

# Research on Multi-Objective Optimization of Heliostat Field Based on DELSOL3 Layout

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**Abstract.** With the intensification of global climate change, it is urgent to reduce greenhouse gas emissions and protect the environment. To address this issue, it is crucial to develop the new energy industry and increase the proportion of clean energy. Tower solar power, as an innovative and environmentally friendly technology with low carbon emissions, has great potential and broad prospects. This study determines the position of the absorption tower, heliostat size, and installation height. By utilizing the ground coordinates of the heliostats and given formulas, parameters such as average optical efficiency, cosine efficiency, shadow blocking efficiency, and cut-off efficiency are calculated. The focus is on power loss caused by shading, so a shadow blocking model is constructed by using differential methods. The heliostat plane is divided into equal sections, and it is determined whether the transformed coordinates of the mirror plane are within the grid. The effective blocked area is then calculated to obtain the shadow blocking efficiency. To improve the efficiency and reduce costs of solar thermal power plants, the standard radial staggered layout in DELSOL3 empirical layout is adopted. A multi-objective optimization model is established with heliostat size and height as variables. The optimal solution for the average output thermal power per unit mirror area is obtained through genetic algorithms. Through mathematical modeling and solution methods, this study provides theoretical basis for the application of tower solar power.

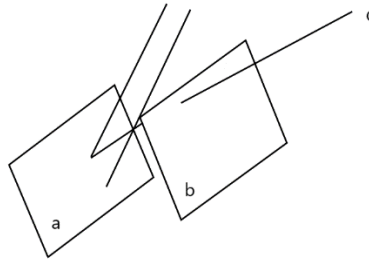
**Keywords:** Heliostat Field, Difference Method, Multi-objective Optimization, Genetic Algorithm.

## 1. Introduction

Zhang Ping has conducted a detailed analysis of the shadow and light loss in solar power generation systems, including the shadow and light loss between towers and mirror fields, as well as between heliostats<sup>[1]</sup>. He proposed the use of ray tracing and differential methods to construct a shadow blocking model for calculating the blocking efficiency of heliostats<sup>[2]</sup>. Meanwhile, Sun Hao modeled the optical efficiency of heliostats, particularly focusing on the calculation process of shadow blocking efficiency<sup>[3]</sup>. In addition, the DELSOL3 empirical layout is widely used in solar power systems, which alternately places heliostats at constant radius along equal azimuth lines. To optimize this layout, researchers have introduced genetic algorithms to solve multi-objective optimization problems<sup>[4]</sup>.

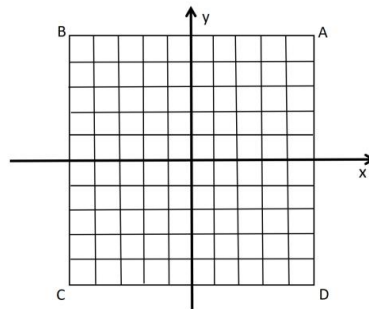
## 2. Research on average shadow occlusion efficiency based on ray tracing method

The shadow blocking loss mainly includes three parts: propagates along a straight line, and sunlight cannot bypass the absorption tower and collector to illuminate the rear heliostat; During the propagation of sunlight, the front row of heliostats blocks the incident light from the rear row of heliostats, causing losses; reflected light from the rear row of heliostats is blocked by the front row of heliostats, preventing the light from spreading to the collector. As shown in Fig 1, this article provides a comprehensive discussion of these three situations:



**Fig 1.** Light blocking diagram

First, the plane of mirror B  $O_{xy}$  is equally divided into 100 parts. A certain point on the plane of mirror A  $O(x, y, 0)$  will  $O$  be transformed to the point on mirror B  $O''(x'', y'', 0)$  through the transformation of the spatial geometric coordinate system. As shown in Fig 2, it is assumed that the shadow of the absorption tower is along  $x$  the axis of the ground coordinate system. At this time, the absorption tower and the collector are regarded as one, collectively called the absorption tower. The shadow coordinates of the two vertices of the absorption tower<sup>[6]</sup> are respectively for  $E(\frac{88}{\tan \alpha_s}, 7, 0)$ ,  $F(\frac{88}{\tan \alpha_s}, 0, 0)$ . Transform the point  $E$  to the B mirror  $E(x_E, y_E, 0)$  through the spatial geometric coordinate system transformation, and the coordinates are.



