Optimization of Heliostat Layout in Central Receiver Solar Power Plants

Pouyan Talebizadeh[1]; Mozaffar Ali Mehrabian[2]; and Hasan Rahimzadeh[3]

Abstract: In this paper, the main aim is to optimize the heliostat layout in central receiver solar power plants in order to achieve the maximum heliostat field efficiency using a genetic algorithm as an optimization tool. First, an algorithm is developed based on vector geometry in order to select an individual heliostat and then calculate its characteristic angles at any time and location. The process of the program will be applied to track the Sun as a control function. The best configuration is obtained by considering the radial staggered layout of the heliostat field. The locations of the heliostats are determined, and the efficiency of each heliostat is calculated to find the most appropriate condition with the highest efficiency. Calculating the power of each heliostat supplied on the receiver will make it possible to determine the absorbed total heat power. At this stage, the genetic algorithm is applied to find the best heliostat layout to obtain the maximum efficiency of the field for a specific absorbed power supplied on the receiver. The results show that by changing the design parameters, i.e., increasing the tower height and decreasing the heliostat height by 7.7 and 19.5%, respectively, the total efficiency of the field is increased by almost 4% and the total area of heliostats is decreased by 17%. In other words, a more efficient heliostat layout can be achieved by choosing new design parameters. **DOI:** 10.1061/(ASCE)EY.1943-7897.0000162.

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Introduction

The idea of a central receiver solar power plant (CRSPP) was first discussed in 1956 by Baum et al. (1957), who planned to use 1,300 mirrors and put them on wagons and turn the wagons around a boiler. The CRSPP is known as one of the least expensive power plants to produce solar electricity on a large scale. In this system, the solar radiation is reflected by the surrounding heliostat field onto a receiver, and then the energy is converted into thermal power to generate electricity. The surrounding heliostat field has a significant cost contribution in CRSPP—almost 50% of the total cost and 40% of the total losses are assigned to the heliostat field. Therefore, the design and optimization of the heliostat field layout are very important (Kolb et al. 2007). Lipps and Vant-Hull (1975) studied four categories of heliostat arrangement for a 100 MW power plant. They introduced a cell model to establish an array of representative heliostats. They showed that a north–south staggered configuration was suitable for a southern field; however, a radial staggered configuration could be used universally. Collado and Turegano (1989) presented a procedure for evaluating the annual energy produced by a defined heliostat field as a product of annual energy per mirror and annual average mirrors per unit area. They presented an analytical function for the blocking factor as one of the main parameters in the optimization process in a radial staggered configuration that allows the necessary radial increment between consecutive rows that verifies a fixed blocking factor to be established.

Siala and Elayeb (2001) presented a graphical method for a no-blocking radial staggered layout and introduced a mathematical formulation for the method. They divided the field into certain groups to increase the efficient use of land. They showed that the method is simple when compared to a cellwise procedure. In a cellwise method, the heliostat field is divided into a number of units or cells, and each cell includes a set of heliostats. In each cell, the distance between the heliostats is considered constant. This assumption causes an error in calculations. Collado (2009) introduced a simplified procedure to define a large number of heliostat coordinates mainly by two parameters, i.e., a simplified blocking factor and an additional security distance throughout the field. He determined the layout of a heliostat field for a constant blocking factor and height of a tower in Almeria, Spain. He compared his work with the previous cellwise method. Zhihao et al. (2009) modeled a 1 MW solar thermal CRSPP in China that is under construction. They developed a software tool called *Heliostat Field Layout Design* (HFLD) for the heliostat field layout design and performance calculation and simulated the whole CRSPP using the *TRNSYS* model (Schwarzbozl and Eiden 2002) library for solar thermal electric components (STECs). In their work, which is based on energy balance, Zhihao et al. (2009) presented the mathematical procedure for calculating the absorbed power supplied on a receiver. Xiudong et al. (2010) developed a new method for the design of a heliostat layout for a solar power tower. They considered the efficiency factor as the product of the annual cosine efficiency and the annual atmospheric transmission efficiency of a heliostat and showed that the results are as good as considering the annual interception efficiency.

Leonardi and D'Aguanno (2011) developed a new computer program to simulate the optical performance of a CRSPP and to calculate the cosine efficiency and the shading and blocking factors of each individual heliostat. They studied square, circular, and mixed square-circular heliostat layouts. They considered the number, dimension, shape, and position of the heliostats accurately in

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their calculations. In addition to the aforementioned articles, numerous studies in the literature have investigated CRSPP from the viewpoints of efficiency, energy, and distribution of the heliostat field. Kribus et al. (2000) investigated experimentally and numerically the performance of a new kind of rectangular concentrator called secondary concentrators. Kribus et al. (2004) presented a closed-loop control method for tracking the Sun by the heliostats versus the open-loop method and showed lower tracking error with this method. Sanchez and Romero (2006) studied the yearly energy available at any point in a heliostat field for a specific tower height and found the location of each heliostat according to this parameter. Schramek et al. (2009) compared different heliostat layouts and presented a close-packed heliostat field with high ground coverage. They showed that a higher annual performance could be achieved; nevertheless, this layout has more blocking and shading factors. Collado (2010) compared two flux density models, i.e., determining the flux density reflected by a heliostat to a receiver. Xu et al. (2011) presented the theoretical procedures to analyze a CRSPP using molten salt as the heat transfer fluid according to energy and exergy concepts to identify the possibilities of thermodynamic improvement.

The aim of the present study is to optimize a surrounding heliostat field for a given absorbed incident power into a receiver. For this purpose, the heliostats' characteristic angles, the coordinates of each heliostat, the efficiency of the layout, and the power produced by the high-efficiency heliostats should be specified for each set of the operating parameters. The optimization is done for a CRSPP with 20 MW thermal power due to the use of only high-efficiency heliostats. Note that the method of optimization of the heliostat layout presented in this paper is being used for the first time. In other words, to the authors' best knowledge, no one has employed search techniques to optimize the heliostat layout in a CRSPP. In addition, all previous researchers evaluated heliostat fields on the basis of one parameter and found the optimum value for a certain parameter.

