Optimization Design of Tower Solar Heliostat Field Layout of Based on Wheatfield-PSO Model

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Abstract. The heliostat field is an important subsystem of the tower solar thermal power station, and the optimal layout of the heliostat field is one of the key issues to be solved in the early stage of the construction of the tower solar thermal power station. Aiming at the optimization of heliostat field layout and related parameters in tower solar thermal power station, this paper presents a heliostat field layout method based on Wheatfield-PSO model, taking the product of the comprehensive optical efficiency of the mirror field and the land coverage of the mirror field as the optimization objective. Based on the basic parameters of heliostat field in Gansu, China, the Reverse Projection Box Counting Model is innovatively established in this paper to calculate each optical efficiency simply and efficiently. Considering the important influence of heliostat size on system performance, this paper sets the size and mounting height of each heliostat to be the same, and seeks other design parameters under this premise. By introducing the optimization design method of the mirror field of the Wheatfield tower solar thermoelectric system, and using the PSO algorithm to solve it, the optimal parameter combination is found to make the annual average output power per unit mirror area reach the maximum value, and the heliostat mirror field layout is designed.

Keywords: Tower Solar Heliostat Field, Reverse Projection Box Counting Model, Wheatfield-PSO Model.

1. Introduction

With the continuous growth of global energy demand and the increasing concern of environmental protection, tower solar thermal power station as a green and renewable energy technology, how to arrange high efficiency and low-cost heliostat field has become a hot research topic. In order to design the optimal heliostat field layout, scholars have provided many optimization schemes from different angles. For example, Collado et al. [1] proposed the Campo heliostat field layout method, generating a regular and flexible radial staggered heliostat field, which can solve the problem of large shadow and blocking loss of circular outer ring heliostats. O. Farges et al. [2] optimized and redesigned the PS10 solar fields. Sun Hao [3] studied and optimized the heliostat field layout based on the hybrid strategy whale optimization algorithm but failed to comprehensively consider the contradiction between the number of heliostats and the comprehensive optical efficiency of the heliostat field.

In this paper, based on the Monte Carlo Ray Tracing method [4], an innovative Reverse Projection Box Counting Model is established, which effectively solves the problem that the shadow area of a heliostat is repeatedly calculated when it is blocked by multiple heliostats. Taking the product of the comprehensive optical efficiency and the land coverage of the heliostat field as the optimization objective, the Wheatfield-PSO model is established to solve the optimal parameter combination efficiently and accurately.

2. Optical efficiency and thermal power of the heliostat field

In the tower solar thermal power station, the ratio of the energy received by the solar thermal collector to the total energy of the incident light is called the optical efficiency of the heliostat field. The energy conversion rate of the collector to convert light energy into heat energy is called the output thermal power of the heliostat field. The optical efficiency and thermal output power of heliostat field

are affected by many factors such as solar position, environment, heliostat field parameters, etc., which is the basis to measure the optimization degree of a heliostat field layout.

2.1. Calculation of optical efficiency and thermal power

In general, the total optical efficiency of a heliostat field consists of five components: shadow blocking efficiency η_{sb}, cosine efficiency η_{cos}, atmospheric transmission η_{at}, collector truncation efficiency η_{trunc} and specular reflectivity η_{ref}. The formula is as follows:

$$\eta = \eta_{sb} \cdot \eta_{cos} \cdot \eta_{at} \cdot \eta_{trunc} \cdot \eta_{ref} \tag{1}$$

In the actual calculation, the specular reflectivity η_{ref} is usually recorded as a constant, and the other 4 parts are mainly calculated. In this paper, the calculation of cosine efficiency η_{cos}, atmospheric transmission η_{at} and collector truncation efficiency,η_{trunc} is mainly based on the basic algorithm proposed by relevant scholars [5], and a new algorithm — Reverse Projection Box Counting Model is applied to calculate shadow blocking efficiency η_{sb}.

Output thermal power of the heliostat field is E_{field} [6]:

$$E_{field} = DNI \cdot \sum_i^N A_i \eta_i \tag{2}$$

Where DNI is the normal direct radiant irradiance, N is the total number of heliostats, A_i is the light harvesting area of the ith heliostat, η_i is the optical efficiency of the ith heliostat.