**Fig 2.** Mirror B after equalization

If it satisfies  $x_B \leq x'' \leq x_A$  and  $y_D \leq y'' \leq y_A$  or or  $x_B \leq x_E \leq x_A$  and  $y_D \leq y_E \leq y_A$ , then  $P_j^i = 0$ ; otherwise,  $P_j^i = 1$ . Among them,  $i$  it represents the row,  $j$  represents the column, and represents  $P_j^i$  the value of the point in the row and column  $j$  of the grid, that is:

$$P_j^i = \begin{cases} 0, x_B \leq x'' \leq x_A, y_D \leq y'' \leq y_A \text{ or } x_B \leq x_E \leq x_A, y_D \leq y_E \leq y_A \\ 1, \text{else} \end{cases} \quad (1)$$

Taking any small square in the grid diagram as an example, the values of the four vertices are  $P_j^i$  represented by. If one of the four vertices has a value of 1, it is regarded as the occluded area, that is.

$$\text{Obscured area} = \sum_{i=1}^n M \square S_i \quad (2)$$

Among them,  $n = 100$ ,

$$M = \begin{cases} 0, x_B \leq x'' \leq x_A, y_D \leq y'' \leq y_A \text{ or } x_B \leq x_E \leq x_A, y_D \leq y_E \leq y_A \\ 1, \text{else} \end{cases} \quad (3)$$

Represents  $S_i$  the area of each small square, which is 0.36 square meters.

And because the shadow occlusion efficiency is:

$$\eta_{sb} = 1 - \text{Shadowing loss} \tag{4}$$

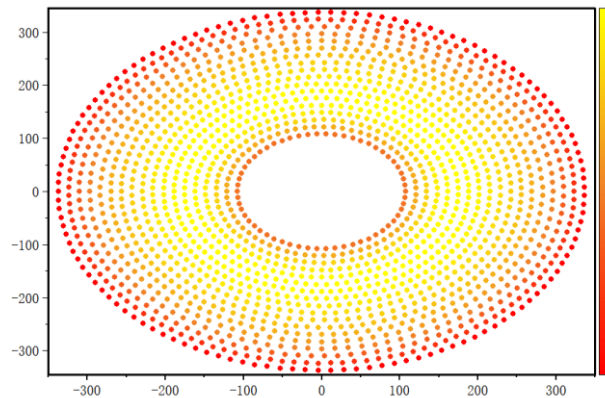
Among them,  $\text{Shadowing loss} = \frac{S_{occlusion}}{S}$ ,  $S = 36$ .

Finally, the average annual shadow occlusion loss is:

$$\text{Annual average shadowing loss} = \frac{\sum \frac{S_{occlusion}}{36}}{12} \tag{5}$$

With the help of the mathematical model of the optical efficiency of a single heliostat, you only need to bring in the corresponding condition requirements and perform ergodic averaging. The specific process is as follows:

Use origin to visualize the coordinate points of the given helioscope, as shown in Fig 3:



**Fig 3.** Heliostat coordinate distribution

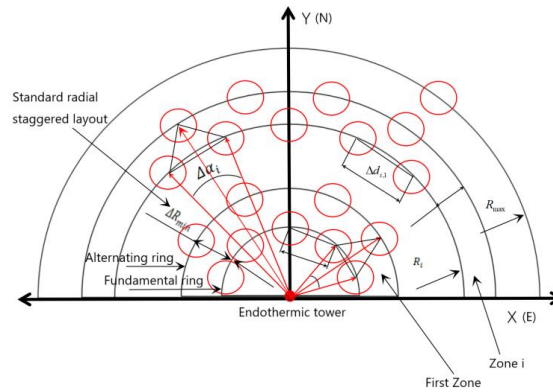
### 3. Optimize the heliostat field based on genetic algorithm and using DELSOL3 empirical layout

