ON SELECTING A METHOD FOR HELIOSTAT FIELD LAYOUT OPTIMIZATION

Shanley L. Lutchman[1], **Paul Gauché**[2], **Albert A. Groenwold**[3]

[1] Solar Thermal Energy Research Group - Department of Mechanical and Mechatronic Engineering, Stellenbosch University, Private Bag X1, Matieland 7602, South Africa; Phone: +27-218084016; E-mail: lutchmsh@eskom.co.za

[2] Stellenbosch University; E-Mail: paulgauche@sun.ac.za

[3] Stellenbosch University; E-mail: albertg@sun.ac.za

Abstract

In central receiver systems the task of designing a suitable heliostat field layout is crucial to the optimal performance of the plant. A number of different methods for heliostat field layout optimization exist each offering their own set of advantages and disadvantages. This makes the task of determining the optimal heliostat field layout for a given site very cumbersome. Following a simple procedure for deciding on a method to use can greatly aid in optimizing for the specific needs of a plant. The current research seeks to establish such a method. This will allow the task of heliostat placements in central receiver system to be done easily and efficiently.

Keywords: heliostat field layout optimization; free variable method; pattern method; field growth method.

1. Introduction

Heliostat field optimization can be done in at least three different ways: the field growth method, the pattern method and the free variable method. A fourth method involves a hybridization of any two of these methods. In this paper each of these methods will be explained comparatively highlighting the advantages and disadvantages of each. Thereafter, a proposed procedure for deciding on which method to use for a specific set of plant requirements and design resources will be presented.

2. Optimization Methods

2.1. The field growth method

The field growth method of heliostat field optimization starts with an empty field. Every point in the field is evaluated to find the best position for one heliostat to be placed. A heliostat is assigned to this best position. Then, every point in the field is once again evaluated to find the best position for a second heliostat to be placed. A second heliostat is placed in this best position. This process is repeated for heliostats three, four and so on until the field is able to meet the system requirements. The procedure is illustrated in Figure 1.

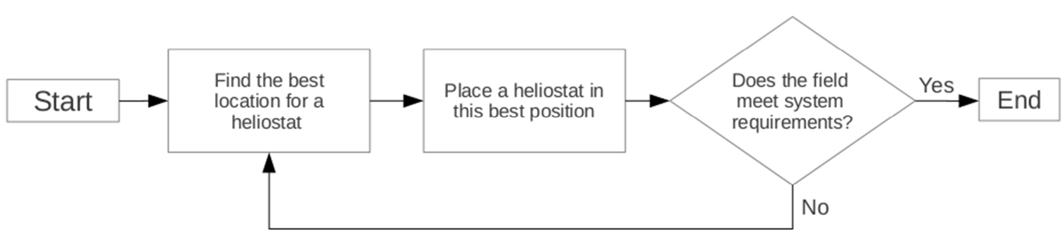

Fig. 1. Field growth method procedure

For the initial evaluation, blocking and shading are not considered since there are no other heliostats in the field. Only once the first heliostat has been placed are the field points evaluated with blocking and shading considerations. The number of points in the field that are evaluated can be varied to improve or decrease accuracy and, consequently, computational time.

A simple search algorithm can be used in the optimization and discontinuities—such as streams, holes or restricted areas where heliostats cannot be placed—can easily be incorporated for evaluation. However, since each heliostat is to be evaluated at all possible locations, the time to determine the location of each successive heliostat rises exponentially. This is because, with each added heliostat, another blocking and shading calculation is added to the search and these operations are the most time-consuming of all the field evaluations. The search time drops again once the possible locations have diminished sufficiently.

In addition, each heliostat allocation is dependent on the preceding allocation. This leaves little space for parallelization of the optimization; it is not possible to place heliostats simultaneously. Parallelization can be employed during the search phase though, that is, for a single heliostat placement, each possible location can be evaluated simultaneously through parallelization.

With the growth method, a feasible field can only be obtained once the optimization has completed. This is unlike the methods that follow which can be halted at any time yet still deliver a feasible field. For this reason, the method is not suitable for large fields when adequate computing power is not available. An example of the growth method follows.

2.1.1. Yearly Normalized Energy Surfaces (YNES)

Sánchez and Romero [1] employ the field growth method in heliostat field layout optimization. Each point in the field is evaluated to determine how much energy can be collected from that point over a year if a heliostat were to be placed there. The authors call this the "yearly normalized energy surface". Then a heliostat is placed at the best location. The yearly normalized energy surface is determined again, this time with the first heliostat placed taken into consideration. The second heliostat is placed at this point. This procedure is repeated until the heliostat field meets the required power output.

