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# Development of performance analysis model for central receiver system and its application to pattern-free heliostat layout optimization

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ABSTRACT

In the present work, a new pattern-free heliostat layout optimization methodology based on the genetic algorithm is introduced. This method is developed to speed up the optimization process attempting to find the global optimum. The novel part of the proposed method is that multiple neighboring heliostats are optimized simultaneously with nearly no restrictions. The proposed methodology is tested with a standard performance analysis model that calculates the annual insolation weighted optical efficiency of the heliostat layout. In order to improve the flexibility of the shadowing and blocking for more complex cases, in which the reflecting polygon is divided into multiple polygons, we adopt the polygon clipping algorithm. With the proposed pattern-free optimization methodology, the insolation weighted optical efficiency of the PS10 heliostat layout has been improved by 0.6% point with 3.7% reduction in the heliostat field area.



## 1. Introduction

Concentrated solar power (CSP) is a renewable energy technology, in which the solar radiation is first concentrated into high quality (or high temperature) thermal energy and then converted into electricity. Central receiver system (CRS) is a branch of CSP technology and employs hundreds or thousands of heliostats to concentrate the solar radiation to the receiver tower. The conversion of solar radiation to heat allows excess heat to be stored in a thermal storage, which can remedy two major issues of all renewable energy technologies, i.e., instability and inconsistency (Zhang et al., 2013). Because the excess thermal energy can be stored in the molten salt, electricity can be generated for hours even in the absence of sunlight. In addition, instantaneous solar intensity fluctuations caused by air and weather conditions can also be augmented by stored thermal energy. Therefore, CRS has the potential to mass produce electricity with stability and consistency.

One of the major issues in CRS is the low land coverage, which is only about 40% (Price, 2003). The overall heliostat field area and cost are thus increased accordingly. Dense packing of heliostats will not be very helpful because the shadowing and blocking loss will become dominant as the heliostats are placed closer to each other. In order to make CRS more cost effective, it is crucial to have as many heliostats reflecting solar radiation to the receiver tower as possible, while keeping each heliostat at the maximum optical efficiency. In order to achieve this goal, heliostat layout optimization can be employed.

The major limitation of heliostat layout optimization is computational time. Theoretically, the global optimum or at least an optimum design close to the global optimum can be found when pattern-free optimization is applied since it utilizes larger design search domain than pattern-based optimizations. However, in heliostat layout optimization involving hundreds or even thousands of heliostats, the pattern-free approach is difficult to obtain the global optimum, which is followed by significant computational time. Consequently, many attempts have been made to reduce computational time by using a certain pattern, such as radial staggered pattern, to the heliostat layout (Pitz-Paal et al., 2011; Lipps and Vant-Hull, 1980; Kistler, 1986).

While the optimization time is indeed reduced drastically, the optimum results are restricted to the global pattern configuration; that is, the opportunity to find better heliostat layouts that are beyond the pattern configuration is lost. In the case of the radial staggered pattern, the pattern is divided into many circular zones,

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in which each zone is optimized separately. Although the usage of zones reduces the global pattern constraint problem to some extent, a similar problem still exists in each zone because all the heliostats in a zone follow the same pattern. Theoretically, heliostat layout with many small zones could solve this problem, but the usage of zones is followed by a new problem: discontinuities between the zones. The discontinuities between the zones cause the heliostats arrangement to change abruptly and so for the heliostats at the boundaries of the zones, the shadowing and blocking are not accounted properly, leading to sudden drops in optical efficiency. This disturbance is minimized by adding extra space between the zones, resulting in larger heliostat field area, which is not desirable.

Lipps (1985) employed cell-wise optimization, in which the heliostat layout is initially divided into smaller groups (i.e., cells), and then, individual cells are optimized separately with radial staggered pattern. Similar to the case of zones in the radial staggered pattern, the cells also cause additional discontinuities in the boundaries of each cell. Noone et al. (2012) proposed a new biomimetic pattern based on the spiral configuration of the sunflower seeds, which produces a continuous heliostat layout. With this pattern, only two variables need to be optimized, and the result showed significant reduction of land space with a slight improvement in the optical efficiency compared to the radial staggered pattern. However, it still does not guarantee that all individual heliostats are placed in their optimum position. More importantly, the biomimetic spiral pattern is not the best for all types of fields (Zhang et al., 2016). For example, the spiral pattern in a circular heliostat field performs worse than either the radial staggered pattern or the hybrid field of both radial staggered and spiral patterns. This leads back to the discontinuity problem in the heliostat layout. Consequently, it is highly likely that a superior layout that does not fit into any simple combinations of patterns exists.