#### 3.1. Preparation of model

Genetic algorithm is an optimization algorithm inspired by natural selection and inheritance in biological evolution. By continuously generating new "offspring" from the initial population and selecting the best ones by evaluating their "fitness"<sup>[5]</sup>. During this process, some individuals will mutate and produce better solutions. Eventually, the genetic algorithm will find the optimal solution.

#### 3.2. Model establishment

In the mirror field coordinate system, this article can determine the bottom position coordinates of the absorption tower as (0,0,0). The number of heliostats is explored by using the DELSOL3 empirical layout. The definition of the DELSOL3 layout is shown in Fig 4. The initial layout of the mirror field is defined on  $O_{XY}$  the plane through some basic parameters. This question decided to use the standard radial staggered layout in the DELSOL3 empirical layout.



**Fig 4.** DELSOL3 layout format

In this layout,  $R_{max}$  and  $R_{min}$  are the land boundary range of the mirror field, the staggered ring is defined as the ring without heliostats, and the basic ring is the ring with heliostats on the north axis of the mirror field.  $DM$  is the characteristic length of the heliostat,  $SW$  is the width of the heliostat, and  $SH$  is the height of the heliostat. The three have a relational expression:

$$DM^2 = SW^2 + SH^2 \quad (6)$$

Divide the mirror field into  $n$  regions. It is defined  $d_{1,1}$  as the azimuth spacing between adjacent heliostats on the first ring of the first region of the mirror field. Similarly,  $d_{i,1}$  it is  $i$  the azimuth spacing of the heliostats on the first ring of the first region of the mirror field. Then the mirror field is divided into regions. The azimuth distance between adjacent heliostats in the first ring of each area of the field can be expressed by the following formula:

$$\Delta d_{1,1} = \Delta d_{2,1} \cdots = \Delta d_{i,1} = (1.791 + 0.6396\theta_L) \square SW + \frac{0.02873}{\theta_L - 0.04902} \quad (7)$$

Among them,  $L$  is the angle between the normal line of the heat absorber surface and the line connecting the center of the heliostat mirror and the target point on the heat absorber.

After the first ring is studied, this article uses geometric methods to solve the azimuthal distance between adjacent heliostats on the remaining rings. Assuming that the azimuth spacing reset limit, factor is, when  $d_{lim}$  the ratio of the azimuth spacing of the heliostats on the last ring and the first ring in the  $d_{lim}$  mirror field area is greater than or equal  $i$  to, the first  $i + 1$  area starts to be arranged. It is defined  $\Delta\alpha_1$  as the azimuth angle of adjacent heliostats in the first area of the mirror field,  $\Delta\alpha_2$  and is the azimuth angle of adjacent heliostats in the second area. Similarly,  $\Delta\alpha_i$  it is  $i$  the azimuth angle of adjacent heliostats in the  $i$ th area, Then the calculation formula of the azimuth angle can be expressed as:

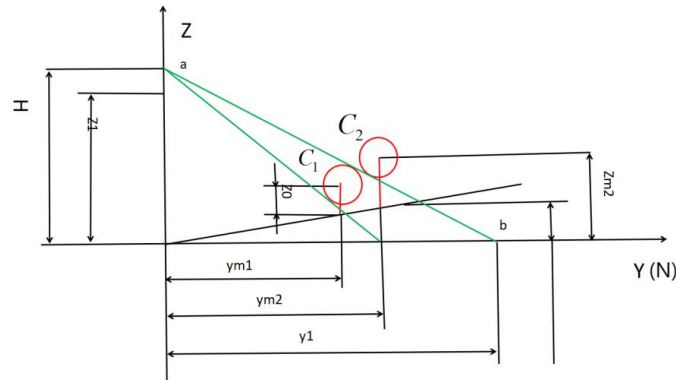
$$\Delta\alpha_1 = 2^0 \Delta\alpha_2 = \cdots 2^i \Delta\alpha_i = \arcsin \left( \frac{\Delta d_{1,1}}{2R_{1,1}} \right) \quad (8)$$

Among them,  $R_{1,1}$  represents the innermost ring radius of the first area of the mirror field,  $R_{1,1} = R_{min}$  ( $R_{min}$  the value is known).