Process of Modeling Heliostat Layout

The method of Colloda (2009) is used in this paper to design a heliostat layout. In this method, the radial increment between consecutive and staggered rows (ΔR) is defined as (Colloda 2009)

$$\Delta R = \left[\left(\frac{\cos\theta}{\cos\varepsilon_T}\right)\left(1 - \frac{(1-f_b)wr}{2wr - (\sqrt{1+wr^2}+ds)}\right)\right] \times LH \quad (1)$$

The parameter f_b is the blocking factor, i.e., the ratio of the heliostat area free of blocking to the total area of the heliostats. The parameter wr is the width-height ratio of the heliostat, the parameter LH is the height of the heliostat, and the parameter $ds \times LH$ is any additional security distance between adjacent heliostats in the same row. The parameter θ is the incidence angle of the sunrays onto the heliostat surface, and the parameter ε_T is the elevation angle of the tower unit vector pointing from the center of the heliostat surface to the receiver. The parameters θ and ε_T are shown in Fig. 1.

To determine the parameters θ and ε_T, an algorithm is developed based on the vector geometry to pick an individual heliostat and calculate its characteristic angles at any time of the day and any day of the year. As shown in Fig. 2, the unit vector along the reflected ray directed to the Sun is shown by $\vec{s}$, the unit vector along the reflected ray directed to the receiver is shown by $\vec{r}$, and the unit vector along the reflected ray normal to the reflective plane is shown by $\vec{m}$.

The unit vector $\vec{m}$ determines the orientation of the mirror plane with respect to the Sun and should be found in such a way that the

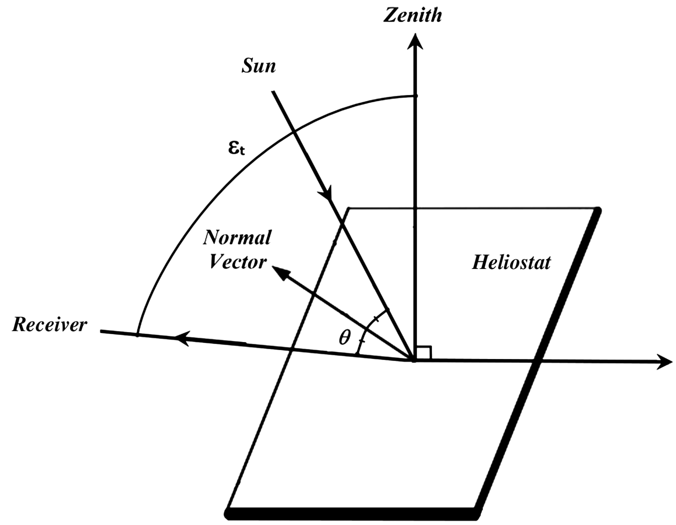

Fig. 1. Characteristic angles of heliostat

reflected ray strikes the receiver. The unit vector $\vec{r}$ is a function of heliostat position with respect to the receiver. If X, Y, and Z are the coordinates of the heliostat center, the components of $\vec{r}$ are defined as follows:

$$r_x = -\frac{X}{\sqrt{X^2 + Y^2 + (\mathrm{THT} - Z)^2}} \quad (2)$$

$$r_y = -\frac{Y}{\sqrt{X^2 + Y^2 + (\mathrm{THT} - Z)^2}} \quad (3)$$

$$r_z = \frac{H - Z}{\sqrt{X^2 + Y^2 + (\mathrm{THT} - Z)^2}} \quad (4)$$

where THT is the height of the heliostat.

The unit vector $\vec{s}$ can be defined in terms of three angles: latitude ϕ, solar hour angle ω, and solar declination angle δ. The components $\vec{s}$ are defined as follows (Mehrabian and Aseman 2007):

$$s_x = -\cos(\omega)\sin(\phi)\cos(\delta) + \cos(\phi)\sin(\delta) \quad (5)$$

$$s_y = \sin(\omega)\cos(\delta) \quad (6)$$

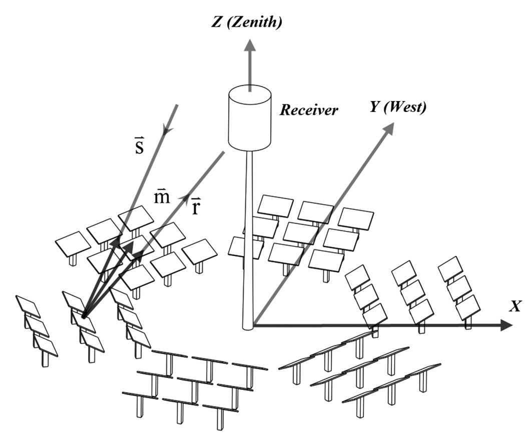

Fig. 2. Unit vectors $\vec{s}$, $\vec{r}$, and $\vec{m}$ in main coordinate system

$$s_z = \cos(\omega)\cos(\phi)\cos(\delta) + \sin(\phi)\sin(\delta) \quad (7)$$

The definition of ω and δ are given in Duffie and Beckman (2006). From the laws of reflection we have

$$\vec{r} \times \vec{m} = \vec{m} \times \vec{s} \quad (8)$$

Therefore, the components of unit vector $\vec{m}$ are derived as follows (Mehrabian and Aseman 2007):

$$m_x = \frac{|s_z + r_z|}{s_z + r_z}(s_x + r_x) \times \frac{1}{\sqrt{(s_x + r_x)^2 + (s_y + r_y)^2 + (s_z + r_z)^2}} \quad (9)$$

$$m_y = \frac{|s_z + r_z|}{s_z + r_z}(s_y + r_y) \times \frac{1}{\sqrt{(s_x + r_x)^2 + (s_y + r_y)^2 + (s_z + r_z)^2}} \quad (10)$$

$$m_z = |s_z + r_z| \times \frac{1}{\sqrt{(s_x + r_x)^2 + (s_y + r_y)^2 + (s_z + r_z)^2}} \quad (11)$$