2.2. The pattern method

Heliostats in a field can also be arranged in elegant geometric patterns. Examples of these patterns can be seen in Figure 2. The patterns have certain parameters that define them. The radial stagger pattern from Stine and Geyer [2], for example, shown in Figure 3a, is defined by the two parameters *A* and *R* which characterize the spacing between the heliostats. To optimize a pattern, the only variables that need to be optimized are the defining parameters.

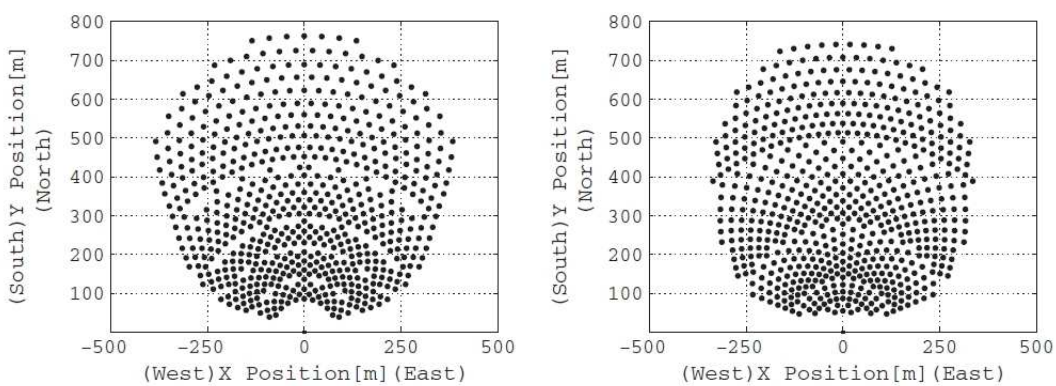

Fig. 2. Pattern layouts [3]

In the case of the stagger pattern, there are only two variables that need to be optimized. Since this is a very small optimization computationally, it is simple to add a few more variables that may assist in field design. These could include (amongst other parameters) the tower height, heliostat size and perhaps the position of the first row of heliostats relative to the tower.

For the pattern method, several patterns are available. These include rows, radially staggered, spirals, and the biomimetic patterns. Biomimetic patterns are patterns that mimic naturally occurring patterns, such as the phyllotaxis disc pattern employed by Noone *et. al.* [3]. This pattern is shown in Figure 3b.

A drawback of the pattern method is that an optimized pattern does not necessarily result in an optimal field. Buck [4] has shown that improvements are possible. In the pattern method, it is not the *x*-*y* co-ordinates that are being optimized for; it is the pattern parameters. The *x*-*y* co-ordinates are dependent on the pattern parameters. The pattern method essentially determines the best adaptation of the pattern for the problem and not necessarily the best *x*-*y* co-ordinates for optimal plant performance.

In addition the pattern method is not able to handle efficiently elevation variations and discontinuities within the site. To use a field optimized by the pattern method to its full potential, the site needs to be levelled and continuous.