The number of heliostats on each ring of the mirror field in the same area is equal. Assuming that it  $N_{r_i}$  represents  $i$  the number of heliostats on each ring in the area, then:

$$N_{r_i} = \frac{2\pi}{\Delta\alpha_i} \quad (9)$$

Starting from the first ring of the first area of the mirror field, set  $\Delta R$  the constant  $DM$ . As the ring radius gradually increases, the heliostat begins to suffer from shadow and occlusion losses. When the ring radius increases to the  $i$  area  $j$  ring, the radial spacing of the ring  $\Delta R_{i,j-1}$  is equal to the  $DM$  value that cannot meet the requirements of no shadow and no occlusion loss. The heliostats on the  $j$  ring begin to experience shadow and occlusion losses, so the value needs to be increased  $R$  and recalculated starting from the ring  $R$ , and then determined according to the minimum radial spacing of adjacent heliostats without shadow occlusion losses  $\Delta R$ , and the drawing method is used to draw as follows Fig 5 shows a schematic diagram of the ring radius without occlusion loss.



**Fig 5.** Schematic diagram of ring radius without occlusion loss

In Fig 5, it is assumed that  $C_1$  the heliostat on the first  $C_2$  regional ring of  $j-1$  the mirror field represents  $i$  the heliostat on the first  $ab$  regional ring of  $j$  the mirror field. The line segment  $i$  represents the process of the heliostat  $C_1$  reflecting sunlight to the collector. The reflected light has no The lowest route of occlusion intersects  $C_1$  the circle at  $e$  the point and  $Y$  the axis at  $b$  the point.  $z_1$  is the height of the lowest point of the collector  $a$  from the ground,  $y_1$  is  $b$  the distance from the point to the bottom of the absorption tower,  $z_0$  is the vertical distance from the center of the heliostat to the ground;  $y_{m1}$ ,  $y_{m2}$  are the radius of  $i$  the regional  $j-1$  ring (known ring) and  $j$  ring (unknown ring) respectively,  $\beta_L$  Indicates the land tilt angle of the mirror field relative to the absorption tower, taken  $\beta_L = 0$ .

the straight line can be obtained from the geometric relationship  $ab$  :

$$\frac{y}{y_1} + \frac{z}{z_1} = 1 \quad (10)$$

According to  $C_2$  the coordinate equation of the circle,  $(y - y_{m2})^2 + (z - z_{m2})^2 = (0.5SH)^2$  the radius of the ring of the first  $R_{i,j}$  area  $j$  of the mirror field can be obtained  $i$  as:

$$R_{i,j} = y_{m2} = \frac{-B - \sqrt{B^2 - 4AC}}{2A} \quad (11)$$

Among them,  $A = -z_1^2 y_1^2$ ,  $B = 2z_1 y_1 (z_1 - z_0)$ ,  $C = \left(\frac{SH}{2}\right)^2 (1 + z_1^2 y_1^2) - (z_1 - z_0)^2$ ,  $y_1 = \frac{-b + \sqrt{b^2 - 4ac}}{2a}$ ,  
 $a = z_1^2 \left[ (0.5SH)^2 - y_{m1}^2 \right]$ ,  $b = 2y_{m1} z_1 (z_1 - z_0)$ ,  $c = (0.5SH)^2 - (z_0 - z_1)^2$

