$of heliostat pointing towards interferometric heliostat B

(3) The possibility of heliostat interference is determined as follows:

(a) Assuming that heliostat B is within the target range of interfered heliostat A, calculate the dot product of the mirror method of heliostat A and the vectors $\boldsymbol{n_A}$ and $\boldsymbol{i_B}$, as shown in Equation (16).

$$\boldsymbol{\lambda = n_A . i_B} \tag{16}$$

In the formula, if $\boldsymbol{\lambda}$ <0, no shadow occlusion loss will occur.

(b)The maximum interference length is calculated based on the vertex coordinates PA and PB of heliostatic mirror A and B.

The height of mirror A is H_A, the mirror tracking vector of heliostatic mirror A is t_A, and the zenith Angle of the tracking vector is $\emptyset_{t,b}$The maximum interference length can be calculated by the following formula (17).

$$L_{int} = \frac{P_{B,Z} - P_{A,Z} + H_A sin_{\emptyset_{t,B}}}{\frac{t_{B,K}}{\sqrt{t_{B,i}^2 + t_{K,j}^2}}} \tag{17}$$

Where, if the distance between heliostat A and B is greater than Lint, the heliostat will not interfere and the shadow blocking efficiency is 1; Lint usually cannot exceed $100H_A$ when the sun altitude Angle is low, which can reduce the number of heliostat B that may cause interference and meet the calculation requirements.

(4) Project $\boldsymbol{i_B}$ from two corners of heliostat B onto plane A to determine whether the intersection is in plane A.

(5) Calculate the area of the disturbed region A_{inter} according to the coordinates of the intersection of $\boldsymbol{i_B}$ in plane A.

The heliostat area is Am, then the shadow and occlusion efficiency of the disturbed heliostat A can be expressed by equation (18).

$$\eta_{sb} = 1 - \frac{A_{inter}}{A_m} \tag{18}$$

2.2.4. Cosine efficiency mathematical model

Cosine efficiency loss is one of the most serious efficiency losses in mirror field. In order to reflect sunlight onto the heat absorber, there must be an Angle and an Angle between the incoming sunlight and the heliostat mirror method. The cosine value of this Angle is defined as the cosine efficiency,

and the Angle θ is the cosine Angle. The cosine efficiency represents the actual lighting area of the mirror. Figure 3 shows the schematic diagram of cosine efficiency, the cosine efficiency value is equal to the ratio of the actual lighting area of the heliostat to the mirror area. The smaller the Angle θ, the higher the cosine efficiency, and vice versa. The relevant schematic diagram is shown in Figure 4 below [7]:

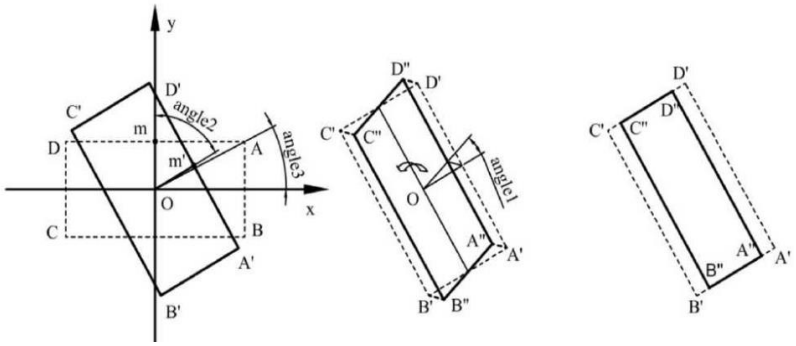


Figure 4. Cosine efficiency diagram

Hypothesis: the center coordinate of the heliostatic mirror is (x, y, z), the coordinate of the target point on the heat absorber is (0, 0, H), H is the height of the center point of the heat absorber from the ground, s is the unit vector of the sun incident light, r is the unit vector of the mirror reflected light, and n is the unit vector of the mirror normal. According to the reflection law of mirror light, the incidence Angle of heliostat mirror is equal to the reflection Angle, and the calculation formula of cosine efficiency obtained by combining geometric vector method is shown in Equation (19).