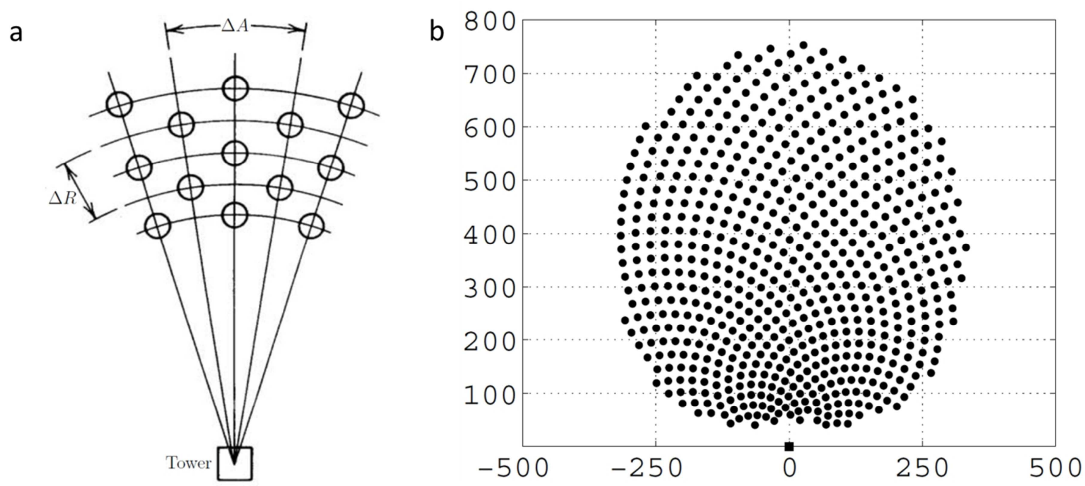

Fig. 3. Pattern layouts: (a) radial stagger pattern [2]; (b) biomimetic pattern [3]

2.3. The free variable method

The free variable method is a method of heliostat field optimization that follows a more classical approach to optimization. This involves iterative evaluation of the some function, determining of the gradients of the function with respect to each variable and then adjusting each variable to follow the gradient at an optimal step length in the direction of a better function value until a certain objective is achieved. The objective may be the maximization or minimization of the function value.

In the case of heliostat field optimization, the function may be any of the available field analysis methods such as ray tracing or approximation methods. The objective may be to determine the maximum of the function. As an example, the function may be a calculation of the optical efficiency of the field and the objective may be a maximization of this function. The optimization will keep altering the locations of the heliostats until it can no longer improve the optical efficiency.

To determine the gradient of the function with respect to each variable, a differentiated function is required. If a differentiated function is not available, the gradients may be obtained by finite difference calculations. If, for example, a ray tracer is used as the function, the gradients may be obtained either by finding the partial derivatives of the ray tracer function with respect to each variable or by finite difference calculations where the objective function is evaluated by small perturbations of each variable which, in this case, is each *x* and *y* co-ordinate of every heliostat.

At the start of the optimization, the variables may each be assigned a sensible or random value. Figure 4 shows an example of an implementation of this method. The initial field was the random field indicated in Figure 4a. An approximation tool was used as the function. The tool calculates the total energy that can be collected by the field over 12 days of a year (one day per month) with the heliostat co-ordinates as input variables. The objective of the optimization was to maximise this value. The result was the field indicated in Figure 4b. Close inspection of the optimized field will reveal that the optimization produced a pattern similar to the arrangement of sunflower petals.

Any number of equality or inequality constraints can be implemented into the optimization. In heliostat field optimization this could include site boundary limitations, distances of heliostats to the tower and distances of heliostats from each other. Furthermore, since heliostats are not limited to a pattern, their motion through the field during optimization is free which allows for highly effective consideration of elevation variations within the site as well as discontinuities.

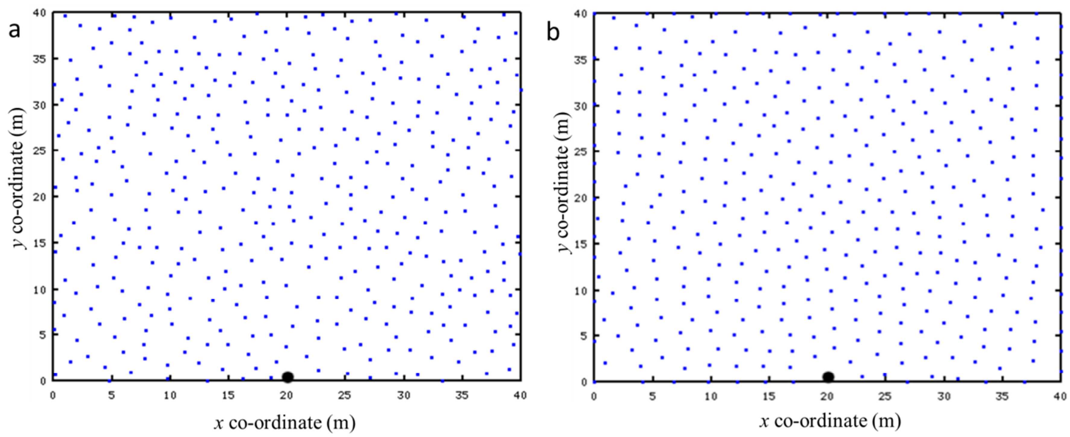

Fig. 4. Free variable method: (a) random field; (b) optimized field

The main drawback of the free variable method in the context of heliostat field layout optimization is the complexity of the optimization algorithm needed and, as a result, the computational expense. Lutchman *et. al.* [5] have shown that the free variable method requires the number of optimization variables to be at least double the number of heliostats. The authors also show that the number constraints far outnumber the variables. To effectively perform this optimization operation, the authors have shown that a constrained gradient-based optimization algorithm can be used. This optimization algorithm is far more sophisticated, and thus computationally expensive, than the algorithms that may be used for the pattern and the growth methods.