2.2. Guidelines for the evaluation of heliostat field efficiency:

The optical efficiency of heliostat field varies from moment to moment due to changes in the sun's position. In order to comprehensively evaluate the optical efficiency and thermal output of heliostat field, the "monthly average method" is adopted as the evaluation index of heliostat field.

"Monthly average method" means that one day is selected as the representative day of the month in a certain way in the 12 months of a certain year, and the optical efficiency and output thermal power of each moment are calculated respectively on the representative day, and then the average value is calculated to approximately represent the average annual optical efficiency and output thermal power of the heliostat field. The calculation formulas are as follows:

$$\tilde{\eta} = \sum_{i=1}^{12} \int_{t_1}^{t_2} \eta(t)\, dt / \left(\sum_{i=1}^{12} \int_{t_1}^{t_2} dt\right) \tag{3}$$

$$\widetilde{E_{field}} = DNI \cdot \sum_m^N A_m \widetilde{\eta_m} \tag{4}$$

where i is the month serial number, t_1 and t_2 are the starting and ending time points of daily observations; m is the heliostat serial number.

2.3. Calculation of shadow blocking efficiency

In order to improve the calculation accuracy of the optical efficiency of heliostat field, so as to better measure the optimization degree of heliostat field layout, the Reverse Projection Box Counting Model is used to calculate the shadow blocking efficiency.

The reverse projection model is mainly used to distinguish the blocking problem of adjacent heliostat. The accurate identification of the blocking problem of adjacent heliostats is the basis of the optimization of the heliostat field arrangement rule, and the accurate solution of this problem can effectively improve the comprehensive efficiency of the heliostat field. The basic principle of blocking discrimination is shown in Figure 1.

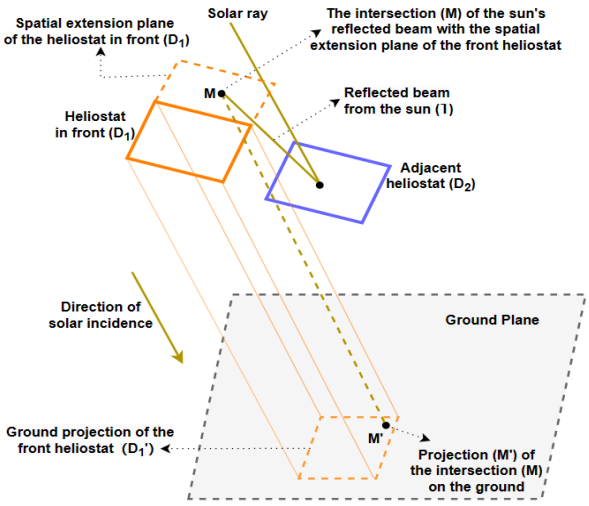


Figure 1. The principle of blocking discrimination

If $M' \in D_1'$, there is an obstruction; if $M' \notin D_1'$, there is no obstruction.

The box counting model mainly uses the idea of differential element to divide the mirror evenly and densely into several squares and solves the problem of repeated calculation of the blocking area and the difficulty of calculating the irregular blocking area by the method of the feature representing the whole. The calculation principle is shown in Figure 2.

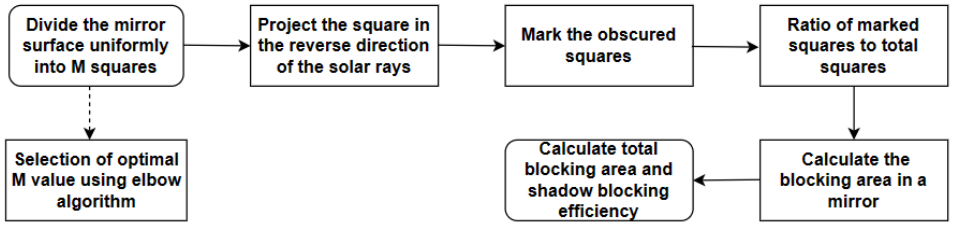


Figure 2. The principle of Box counting model

Assuming that the area of the mirror is S, the number of markers is I, then the blocking area of a heliostat is:

$$A_{sb} = {}^{I}/_{Z} \cdot S \tag{5}$$

the shadow blocking efficiency is:

$$\eta_{sb} = \frac{A_i}{A_t} = 1 - \frac{\sum_i^N A_{sbi}}{A_t} \tag{6}$$

where A_t is the total heliostat area, N is the total number of heliostats, and i is the serial number of heliostats.