Where the vectors $\vec{r}$, $\vec{m}$, and $\vec{s}$ are involved, θ is defined as

$$\cos\theta = \rightarrow s \cdot \rightarrow m \Rightarrow \theta = \cos^{-1}(s_x m_x + s_y m_y + s_z m_z) \quad (12)$$

If the unit vector $\vec{k}$ is defined as [0 0 1], then ε_T is calculated as follows:

$$\cos\varepsilon_T = \rightarrow k \cdot \rightarrow r \Rightarrow \varepsilon_T = \cos^{-1}(r_z) \quad (13)$$

Fig. 3 displays a schematic view of the locations of heliostats in a radial staggered configuration where the diameter of the heliostat (the length of the inner segment in the circles) is

$$DH = \sqrt{LH^2 + wr^2 LH^2} = \sqrt{1 + wr^2} \times LH \quad (14)$$

This diameter, plus the security distance (the diameter of the circles), will be

$$DHs = \left(\sqrt{1 + wr^2} + ds\right) \times LH \quad (15)$$

As an approximation to the minimum increment of the radius between consecutive rows,

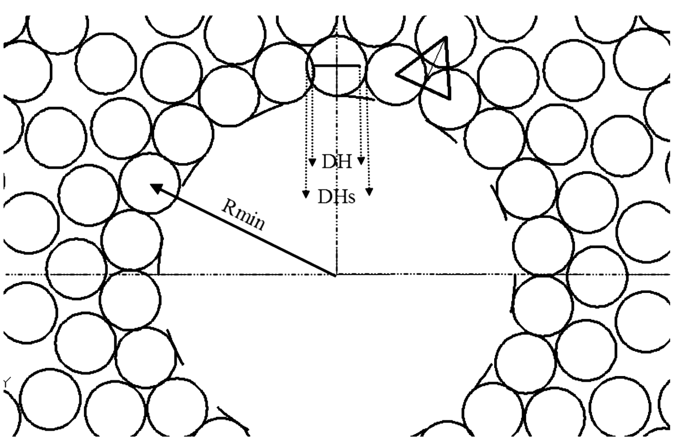

Fig. 3. Schematic view of locations of heliostat

$$\Delta R \min \approx DHs \cos 30° \quad (16)$$

Then the constant azimuth angle increment used in a zone that is also the azimuth angle of the tower unit vector would be (Collado 2009)

$$\Delta\alpha_T = 2\tan^{-1}[(DHs/2)/R_{\text{zone}}] \quad (17)$$

where the parameter R_{zone} is the radius used for generating the first row of such a heliostat zone. This azimuth increment will be conserved in the later outward rows in the same zone. Thus, adjacent heliostats in the same row become more separated from each other as the radius of the heliostat field increases. This will be continued until it is possible to place one extra heliostat between them. Then it should be necessary to start a new zone beginning with the first row, at a new R_{zone}, in which the adjacent heliostat circles would be tangent to each other again (Collado 2009).

Given the first row and the azimuth increment for a zone, the problem is now to derive each local ΔR in the successive (staggered) rows with a fixed blocking factor. Now, the position of the heliostats can be defined with $R_{\text{zone}}, \Delta R, \alpha_T$. On the other hand, the values of ω and ε_T can be found if the location of heliostats are known. So, an iterative process is scheduled, which is fed with $\Delta R_{\min}$ as the first approximation.

After the coordinates of all the heliostats are determined, the local heliostat field efficiency η_f should be calculated as a parameter to find the best locations for placing the heliostats. It will be defined as the product of cosine efficiency ($\cos\omega$), the blocking factor (f_b), the spillage factor (f_{sp}), and the attenuation factor (f_{at}). The spillage factor is the fraction of the energetic spot reflected by the heliostat that hits the receiver surface. Actually, it is assumed that the heliostat reflects all the sunlight to the center of the receiver, called the energetic spot, and this assumption is corrected by the spillage factor. The attenuation factor is the attenuation of the reflected beam as it travels from the heliostat to the receiver. Therefore, η_f is defined as

$$\eta_f = \cos\omega \cdot f_b \cdot f_{sp} \cdot f_{at} \quad (18)$$

The spillage factor is calculated as follows (Collado and Turegano 1989):

$$f_{sp} = \frac{PH\left(\frac{wr \cdot LH}{2\sqrt{2}\sigma_r}, -a_r, a_r\right) \times PH\left(\frac{LH}{2\sqrt{2}\sigma_r}, -a_r, a_r\right)}{a_r^2} \quad (19)$$

where $a_r = \sqrt{A_h}/2\sqrt{2}\sigma_r$ and σ_r is the dispersion of the effective sun shape on the receiver and is considered to be 2.51E-3 rad. The function PH is also calculated as follows:

$$\begin{aligned} PH(\xi_r, -a_r, a_r) = \frac{1}{2}\{&(\xi_r + a_r)erf(\xi_r + a_r) \\ &+ \frac{1}{\sqrt{\pi}}\exp[-(\xi_r + a_r)^2] \\ &- (\xi_r - a_r)erf(\xi_r - a_r) \\ &- \frac{1}{\sqrt{\pi}}\exp[-(\xi_r - a_r)^2]\} \end{aligned} \quad (20)$$

According to (Vittitoe and Biggs 1978), the parameter f_{at} on a clear day (23 km visibility) is calculated as follows:

$$f_{at} = 0.99326 - 0.1046S + 0.017S^2 - 0.002845S^3 \quad (21)$$

where the parameter S = distance from a heliostat to the receiver in kilometers.