$$\eta_{cos} = \cos\theta = \left|\frac{(1+\cos(2\theta))}{2}\right| = \left|\sqrt{\frac{1-s.r}{2}}\right|$$
$$s = (-\cos\alpha_s \sin\gamma_s, -\cos\alpha_s \cos\gamma_s, -\sin\alpha_s) \quad (19)$$
$$\text{r}=(-x,-y,H-z)/\sqrt{x^2+y^2+(H-z)^2}$$

2.2.5. Mathematical model of atmospheric transmittance

In the process of solar light reflection from heliostat to heat absorber, there is the absorption and scattering of solar radiation by atmosphere, which causes the loss of attenuation efficiency. The degree of attenuation is usually related to altitude, atmospheric conditions (e.g. dust, evaporation,Gas, carbon dioxide) and other factors. The atmospheric attenuation efficiency is the ratio of the solar radiation energy reaching the opening of the heat absorber to the solar radiation energy reflected by the heliostat. The relevant calculation formula is as follows:

$$\eta_{at} = 0.99321 - 0.0001176 d_{HR} + 1.97\times10^{-8}\times d_{HR}^2 \quad (20)$$

Among:

$$d_{HR}=\sqrt{x^2+y^2+(H-Z)^2} \quad (21)$$

d_{HR} is the distance from the center of the mirror to the center of the collector.

2.2.6. Collector truncation efficiency model

As an important part of the optical efficiency of heliostat field, truncation efficiency refers to the ratio of the solar radiation energy projected on the surface of the heat absorber to the total solar radiation energy reflected by the heliostat. The formula for solving the collector truncation efficiency is as follows:

$$\eta_{trunc}=\frac{\text{The collector receives energy}}{\text{Total reflection energy} - \text{Shadow occlusion energy loss}} \quad (22)$$

2.2.7. Heliostat field output thermal power per unit time calculation

$$E_{field} = DNI \cdot \sum_i^N A_i \eta_i \tag{23}$$

DNI is the irradiance of normal direct radiation;N is the total number of heliostats (unit: face);Ai is the daylighting area of the i heliostat (unit: m2); ηi is the optical efficiency of i mirror[8].

2.2.8. Calculation of annual average output thermal power of heliostat mirror field

$$E_{field,y} = \frac{\sum_{i=1}^{12} \sum_{j=1}^{5} \int_{t_1}^{t_2} E_{field}}{60} \tag{24}$$

Among them, t_1 is 9:00, 10:30, 12:00, 13:30, 15:00 on the 21st of every month local time; t_2 is the time after 30s interval with each t_1 ;$Efield$, y is the average annual output thermal power of heliostat field[9].

2.2.9. Heliostat field output thermal power per unit area per unit time

$$E_{field,s,t} = DNI \cdot \sum_i^N \eta_i \tag{25}$$

Where, $E_{field,s,t}$ are the output thermal power per unit area per unit time of fixed day field.

2.2.10. Calculation of average annual output thermal power per unit area of heliostat field:

$$E_{field,s,y} = \frac{\sum_{i=1}^{12} \sum_{j=1}^{5} \int_{t_1}^{t_2} E_{field,s,t}}{60} \tag{26}$$

Where $t_1$is 9:00, 10:30, 12:00, 13:30, 15:00 on the 21st of every month local time; t_2 is the time after 30s interval with each $t1$; $E_{field,s,y}$are the average annual thermal output power per unit area of heliostat field.

2.2.11. Typical daily mean optical efficiency distribution

Due to the limitation of data processing time, the average optical efficiency distribution of typical days can be calculated first, and then the annual average optical efficiency can be solved by this method. The average optical efficiency distribution of typical days can be further calculated from the average daily optical efficiency of any heliostat.

The daily average optical efficiency of any heliostat is calculated as follows:

$$\bar{\eta}_{field,d} = \frac{\sum_{i=1}^{5} \int_{t1}^{t2} \eta_i(t) dt}{5 \int_{t1}^{t2} dt} \tag{27}$$

In the above formula, t_1 is 9:00, 10:30, 12:00, 13:30, 15:00 on the 21st of every month local time; t_2 with each$t_1$time interval after the 30 s, $\bar{\eta}_{field,d}$ is mirror of the daily average optical efficiency of heliostat I value; $\eta_i(t)$ is the optical efficiency of any heliostat i at time t in the mirror field.