3. Establishment of Wheatfield-PSO model

3.1. Wheat field layout optimization method

This paper adopts an optimization design method for the heliostat field of a wheat field tower solar thermoelectric system [7], which takes the product of the comprehensive optical efficiency and the land coverage of the heliostat field as the optimization objective and adopts the simplex algorithm to optimize the distance from the first arranged heliostats to the absorption tower in the heliostat field, and the column distance and row distance between each heliostat. So that the number and arrangement of heliostats in a particular case, optimize the target value of the maximum. This method can solve

the contradiction between the number of heliostat and the optical efficiency of the heliostat field, and the simplex algorithm has better robustness and stability.

3.1.1 Simplex optimization algorithm

In this paper, the heliostat field optimization design method of the Wheatfield tower solar thermoelectric system is used. The simplex optimization algorithm is used to obtain the optimal solution of heliostat size and heliostat coordinate under the condition that the product of the total optical efficiency and the land coverage of the heliostat field is optimal [8]. The simplex optimization algorithm flow is shown in Figure 3.

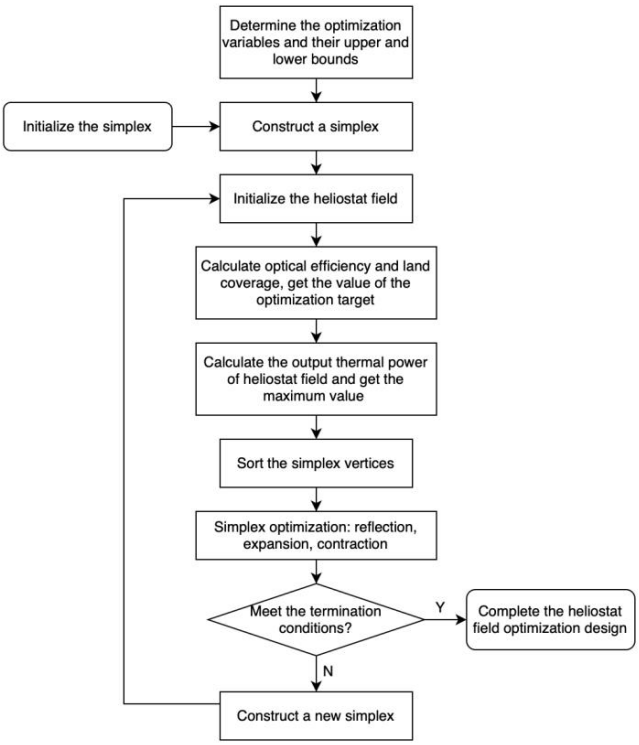


Figure 3. Flow chart of simplex optimization algorithm

3.1.2 Establishment of wheat field tower solar heliostat field

Define the safe distance between two adjacent heliostats $A(size: a_A \times b_A)$and$B(size: a_B \times b_B)$ without collision:

$$DM = 0.5a_A + 0.5a_B + 5 \tag{7}$$

In order to reduce the search time of the algorithm, the maximum row spacing and column spacing between heliostats (that is, the search upper bound) should ensure that there is no obstruction between heliostats, that is, when sunlight is tangent to the equivalent circles of helioscopes A and B respectively, l is the maximum. If l is greater than $0.5a_A + 0.5a_B$, then B will not block A at any time, so take $L_1 = a_A + a_B$, as shown in Figure 4.