There have been many attempts to break the layout pattern. For example, Sanchez and Romero (2006) proposed a method, in which heliostats are placed consecutively according to yearly normalized energy surfaces. The major disadvantage with this approach is that yearly normalized energy surfaces cannot properly consider the shadowing and blocking effects because the heliostats that are added later are not considered when estimating the shadowing and blocking loss of the initially added heliostats. Yao et al. (2015) and Carrizosa et al. (2015) attempted similar pattern-free methodologies, but these methodologies also do not fully consider the effect of newly added heliostats. Buck (2014) proposed a refinement method, where individual heliostat from a pre-pattern optimized heliostat layout is optimized freely, one by one, while keeping the rest of the heliostats fixed. This refinement increased the average optical efficiency by 0.8% point compared to the pre-pattern optimized heliostat layout. However, because the shadowing and blocking is a phenomenon involving multiple neighboring heliostats, optimizing only a single heliostat at a time could either limit the result or cause excessive optimization time. The problem of excessive calculation time can be quite detrimental because about 145 days were required for the whole optimization process. Therefore, this work aims to make a feasible pattern-free optimization methodology, in which a group of neighboring heliostats are optimized at the same time. The proposed methodology can be applied to any type of heliostat fields, including the circular heliostat layout, and can remove the discontinuity in heliostat layouts.

The main obstacle for overcoming long computation time is the calculation of the shadowing and blocking efficiency. Many models have been developed to reduce the computational cost of estimating the shadowing and blocking. In general, there are two algorithms used to calculate the shadowing and blocking: the projection method (Sassi, 1983) and the heliostat discretization method (McFee, 1977). Many models (Collado and Guallar, 2013; Besarati and Goswami, 2014; Atif and Al-Sulaiman, 2015) have been developed based on Sassi's method, but these models assume that neighboring heliostats are perfectly parallel to each other, resulting in unrealistic rectangular projections. The resulting error could be as high as 7% (Huang et al., 2013). Recently, Leonardi and D'Aguanno (2011) and Noone et al. (2012) have applied the discretization method. With dense discretization of the heliostat, the shadowing and blocking efficiency can be accurately calculated but with a proportional increase of calculation time. Consequently, in the discretization method, either accuracy or calculation speed must be sacrificed. Later, Zhang et al. (2016) and Yao et al. (2015) combined the projection and the discretization method, but achieved only slight improvement in the calculation time.

In the present study, we adopted polygon clipping algorithm (Ramos and Ramos, 2014) in estimating the shadowing and blocking efficiency. The polygon clipping algorithm calculates the reflecting polygon area analytically; thus, it can be as fast as the projection method, and also as accurate and flexible as the discretization method. With a standard analysis model, the pattern-free optimization methodology will be demonstrated by further improving the PS10 system.

## 2. Performance analysis model

In this section, we provide a brief description of the functional expressions used in calculating the performance of central receiver system. Emphasis will be given on algorithm to improve the calculation speed, which is crucial for making the pattern-free optimization feasible.

The optical efficiency ($\eta$) of a heliostat layout can be expressed as:

$$\eta = \eta_{ref} \times \eta_{cos} \times \eta_{att} \times \eta_{int} \times \eta_{s\&b} \tag{1}$$

where $\eta_{ref}, \eta_{cos}, \eta_{att}, \eta_{int}$, and $\eta_{s\&b}$ represent the heliostat reflectivity, the cosine efficiency, the atmospheric attenuation loss, the interception efficiency, and the shadowing and blocking efficiency, respectively. Because the incident solar radiation changes with respect to time of the day ($t$) as well as day of the year ($n$), the optical efficiency given in Eq. (1) is a function of time and day. Therefore, the insolation weighted optical efficiency can be estimated from:

$$\bar{\eta}_{insol} = \frac{\sum_{n=1}^{365} \int_{sunrise}^{sunset} \eta(t,n) \times I_b(t,n)dt}{\sum_{n=1}^{365} \int_{sunrise}^{sunset} I_b(t,n)dt} \tag{2}$$

where insolation $I_b(t,n)$ is the solar radiation flux for a given time and day.

Significant amount of radiation is lost through scattering and atmospheric attenuation, as the sun ray passes the atmosphere. Although the actual insolation heavily depends on the air and weather conditions, calculations have been done under cloudless weather condition for the consistent testing conditions. In the present work, the model by Kasten and Young (1989) has been applied to calculate the insolation. Except for the heliostat reflectivity that is assumed to be a known constant, all the optical efficiency components are explained in the following subsections.

### 2.1. Cosine efficiency

During the day, heliostats track the position of the sun and reflect solar radiation to the receiver. Cosine effect is the optical loss due to the sun rays obliquely incident on heliostat. The effective reflecting area of a heliostat decreases with the cosine of incidence angle ($\theta$) as