The free variable method is best performed on a high performance computer. The scope for parallelization is vast—obtaining gradient information, analysing separate heliostats, blocking and shading calculations—to name just a few. The free variable method performed on a high performance computer with extensive parallelization is capable of yielding highly desirable results.

2.4. Hybrid methods

Hybrid methods are methods which utilize two or more of the aforementioned methods for the same problem. Two examples of these follow.

2.4.1. Non-restrictive optimization

Buck [4] applies a pattern method along with an adaptation of the free variable method called “non-restrictive optimization”. A field that has been optimized by a pattern method is further improved by localized gradient-based optimization. This is done by perturbing each heliostat position within a small area around the heliostat to find a better function value. If a heliostat perturbation does produce a better function value the new location is kept. Buck achieved a 0.7% improvement in annual intercepted energy on the PS10 field.

2.4.2. DELSOL

DELSOL [6] is an example of a hybrid method because it employs both a field growth method and a pattern method for heliostat field layout design. Initially, individual heliostats are not taken into account. The heliostat area surrounding the tower is divided into a number of zones and the average field performance at each zone is calculated. The zoning is shown in Figure 5. Once the best zones are selected, DELSOL places and optimizes a radial stagger pattern heliostat sub-field inside each zone.

So, the field growth method is used to determine what zones within the site to use and the pattern method is used to determine where individual heliostats should be placed inside the chosen zones. The zones are rated by a performance/cost ratio. Then, starting with an empty field, zone by zone is added to the heliostat field giving zones with better performance/cost ratio preference until the total power output required is reached.

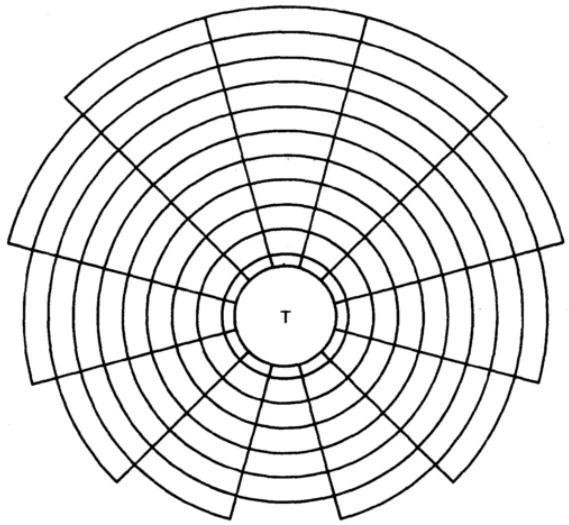

Fig. 5. Zoning in DELSOL [6]

With DELSOL, the optimization variables include not only the pattern parameters but also the tower height and receiver size. The main inputs for the design are (1) receiver type (2) a range of possible receiver sizes (3) a range of tower heights (4) a range of power levels and (5) flux and land constraints. Using these inputs the code generates the optimal radial stagger field layout, that is, the radial stagger layout that gives the lowest energy cost. This is done over the range of receiver sizes and tower heights. The result is an optimal radial stagger field layout with corresponding optimal tower height and receiver size on a performance/cost basis. Further optional optimization may be done by varying the heliostat density within each zone.

Table 1 provides a summary of the advantages and disadvantages of each of the optimization methods.

Method	Advantages	Disadvantages
Field growth	Wholly optimal fields	Computationally expensive for large fields
Pattern	Computationally reasonable	Poor discontinuity handling
Free variable	Wholly optimal fields	Requires a sophisticated optimization algorithm

Table 1. Advantages and disadvantages of optimization methods

3. Method selection

3.1. Key questions

Based on the above advantages and disadvantages of each of the optimization methods, it is beneficial to have a certain procedure for determining which method to employ. There are only three essential questions to be considered when deciding on an optimization method:

1. Is a high performance computer available?
2. Is a sophisticated optimization algorithm available?
3. Are there significant discontinuities in the site?