The total efficiency of the surrounding heliostat field is the average of the efficiencies of all heliostats. To calculate the input power on the receiver, the power produced from each heliostat is determined and the dissipations of the receiver are subtracted from it. According to Collado and Turegano (1989), incident power into a receiver per unit area of mirror is calculated as follows:

$$P_{m,A} = I \cdot \rho \cdot \cos\omega \cdot f_{sp} \cdot f_{sb} \cdot f_{at}(\mathrm{W/m^2}) \tag{22}$$

where the parameter ρ = reflectivity coefficient; the parameter I ($\mathrm{W/m^2}$) = direct solar irradiation at the design point; and the parameter f_{sb} = fraction of area free of shadows and blocking. Due to the more pronounced effect of f_b on the layout of the heliostat field, f_{sb} is assumed to be equal to f_b (Falcone 1986).

According to Collado (2008), some other efficiencies should be considered to estimate the total input power from each heliostat as follows:

$$P_{tot,A} = P_{m,A} \cdot \eta_{\mathrm{ave}} \cdot \eta_R \cdot \eta_{sto} \cdot \eta_{tra}(\mathrm{W/m^2}) \tag{23}$$

where η_{ave} = field availability performance factor, which includes maintenance, outages, for example, and is set to 0.99, which would correspond to commercial plant predictions (Pacheco et al. 2000). Furthermore, in the solar-two project, the receiver efficiency η_R was defined as the quotient of power/incident power into a receiver, which was determined to be 88%, and the same value is incorporated into the present study (Pacheco et al. 2000). The parameter η_{sto} is the storage tank efficiency, which is about 99% for the molten salt storage tanks (Collado 2008). There is another efficiency that should be considered that is related to the tracking error, i.e., η_{tra} which is considered to be 99% in this paper.

Therefore, the heat power into the receiver by each heliostat is evaluated by

$$\dot{Q}_{\mathrm{inc}} = P_{\mathrm{tot},A} \times A_h(\mathrm{W}) \tag{24}$$

where A_h = area of heliostats and is equal to $wr \cdot LH^2$. Finally, the produced power of all heliostats is determined as follows:

$$\dot{Q}_{\mathrm{inc,tot}} = \sum_{i=1}^{n} \dot{Q}_{\mathrm{inc},i}(\mathrm{W}) \tag{25}$$

where n = number of heliostats.

The net absorbed heat power of the receiver is defined as (Zhihao et al. 2009)

$$\dot{Q}_{\mathrm{net}} = \alpha\dot{Q}_{\mathrm{inc,tot}} - \dot{Q}_{\mathrm{conv}} - \dot{Q}_{\mathrm{emi}}(\mathrm{W}) \tag{26}$$

where the parameter α = absorption coefficient of the receiver. The parameter $\dot{Q}_{\mathrm{conv}}$ is the convection loss, which is defined as follows (Zhihao et al. 2009):

$$\dot{Q}_{\mathrm{conv}} = hA_r(T_w - T_a)(\mathrm{W}) \tag{27}$$

where the parameter h = combined force and natural convection coefficient, which is found in Zhihao et al. (2009); and the parameter A_r = area of the receiver.

The radiation loss is calculated as follows:

$$\dot{Q}_{\mathrm{emi}} = \sigma\varepsilon A_a(T_w^4 - T_a^4)(\mathrm{W}) \tag{28}$$

where $\sigma = 5.67 \times 10^{-8}(\mathrm{W/m^2\,K^4})$; ε = emissivity; and A_a = receiver aperture area.

Note that the difference between the present study and that of Zhihao et al. (2009) in the calculation of the absorbed heat power is that in the present study, the absorbed heat powers of individual heliostats are first calculated and then added to each other to calculate the total absorbed heat power. However, Zhihao et al. (2009) considered the constant cosine efficiency and constant attenuation efficiency for all the heliostat fields, and due to the variation of this parameter from one heliostat to another, the process in this study is more accurate than that of Zhihao et al. (2009). In addition, some other efficiencies (η_{ave}, η_R and η_{sto}) are also considered in this paper.

In this paper, an in-house computer code was developed to determine the location of each heliostat iteratively. Since the position of the heliostats can be defined by R_{zone}, ΔR, and α_T, given the first row and the azimuth increment for a zone, ΔR is calculated in the successive (staggered) rows with a fixed blocking factor. Then R_{zone} and $\Delta\alpha_T$ are determined for the second zone. On the other hand, the values of ω and ε_T can be found if the location of the heliostats is known. Thus, an iterative process is scheduled, which is fed with ΔR_{min} as the first approximation. Then when the location of each heliostat is known, the efficiency and the input power of each heliostat can be calculated. The total efficiency and the total thermal power of the heliostat field are then determined. Therefore, with known input data, the heliostat field is designed. This process is continued until the desired input power is obtained.

Genetic Algorithm

A genetic algorithm (GA) is a search technique used in computing to find exact or approximate solutions for optimization and search problems. GAs are categorized as global search heuristics. The method was developed by John Holland (1975) in the 1960s and 1970s and finally popularized by one of his students, David Goldberg, who was able to solve a difficult problem involving the control of gas-pipeline transmission for his dissertation (Goldberg 1989). Holland's original work was summarized in his books (Holland 1975, 1992). He was the first one to try to develop a theoretical basis for GAs through his schema theorem. The work of De Jong (1975) showed the usefulness of GAs for function optimization and made the first concerted effort to find optimized GA parameters. The use of GAs can be found in many engineering problems as well as solar systems to find the best design and to find the best solution to problems (Talebizadeh et al. 2011). The single objective GA optimization method is used in this paper to optimize the characteristics of the heliostat layout, i.e., tower height, heliostat height, security distance, and height-width ratio. A program is developed to find the best possible answer by variation of the four parameters of the heliostat field.