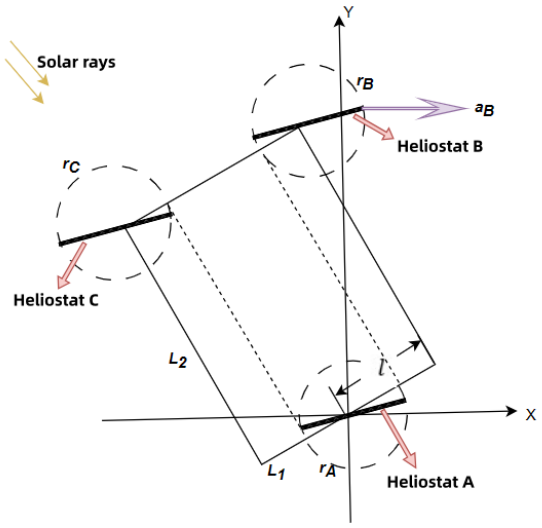


Figure 4. Geometric analysis of heliostat spacing

Therefore, the search upper and lower bounds of column spacing between heliostats are $[DM, a_A + a_B]$. By analyzing the tangent relationship between the incident solar rays and the lower edge of heliostat, it can be concluded that the search upper and lower bounds of the line spacing between heliostat is $[DM, \max(DM, (b_A + b_B)/sin\alpha_s)]$.

The number of heliostats in the field can be calculated according to the distance between the heliostats and the absorption tower in the first arrangement, the values of column spacing dx and row spacing dy, as well as the land area of the given circular region and the size of the heliostats. The calculation formula for the number of columns $JMAX$ and the number of rows $IMAX$ of heliostats in the field is as follows:

$$\begin{cases} JMAX = floor(700/dx) \\ IMAX = floor(700/dy) \end{cases} \tag{8}$$

where $floor$ is rounded down.

Therefore, the coordinate expression of the heliostat in row j and column i is:

Even lines (counting from line 0):

$$\begin{cases} x = i \cdot dx - (IMAX - 0.5) \cdot dx/2 \\ y = -j \cdot dy \\ z = H_h \end{cases} \tag{9}$$

Odd lines:

$$\begin{cases} x = (i + 0.5) \cdot dx - (IMAX - 0.5) \cdot dx/2 \\ y = -j \cdot dy \\ z = H_h \end{cases} \tag{10}$$

The center coordinate $O_n(x_n, y_n, z_n)$ of all heliostats in the field are calculated and the heliostat field is generated.

3.2. Multi-start point particle swarm optimization algorithm (PSO algorithm)

The multi-start point particle swarm optimization algorithm comes from the research on the predation behavior of birds [9] and seeks the optimal solution through the cooperation and information sharing among individuals in the group. The basic idea of PSO algorithm is the solution of the target problem is called "particle", and the particle is searched in n-dimensional space. The current position of the particle is a candidate solution of the corresponding optimization problem, and the search speed of the particle can be dynamically adjusted according to the historical optimal position of the particle and the historical optimal position of the population. The optimal individual

extremum in the particle swarm is taken as the current global optimal solution, and the speed and position are updated iteratively, and finally the optimal solution satisfying the termination condition is obtained.

The formula for particle iteration update rate and position is as follows:

$$v_i = \omega \times v_i + c_1 \times rand() \times (pbest_i - x_i) + c_2 \times rand() \times (gbest_i - x_i) \quad (11)$$

where v_i is the velocity of the particle; $rand()$ is a random number in $(0:1)$; x_i is the current position of the particle; c_1 and c_2 is the acceleration factor; ω is a dynamic and inertial factor, and its value is non-negative. According to the dynamic change of some measure function of PSO performance, the greater the value, the stronger the global optimization ability and the weaker the local optimization ability.

Here we use a linearly decreasing weight function:

$$\omega = \frac{(\omega_{ini} - \omega_{end})(G_k - g)}{G_k} + \omega_{end} \quad (12)$$

where, G_k is the maximum number of iterations; ω_{ini} is the initial inertia weight, which is 0.9; ω_{end} is the inertia weight when iterating to the maximum evolutionary algebra, where 0.4 is taken.

The algorithm flow chart is shown in Figure 5.