A sophisticated algorithm is an algorithm capable of very large scale optimization where there are a large number of variables and constraints. A high performance computer is a computer that performs significantly better than the average desktop computer and is able to satisfactorily handle the optimization algorithm.

The above questions highlight the differences between the optimization methods. The objective function, topology and plant requirements do not need to be considered here since they only affect the technical model of the plant. Any technical model can be used in combination with any of the optimization methods.

3.1. Decision flowchart

Figure 6 diagrams these questions into a flow diagram that can be used in the decision making process when deciding which of the methods to use. For a wholly optimal field, the free variable method is the method of choice since it is best at discontinuity considerations and can be halted at any convenient time. However, it is necessary to have a sophisticated optimization algorithm due to the large number of variables and constraints.

A pattern method can be used on average desktop computers. However, with a large discontinuity count, a pattern method would not be suitable and thus the growth method or the free variable method is recommended albeit on a slower machine. The main points that the flow diagram seeks to achieve is that the free variable method should not be done with a basic algorithm and the pattern method should not be used when significant discontinuities in the site are present.

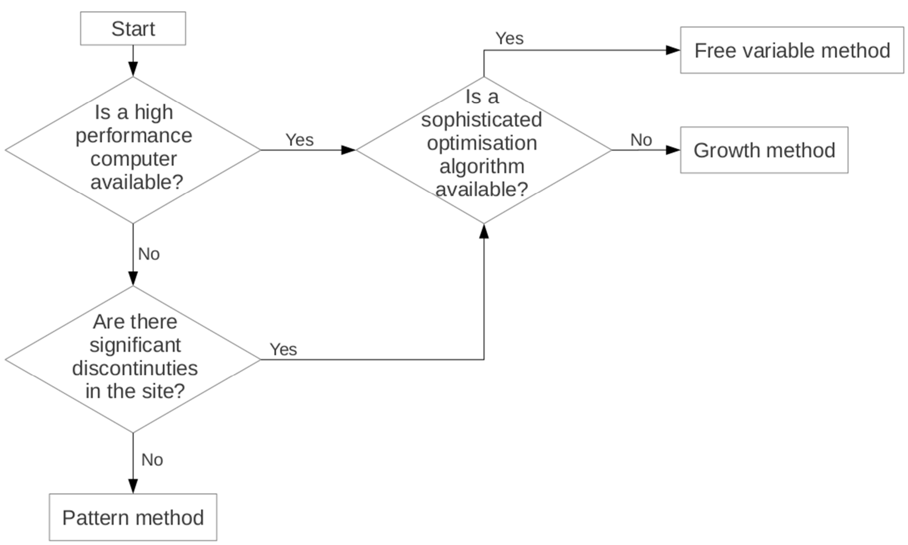

Fig. 6. Decision flowchart

The time to obtain a satisfactory solution is dependent on the computing power available. The pattern method can deliver an elegant and reasonable solution in a relatively short period of time with an average desktop computer. The growth method will require more time, but will deliver better results, especially when discontinuities are present, with the same computational power.

For the pattern method, a number of patterns exist. The choice of a pattern is left to the designer. Site limitations can be considered here; the designer may choose an elongated pattern instead of a more spread-out pattern based on the site boundaries. Local resources can also be considered; the designer may wish to locate the tower close to some local resource, such as a water source, and thus decide on a one-sided field pattern verses a surrounding field pattern.

Conclusion

Each of the three basic methods for heliostat field layout optimization has their unique set advantages and disadvantages. The procedure proposed in this paper for deciding on which optimization method to use can aid the heliostat field layout designer in choosing which method to use based on plant requirements and available design resources.

Acknowledgements

The authors are grateful to the Eskom Power Plant Engineering Institute (EPPEI) for financial and organizational support.

References

[1] M. Sánchez, M. Romero, Solar Energy, vol. 80, no. 7 (2006) 861-874.

[2] W.B. Stine, (2001). Power from the Sun, www.powerfromthesun.net.

[3] C.J. Noone, M. Torrilhon, A. Mitsos, Solar Energy, vol. 86, no. 2 (2012) 792-803.

[4] R. Buck, Proceedings SolarPACES 2012.

[5] S.L. Lutchman, A.A. Groenwold, P. Gauché, S. Bode, Proceedings SolarPACES 2013.

[6] B. Kistler, (1986). A user's manual for DELSOL3, Sandia National Laboratories, California.