The independence of the answers to the initial population is first done and then 30 is selected as the number of initial random sets. Then optimization is initiated by applying 30 random sets as the first population. Each set is called a chromosome, and chromosomes have four random numbers equal to the number of optimization parameters in the range of given values as follows:

$$\mathrm{chromosome} = [p_1, p_2, p_3, p_4] \tag{29}$$

where p = optimization parameter. Then the cost function is calculated for each chromosome as follows:

$$\mathrm{cost} = f(\mathrm{chromosome}) = f(p_1, p_2, p_3, p_4) \tag{30}$$

Sensitivity is the key quality in evaluating the fitness of these random sets, so for the first population sensitivity is evaluated and fitness is assigned. In the selection step, the 15 best results of the cost function, which are selected after sorting the results from the minimum value to the maximum one, are saved and used in the crossover step as the parents of the next generation. In this paper, a tournament selection is used to select each parent for the crossover procedure (Haupt and Haupt 2004). The crossover step is carried out by creating two new sets of members from the selected parents. In this step, two parents exchange some members for others. The number of members that should be substituted is defined by a random value called the crossover point (λ) and is between one and four (which is equal to the number of variables). For example, if $\lambda = 3$, then the offspring are as follows:

$$\text{parent1} = (p_{m1}, p_{m2}, p_{m3}, p_{m4})$$
$$\text{parent2} = (p_{d1}, p_{d2}, p_{d3}, p_{d4}) \tag{31}$$

$$\text{offspring1} = (p_{m1}, p_{m2}, p_{m3}, p_{d4})$$
$$\text{offspring2} = (p_{d1}, p_{d2}, p_{d3}, p_{m4}) \tag{32}$$

The problem is that in this method, the value of each optimization parameter is not changed but merely transferred to the offspring. Therefore, one of the optimization parameters that is selected according to the crossover point is changed and calculated as follows:

$$p_{new1} = p_{m\lambda} - \beta[p_{m\lambda} - p_{d\lambda}] \qquad p_{\text{new2}} = p_{d\lambda} + \beta[p_{m\lambda} - p_{d\lambda}] \tag{33}$$

where β is a random number between 0 and 1. Therefore, the offspring are as follows:

$$\text{offspring1} = [p_{m1}, p_{m2}, p_{\text{new1}}, p_{d4}]$$
$$\text{offspring2} = [p_{d1}, p_{d2}, p_{\text{new2}}, p_{m4}] \tag{34}$$

In the mutation process, four new sets, which were created in the last step, are changed by substituting the members by random digits within boundaries. This step prevents the program from cycling around definite sets and converging to a local optimization point. Similar to the selection of the crossover point, the random number γ is selected between one and four and then the new optimization parameter is calculated as follows:

$$p_{\text{new}\gamma} = (\text{upperbound}_\gamma - \text{lowerbound}_\gamma) \times \text{random} + \text{lowerbound}_\gamma \tag{35}$$

Now the first generation is completed and the second one is started. The number of generations is the number of iterations in the solution of the GA problem. The regeneration process includes selecting mates, crossover step, and mutation in each generation. The stopping criterion is the number of iterations. After 400 iterations, the difference between the best members of consecutive generations is also checked, and if it is as close as desired (which is 10^{-4} in this paper), the optimization is finished and the optimized results are obtained. In this paper, a GA computer code is provided in order to find the optimization parameters. Then this code is validated by applying the six-hump camel back function as one of the benchmarks related to the optimization process. The six-hump camel back function is a typical hard global minimization problem that is often used to test the performance and reliability of optimization algorithms. This function has six local minima, as the name of the function implies, and has one global minimum value. Many algorithms can only find local minimum values; however, a few can find global minimum values. Therefore, this function is a proper function to test the validity of an algorithm (Xuan et al. 2010).

Results and Discussion

To optimize a heliostat field, the distribution of the heliostats should initially be determined for any input parameter and then the absorbed heat power should be calculated. After that, the optimization process is initiated using the GA. Fig. 4 illustrates the stages of the GA for the present study. As shown in this figure, a population is set for each four independent parameters as the input of the system in order to include the entire domain. Then, after conducting the aforementioned stages, the optimization parameters and the maximum function value (the total efficiency of the heliostat field for a constant absorbed power) are calculated.

In this section, the validation of the code is studied first and then the design of the heliostat layout is discussed. At the end, the optimization procedure is investigated and the heliostat layout based on the present study is compared with the previous design.

For the validation, the results of the computer code are compared with the results of Collado. In Table 1, the values of the constant parameters used in the design of the heliostat layout modeled by Collado are listed. Note that in this paper, approximated annual averages based on the spring equinox (solar noon) are considered as the design point (Collado 2008, 2009; Zhihao et al. 2009; Kistler 1986). It is clear that a more accurate option would be to consider the time-averaged distribution of the incidence angle of the sunrays (Collado 2009). However, Collado (2008) claimed that the instantaneous power collected at solar noon of the spring equinox differs little from the annual average power, which ranges between 1 and 1.5%. Furthermore, this paper is focused more on the optimization process.

The parameters A_r, A_a, and ε, which are used in the calculation of the total input power, are also listed in Table 1 (Zhihao et al. 2009).