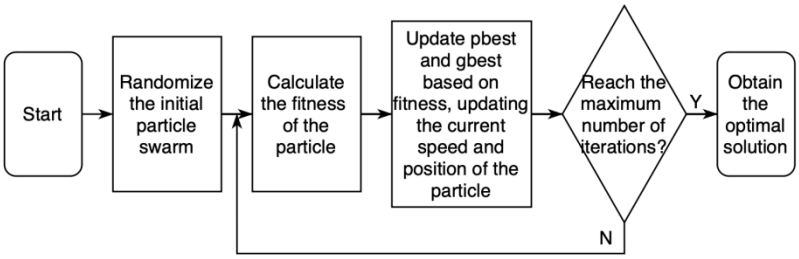


Figure 5. Flow chart of PSO algorithm

4. Model solving and testing

4.1. Parameter Settings

In order to verify the rationality and accuracy of the model, this paper refers to the relevant parameters of "Rongyan Tower Photothermal Power Station" in the photoelectric industrial park of Dunhuang City, Gansu Province, China, and selects five typical time points (9, 10:30, 12:00, 13:30, 15:00) on the 21st of each month in 2021 as the simulation time. The optimal layout of heliostat field, optical efficiency and maximum output thermal power are calculated by using the model with given parameters. The related parameters are set in Table 1.

Table 1 Parameters of target heliostat field

Parameters	Numerical value
Latitude/(°)	39.4
Longitude/(°)	98.5
Altitude/(m)	3000
Absorption tower height/(m)	80
Collector height/(m)	8
Collector diameter/(m)	7
Heliostat field radius/(m)	350
Specular reflectance	0.92

4.2. Solution result

In this paper, the special situation of wheat field optimization method is considered, that is, the heliostat size and mounting height of each side are set to be the same, and the optimal solution is carried out.

Settings:

$$\begin{cases} a_A = a_B \\ b_A = b_B \\ z_A = z_B \end{cases} \tag{13}$$

Total number of heliostats

$$m = JMAX \times IMAX \tag{14}$$

Total area of heliostats

$$S = \sum_1^m (a_n \cdot b_n) \tag{15}$$

where a_n, $b_n$is the size of the heliostat n.

Particle swarm optimization (PSO) is used to solve the problem. The results of relevant heliostat field parameters are shown in Table 2. The solution results of each optical efficiency and maximum output thermal power are shown in Table 3. The heliostat field layout is shown in Figure 6.

Table 2 The result of the model calculation in heliostat field

Absorption tower position coordinates	Heliostat size$(m \times m)$	Heliostat height (m)	Number of heliostats	Total heliostat area(m^2)
(0, -200)	3.5×3.5	2	8440	103390

Table 3 The result of the model calculation in optical efficiency

η $/year$	η_{cos} $/year$	η_{sb} $/year$	η_{trunc} $/year$	E_{field} $/year\ (MW)$	$E_{field}/mirror/year\ (kW/m^2)$
0.6169	0.8501	0.8262	0.9976	62.1498	0.6012

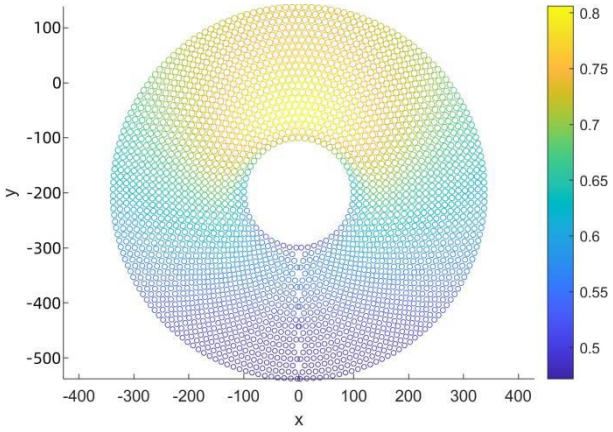


Figure 6. Schematic diagram of heliostat field distribution

4.3. Model test

Monte Carlo Ray Tracing method is one of the main methods to study the optical efficiency of heliostat field, but large sample data will greatly delay the calculation speed. Based on this dilemma, Noone [10] proposed a boundary grid method with low computational accuracy based on relevant knowledge of computational fluid mechanics. The Wheatfield-PSO model proposed in this paper has high calculation speed and good calculation accuracy, and the overall optical efficiency reaches more

than 80%, which is 10% higher than the existing general heliostat field. The comparison of computing speed between Maitian PSO model and Noone model is shown in Figure 7.