2.2.12. Annual mean optical efficiency distribution of mirror field

The calculation of the annual average optical efficiency of the mirror field can be obtained by summing and averaging the typical daily average optical efficiency distribution. The set typical day is the 21st day of the month, so only these 12 data can be calculated, which greatly reduces the calculation amount, but has reliable results.

$$\bar{\eta}_{field,t} = \frac{\sum_{i=1}^{12} \bar{\eta}_{field,d}}{12} \tag{28}$$

$\bar{\eta}_{field,t}$ is the annual average optical efficiency of the mirror field calculated by the typical heliographic efficiency.

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average daily optical efficiency of any heliostat. The daily average optical efficiency of any heliostat is calculated as follows [10]:

$$\bar{\eta}_{field,d} = \frac{\sum_{i=1}^{5}\int_{t1}^{t2}\eta_i(t)dt}{5\int_{t1}^{t2}dt} \tag{29}$$

Heliostat field output thermal power per unit area per unit time:

$$E_{field,s,t} = DNI\cdot\sum_{i}^{N}\eta_i \tag{30}$$

Based on the calculation formula of relevant parameters of heliostat field and Wolf pack optimization model, the final heliostat field optimization layout model is established:

$$\begin{cases} X(t+1)=F(x) \\ E_{field,s,t} = DNI\cdot\sum_{i}^{N}\eta_i \\ E_{field,s,y} = \frac{\sum_{i=1}^{12}\sum_{j=1}^{5}\int_{t_1}^{t_2}E_{field,s,t}}{60} \end{cases}$$

3. Result analysis

Four decision variables are introduced into the Grey Wolf optimization algorithm, namely: heliostat size, mirror heightD_1 , mirror width D_2, position coordinate of absorber (x_0,y_0), installation height H. Every time the Wolf pack updates the data, the four variables will be substituted into the formula of DELSOL3 empirical layout in the model preparation, the coordinates of each heliostata $(x_i,y_i)$and its number N will be calculated, and the data will be saved, and all the data will be compared after iteration. The optimal solution of the average annual thermal output power per unit mirror area E_F is obtained. The iterative operation diagram and related mirror field layout parameters are shown as follows(Figures. 5, 6, 7):