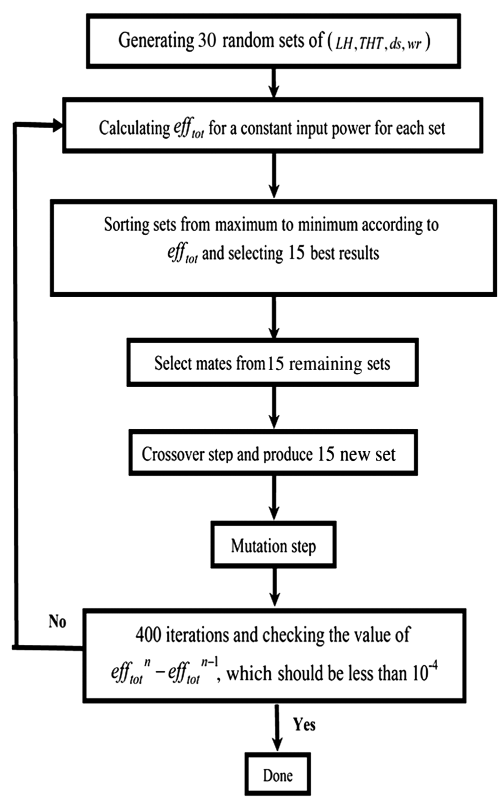

Fig. 4. Flowchart of genetic algorithm for heliostat field optimization

Table 1. Constant Parameters Used in This Paper According to Collado (2009) and Xiudong et al. (2010)

Parameter	Value
A_a	25 m^2
A_r	40 m^2
ds	0.3
f_b	0.95
Fraction of mirror area in heliostat	0.9583
I	918 W/m^2
LH	Sqrt (120) m
$R_{\min}$	65 m
Standard deviation of Sun shape	2.51 mrad
T_a	25°C
T_w	430°C
	130 m
wr	1
α	0.97
ε	0.88
ρ	0.888

Fig. 5 displays the distribution of the surrounding heliostat field achieved in this paper according to the constant parameters of Table 1 for Almeria, Spain. In this figure and the others that illustrate the distribution of the heliostats, different symbols are used to show the efficiency of the heliostats. For example, the circle is used for the heliostats which have the efficiency between 70 and 80%. As shown in Fig. 5, the results are in excellent agreement with the results of Collado (2009).

In the process of modeling the heliostat layout, as mentioned earlier, first the heliostats with higher efficiencies are chosen to be located in the field. The aim of this study is to find the most efficient heliostat field for constant absorbed power. To calculate the absorbed heat power gain in a tower, heliostats from the highest to the lowest efficiency are located one by one, and their input power is calculated and summed until the total input power is equal to the desired value, which is equal to 20 MW in this paper. Then the computer code is stopped and the distribution of the heliostats is found. Note that in Fig. 5, the power generated by heliostats with an efficiency of more than 90% is 3.07 MW and that generated by heliostats with an efficiency between 80 and 90% is 27.7 MW.

The distribution of the heliostat field for a plant with 20 MW input power using the constant parameters listed in Table 1 for Almeria, Spain, is displayed in Fig. 6. As shown in this figure, with 303 heliostats, the total efficiency of the heliostat layout is 86.81%, and the total area of the heliostats is $36,360$ m^2. With the same process, the distribution of the heliostat field for different given input power can be modeled. Note that Figs. 5 and 6 are the same. However, Fig. 6 displays the heliostat field with 20 MW input power, whereas Fig. 5 displays the whole heliostat layout, without considering the power, and is used to show the validation of the present code.

As mentioned earlier, four parameters, i.e., heliostat height, width-height ratio, tower height, and security distance, are chosen as the optimization parameters, and the total efficiency and total input power of the heliostat field are chosen as the cost function and the constraint in the GA, respectively.

The weight of the receiver is one of the important design parameters. The tower structure is made of steel or concrete. If the height of the tower is less than 120 m, steel structures would be less expensive; however, for larger tower heights, concrete structures would be more economical. According to the Sterns Roger Engineering Company (1979), a tower height between 50 and 300 m is economical. Therefore, in this paper, a tower height in this range is considered for optimization. Today, the area of the heliostat is designed to be between 25 and 150 m^2 (William et al. 2001). Therefore, in this paper, the height of the heliostat is considered to be between 5 and 20 m. The security distance and the width-height ratio are also considered to be between 0.1 and 0.5 and 1 and 2, respectively, since there are no special limitations. The range of the optimization parameters is listed in Table 2.

Note that since it is obvious that the larger the f_b, the higher the efficiency that can be achieved. Therefore, this parameter is not considered an optimum parameter and its best value is equal to 0.95 for the blocking factor, according to Collado (2009) and Vittitoe and Biggs (1978). Furthermore, since the spring equinox–solar noon is considered as a design point, the optimization process is performed for this time period in the present paper.