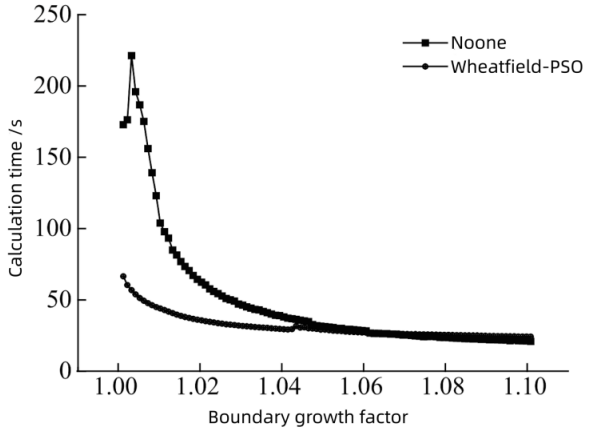


Figure 7. Computing speed comparison chart

5. Conclusion

In this paper, a more efficient and accurate model, the Wheatfield-PSO model, is proposed to optimize the heliostat field layout in the tower solar thermal power station. After solving calculation and analysis, the following conclusions are obtained:

(1) The reverse projection box counting model proposed in this paper can effectively solve the problems of repeated calculation of the blocking area between adjacent heliostats and the difficult calculation of irregular blocking area, and better and more efficiently solve the layout optimization problem of the heliostat field.

(2) The Wheatfield-PSO model proposed in this paper solves the contradiction between the number of heliostats and the comprehensive optical efficiency of the heliostat field. The calculation speed is fast, the calculation accuracy is good, and it has better robustness and stability, which greatly improves the maximum output thermal power of the heliostat field and provides a reference for the future design of the heliostat field.

(3) PSO algorithm is simple and easy to operate, but its performance largely depends on the selection of parameters. The selection of these parameters needs to be adjusted according to the problem, and this process usually requires a certain amount of experience and experimentation.

References

[1] Gao Bo, Liu Jianxing, Sun Hao et al. Optimal arrangement of heliostat field based on adaptive gravitational search algorithm[J]. Journal of Solar Energy, 2022, 43(10): 119-125.

[2] O. Farges, J.J. Bezian, M. El Hafi, Global optimization of solar power tower systems using a Monte Carlo algorithm: Application to a redesign of the PS10 solar thermal power plant [J], Renewable Energy, 2018, 119: 345-353.

[3] Sun H. Research and optimization of heliostatic mirror field layout based on hybrid strategy whale optimization algorithm [D]. Lanzhou Jiaotong University, 2022.

[4] Bobin D, Jinghui M, Dong Z, et al. Thermal performance of a directional heat radiation device utilizing the Monte Carlo ray tracing method[J]. Applied Thermal Engineering, 2022, 217.

[5] Liu Jianxing. Optical efficiency modeling simulation and heliostat field optimization layout for tower-type photovoltaic power plant[D]. Lanzhou Jiaotong University, 2022.

[6] Du Yuhang, Liu Xiangmin, Wang Xingping et al. Influence analysis of different focusing strategies for heliostatic mirror in tower photothermal power station [J]. Journal of Power Engineering, 2020, 40(05): 426-432.

[7] Guan Guangyi, Zhang Yanmei, Liao Wenjun et al. Effect of Different heliostats Field Arrangement on Optical Efficiency of Mirror Field [J]. Equipment Machinery, 2017(01): 6-10.

[8] Zhang Wenning, Zhou Qinglei, Jiao Chongyang, et al. Particle swarm optimization algorithm with barycentric reverse Learning and simplex search [J]. Computer Engineering and Science, 2023, 45(09): 1629-1638.

[9] Wang Jiangxiang, Xiao Qingquan. Prediction of breast cancer compound activity based on particle swarm optimization [J]. Intelligent Computer and Applications, 2019, 13(07): 45-52.

[10] Noone C J, Torrilhon M, Mitsos A. Heliostat field optimization: A new computationally efficient model and biomimetic layout[J]. Solar Energy, 2012, 86 (2): 792-803.