Then the radial spacing of the  $i$  th area  $j$  ring can be expressed as:

$$\Delta R_{i,j-1} = R_{i,j} - R_{i,j-1} \quad (12)$$

Finally, using the angle between the true north axis of the mirror field and the radiation axis of each region  $\phi$  and the radius of any ring  $R_{i,j}$ , the coordinates of the center point of the heliostat can be calculated  $(x_m, y_m, z_m)$ :

$$\begin{cases} x_m = R_{i,j} \sin \phi \\ y_m = R_{i,j} \cos \phi \\ z_m = z_0 \end{cases} \quad (13)$$

Assume that the installation height of the heliostat is  $h_i$ , the width of the heliostat is  $SW$ , and the height of the heliostat is  $SH$ , where  $2 < h_i < 8$ ,  $2 < SW < 8$ ,  $2 < SH < 8$ . The final multi-objective optimization model established is:

$$\text{Objective function: } \max \frac{60}{SW \square HW}$$

$$s.t. \begin{cases} 2 < h_i < 8 \\ 2 < SW < 8 \\ 2 < SH < 8 \end{cases} \quad (14)$$

### 3.3. Solution of the model

#### 1) Design of initial population

This article studies the coding method of genetic algorithm using real number coding rules. The size and height of heliostats are arranged in order from 1 to 1 in units of meters (which is  $N$  the  $N$  number of heliostats). That is, the disordered arrangement of 1 to 1 represents individual genes, a chromosome  $N$  Corresponds to a type of joint guidance path. According to the initial chromosomes, multiple random arrangements of 1 to 1 are randomly generated as the initial population of the genetic algorithm  $N$  [6].

#### 2) Fitness function design

The fitness function is used in genetic algorithms to evaluate the strengths and weaknesses of each individual in solving problems to evaluate algorithm performance [7]. This article studies the problem that the objective function of the corresponding mathematical model is the maximum value, so the fitness function is constructed as follows:

$$F_m = \bar{E}_{field} \quad (15)$$

#### 3) Genetic manipulation design

(1) Selection operator: According to the selection probability, the random traversal sampling method is used to select a certain number of excellent individuals and store them in the next generation population [8].

(2) Crossover operator: Based on the crossover probability, partial matching crossover is used. The starting and ending positions of several genes in a pair of chromosomes are randomly selected in the parent generation through the crossover probability (the two chromosomes are selected at the same position), and then the selected two groups are exchanged. Gene fragments, based on the mapping relationship between the two gene fragments, perform gene conflict detection on the parents in sequence to ensure that the generated offspring genes have no conflicts [9].

(3) Mutation operator: According to the mutation probability, the gene value of one or some genes is changed to other allele values for each individual in the population [10].

The above steps have completed the simplification of the solution process for the maximum solution of the annual average thermal power output per unit mirror area. The genetic algorithm is used to

screen the combinations of heliostat size and height one by one until the optimal solution that meets the requirements of the problem is screened out. The solution results are shown in the table 1.

**Table.1.** Annual average optical efficiency and output power table

Average annual optical efficiency	Average annual cosine efficiency	Average annual shadow occlusion efficiency	Average annual cutoff efficiency	Annual average thermal power output (MW)	Annual average thermal output of mirror per unit area (kW/m <sup>2</sup> )
0.704	0.855	0.98	0.940	63.470	1.235

#### 4. Conclusion

The ray tracing method is combined with the difference method to propose a new method for calculating shadow occlusion efficiency. This method includes a simplified programming model using the overall coordinate system and an efficient pre-judgment model, which can better calculate the shadow occlusion area., compared with the original ray tracing method, the improved algorithm is significantly better in terms of calculation simplicity, accuracy and calculation speed.

DELSOL3 combines empirical layout and genetic algorithms to find the optimal number of heliostats on the premise of minimizing shadow occlusion between heliostats, and then uses the genetic algorithm to determine the combinations of heliostat sizes and heights one by one. Screening, the improved algorithm improves the land utilization of heliostat fields and the efficiency of tower solar thermal power stations.

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