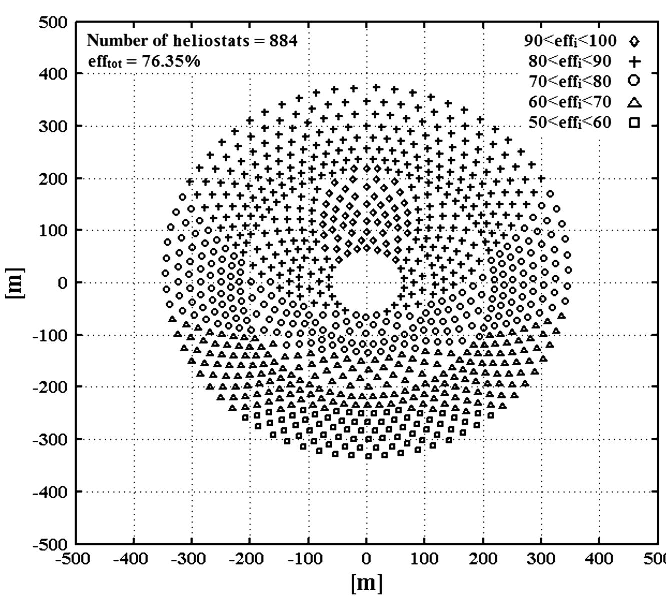

Fig. 5. Distribution of surrounding heliostat field in Almeria, Spain

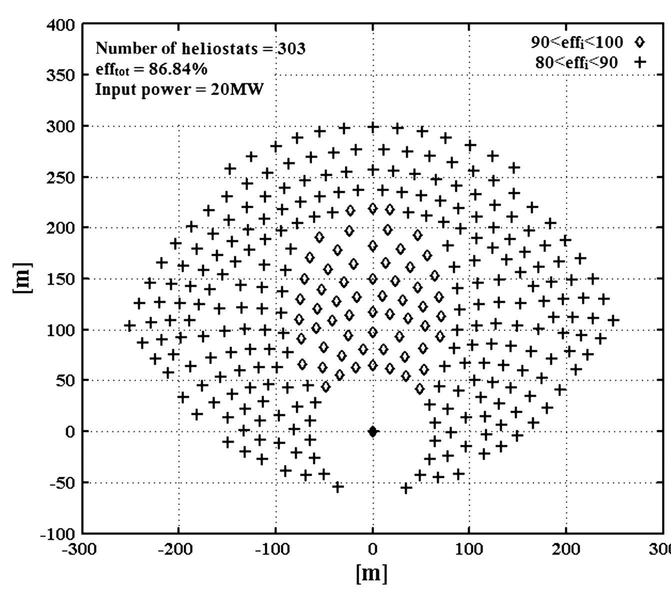

Fig. 6. Distribution of surrounding heliostat field for 20 MWt CRSPP

Table 2. Range of Optimization Parameters

Optimization parameter	Defined range
THT	50–300 m
LH	5–20 m
ds	0.1–0.5 m
wr	1–2

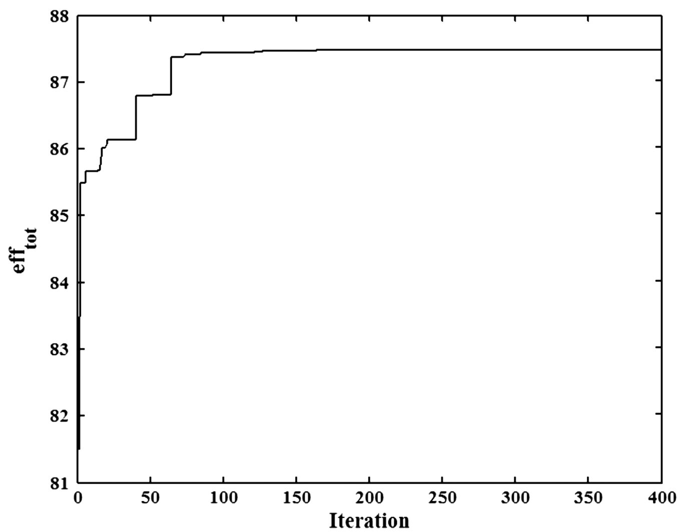

Fig. 7. Total efficiency of heliostat field in each iteration

Table 3. Values of Optimization Parameters and Cost Function

THT_{opt} (m)	LH_{opt} (m)	ds_{opt}	wr_{opt}	(%)
140	8.8	0.1	1	87.31

Fig. 7 displays the total efficiency of the heliostat field with respect to the number of iterations in the GA. As shown in the figure, after almost 200 iterations, eff_{tot} is stable and reaches a constant value.

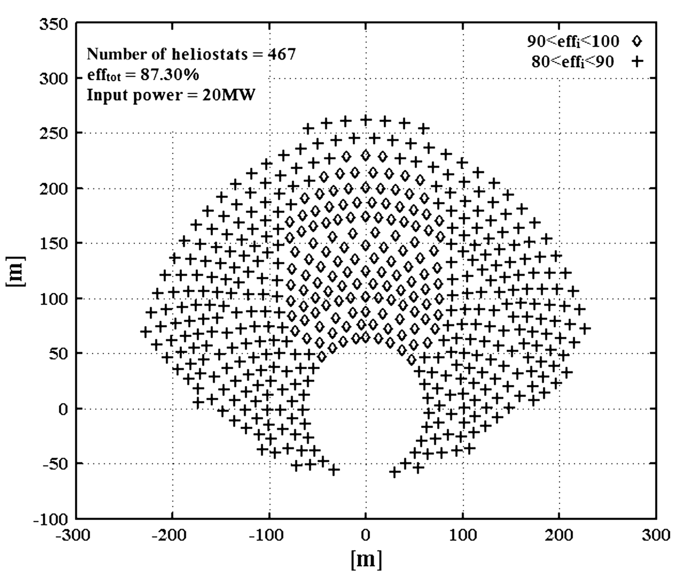

Fig. 8. Distribution of heliostats with optimization parameters

Table 4. Comparison between Results of Collado (2009) and Present Study

Key parameters	Present study	[6]
Number of heliostats	467	303
Total area (m^2)	36164.5	36,360
THT (m)	140	130
R_{max} (m)	260	300
Input power (MW)	20	20
eff_{tot} (%)	87.31	86.81

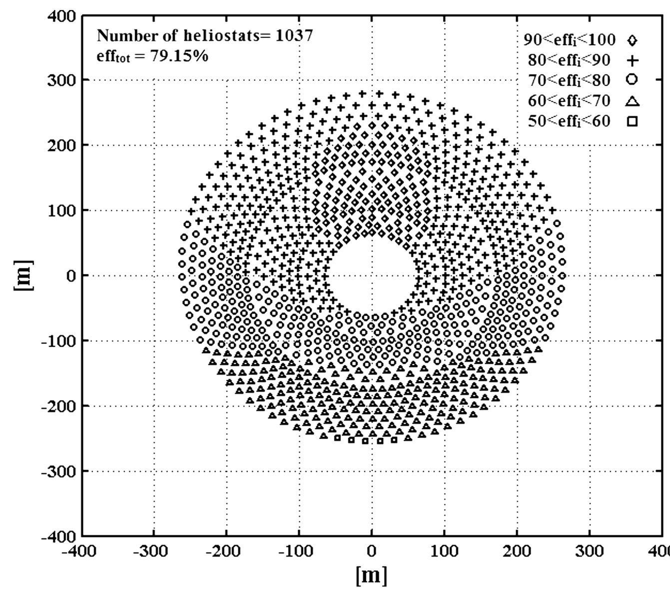

Fig. 9. Distribution of heliostats with optimization parameters

Table 3 lists the values of the calculated optimization parameters and the value of the optimized cost function achieved using the GA, and the distribution of heliostats with these new parameters determined is displayed in Fig. 8.