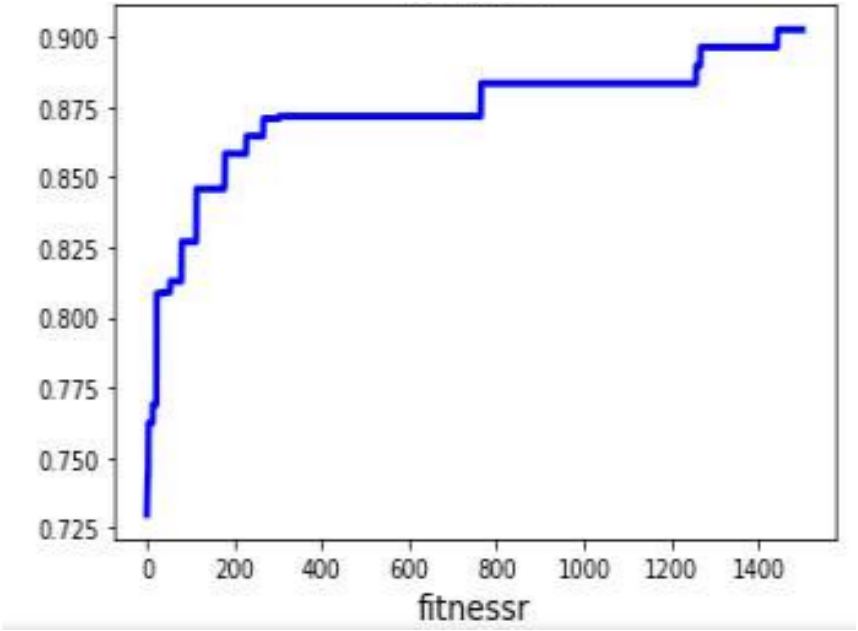


Figure 5. Graph

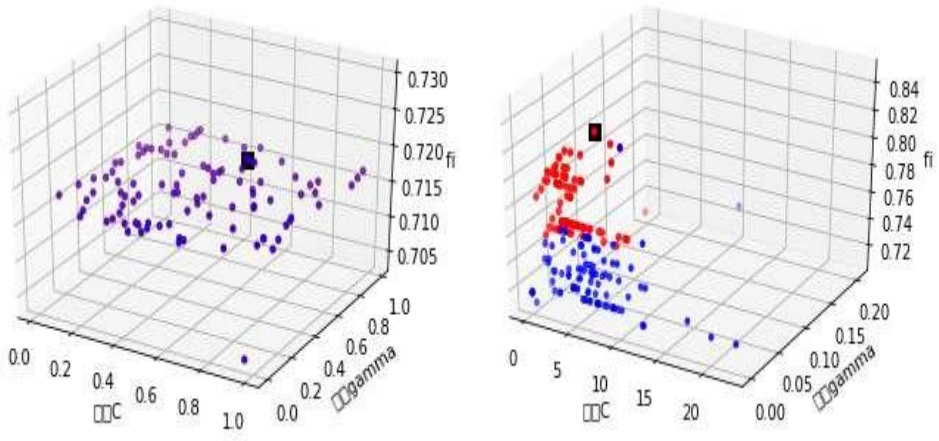


Figure 6. Initial iteration diagram (left) and Wolf pack movement and change diagram (right)

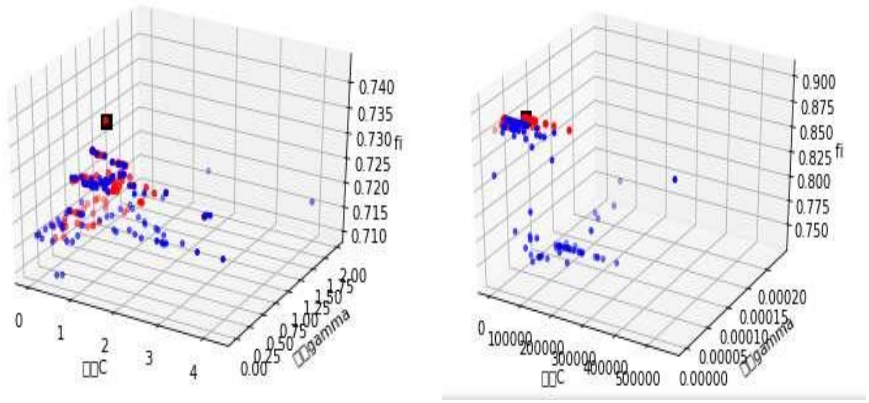


Figure 7. Pack movement and change map (left) and Final iterative pack location map (right)

Table 1. Parameters related to heliostat layout

Average annual optical efficiency	Annual mean cosine efficiency	Average annual shading efficiency	Average annual truncation efficiency	Average annual thermal input power (MW)	Average annual thermal output per unit area (KW/m^2)
0.699321	0.849341	0.96	0.940444	77.07166808	1.118765

From the point of view of data, the parameters of heliostat field obtained by grey Wolf optimization have excellent agreement with the practice, which can fully meet the optimization needs, and the optimization speed is fast and the operation is convenient (Table 1.).

4. Conclusion

The trend of massive heliostatic field data provides a basis for the analysis of layout characteristics and the establishment of optimization models, but the traditional layout methods can not bear such a huge consumption of time and computing resources. The overfitting problem of large sample sets will affect the prediction accuracy. This paper uses the heliostat field parameter calculation mechanism to establish a corresponding calculation model, adopts DELSOL3 empirical layout to make full use of Matlab's powerful data processing function, and establishes a heliostat field optimization model based on Wolf pack optimization algorithm to obtain the heliostat field related

layout parameters. After analysis, the data is in good agreement with the practice, which proves that our model has good practicability.

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