As displayed in Fig. 8, with 467 heliostats having an efficiency greater than 80%, 20 MW absorbed thermal power can be achieved. In Table 4, a comprehensive comparison is made between the results obtained in this study and the results of Collado (2009). As shown in the table, the total efficiency of the heliostat field is increased by 0.5%, and the total area of the heliostats is decreased 195.5 m^2; however, the height of the tower should be increased by 10 m.

In this paper, optimization is performed with a constraint of 20 MW input power; however, it is more effective when more than 20 MW is taken as the absorbed thermal power. Fig. 9 shows the whole heliostat layout with the determined optimum parameters. As shown, the total efficiency of the field is 79.15%, which is 4% more than the designed field in Collado (2009). Moreover, the total number of heliostats is 1,037 in 17 rows, and so the total area of heliostats is 80,305.3 m^2, which is 17.6% less than in Collado (2009).

Conclusion

In this paper, the optimization of a surrounding heliostat field is carried out for central receiver solar power plants. In the process of optimization, the angles of each heliostat are calculated at any time, the heliostat layout is designed, and the absorbed thermal power is determined. A genetic algorithm is applied as a search technique to find the most efficient heliostat field for a given absorbed power. After the validation of the code, the heliostat layout is designed for a 20 MW input power plant using constant parameters as found in the literature. Then optimization is performed with a constraint of 20 MW input power, and the results show that with 467 heliostats with an efficiency of greater than 80%, 20 MW absorbed thermal power can be achieved and the total efficiency of the heliostat field is increased by 0.5%. However, when whole heliostats were considered, the results showed that by increasing the tower height by 7.7% and decreasing the heliostat height by 19.5%, the total efficiency of the field is increased by almost 4% and the total area of the heliostats is decreased by 17%. Note that a genetic algorithm is used for the first time in this paper to optimize a heliostat field. This paper presents some new ideas to improve the performance of solar power towers.

Notation

The following symbols are used in this paper:

A_a = receiver aperture area (m^2);
A_h = area of heliostat (m^2);
A_r = area of receiver (m^2);
A_{tot} = total area (m^2);
a_r = parameter defined through A_h;
DH = diameter of heliostat (m);
DHs = diameter of heliostat plus security distance (m);
ds = security distance–heliostat height ratio;
eff_{tot} = total efficiency of surrounding heliostat field (%);
f_{at} = attenuation factor;
f_b = blocking factor;
f_{sb} = shadow-blocking factor;
f_{sp} = spillage factor;
h = combined force and natural convection coefficient ($W/m^2 °C$);
I = direct solar irradiation at design point (W/m^2);
$\vec{k}$ = k unit vector [0 0 1];
LH = height of heliostat (m);
$\mathrm{lowerbound}_\gamma$ = lower bound of optimization parameter related to random number γ;
$\vec{m}$ = unit vector along reflected ray normal to reflective plane;
n = number of heliostats;
P_1, P_2, P_3, P_4 = optimization parameters;
$P_{d1}, P_{d2}, P_{d3}, P_{d4}$ = optimization parameters selected from father in GA;
$p_{d\lambda}$ = optimization parameter selected from father in GA according to crossover point;
$P_{m1}, P_{m2}, P_{m3}, P_{m4}$ = optimization parameters selected from mother in GA;
$P_{m,A}$ = input power of each heliostat supplied to receiver per unit area of mirror (W/m^2);
$P_{m\lambda}$ = optimization parameter selected from mother in GA according to crossover point;
P_{new1}, P_{new2} = new optimization parameters generated from crossover step;
$p_{new\gamma}$ = new optimization parameter generated from mutation step;
$p_{tot,A}$ = total input power of each heliostat supplied to receiver per unit area of mirror (W/m^2);
PH = spillage function;
$\dot{Q}_{conv}$ = convection loss (W);
$\dot{Q}_{emi}$ = radiation loss (W);
$\dot{Q}_{inc}$ = heat power into a receiver by each heliostat (W);
$\dot{Q}_{inc,tot}$ = produced power of all heliostats (W);
$\dot{Q}_{net}$ = net absorbed heat power of receiver (W);
R_{zone} = radius of each heliostat zone (m);
$\vec{r}$ = unit vector along reflected ray directed to receiver;
S = distance from heliostat to receiver (km);
$\vec{s}$ = unit vector along the reflected ray directed to the sun;
T_a = ambient temperature (°C);
T_w = mean receiver wall temperature (°C);
THT = height of tower (m);
$\mathrm{upperbound}_\gamma$ = upper bound of optimization parameter related to random number γ;
wr = width-height ratio;
X = X-coordinate of heliostat center;
Y = Y-coordinate of heliostat center;
Z = Z-coordinate of heliostat center;
α = absorption coefficient of receiver;
β = random number between 0 and 1;
γ = random number between 1 and the number of variables;
Δ = solar declination angle (°);
ΔR = radial increment between consecutive and staggered rows (m);
ΔR min = minimum radial increment between consecutive and staggered rows (m);
$\Delta\alpha_T$ = constant azimuth angle increment;
ε = emissivity;
ε_T = elevation angle (°);
η_{ave} = field availability performance factor;
η_f = local heliostat field efficiency;
η_R = receiver efficiency;
η_{sto} = storage tank efficiency;
η_{tra} = tracking error;
θ = incidence angle (°);
λ = crossover point;
ρ = reflectivity coefficient;
σ = Stephan–Boltzmann constant (5.67×10^{-8} $W/m^2 K^4$);
σ_r = dispersion of effective Sun shape on receiver;
ϕ = latitude (°); and
ω = solar hour angle (°).

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