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State-of-the-art of heliostat field layout algorithms and their comparison

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Abstract

In this paper a complete review of the most relevant algorithms for the generation of heliostat field layouts is presented. For each of the reviewed algorithms, a description of the layout generation approach, all the input parameters required and the main formulation is provided. The algorithms have been compared for different scenarios covering a range of tower heights, heliostat sizes and acceptance angles (defining to what extent the resulting field is North configuration or surrounding). A robust methodology has been developed, which ensures a fair comparison of the algorithms by analysing the performance of optimized solar fields according to each layout generation method. For this, all the input parameters of each layout generation algorithm are optimized for each scenario prior to comparing the solar field performances. The main conclusion of the present study is that all the analysed layout generation algorithms lead to similar solar field efficiencies when compared for the considered scenarios once they are optimized. Further work is required to check if the algorithms also show similar efficiencies, or to what extent they are similar, when wider scenarios are considered (larger solar field powers, locations, etc.).

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Keywords: Concentrating Solar Power; heliostat field; layout algorithms; solar field optimization.

1. Introduction

As one of the main drivers of the energy costs (around 50 % [1] of the total plant), much work is being spent nowadays in the design of low cost or more cost-effective heliostats and good progress towards costs savings is

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envisaged. One of the main trends that are currently being investigated for achieving substantial cost savings in the heliostat field is the development of small and single facet (or small number of facets) heliostats [2,3,4,5].
However, these developments require also the adaptation and/or improvement of the heliostat field layout to reach optimum optical efficiencies and larger associated savings. Up to now, several algorithms and methods for placing the heliostats in the solar field have been developed and some of them have been applied to real solar fields based on large, multi-facet heliostats, but their applicability to small heliostat is not known. A first step for adapting or improving the heliostat layout is to perform a review and comparison of existing layout generation methodologies when applied to small heliostats in order to assess their behaviour and characteristics. In this work, the different algorithms found in the literature for the heliostat field layout generation are reviewed. In this review the inputs parameters that defines each of the algorithms are specified along with the process for the layout generation. After this review, a robust methodology used for comparing the identified algorithms when applied to small heliostats is presented. Finally, the results obtained for each of the analysed algorithms and their comparison is shown.

1.1. State-of-art of the heliostat field generation algorithms

In the literature, several algorithms have been proposed to improve heliostat solar layouts efficiencies. The Radial Staggered algorithms are the most common but in the last years some other algorithms have been proposed for improving the results obtained with the classical ones. In this study the classical Radial Staggered algorithms and the more recently proposed biomimetic algorithms and other proposed methods are presented and described.

The Radial Staggered configurations were originally proposed by the University of Houston for the RCELL code [8,9]. Lipps et al. present four field configurations that are generated using two spacing values: Radial Oriented Cornfields, Radial Oriented Staggers, North-South Oriented Cornfields, and North-South Oriented Staggers. After the simulation and optimization of a 100 MWe plant case, Stagger configurations (Radial Oriented Staggers and North-South Oriented Staggers) performances were better. Thus, in the following, only these staggered configurations are considered.

The DELSOL/WinDELSOL algorithm described in [7] is a type of radial staggered configuration where the heliostats are placed using a growing procedure. In this procedure the field is divided in different zones and performance for each zone is calculated. The growth method places heliostats starting with the best zones. The input parameters used by DELSOL are: heliostat dimensions, heliostat mirror ratio to total heliostat area, receiver elevation, No. of zones in azimuth direction, No. of zones in radial direction, radius of the nearest heliostat to tower, radius of the farthest heliostat, extra distance factor to the radial spacing, and a min. gap between two rows of different zones. DELSOL creates a surrounding field from the minimum to the maximum radii and divides it in the specified No. of zones. The procedure starts by calculating the values of the parameters that define each of the zones. Using these values, the spacing between centre points of two adjacent radial zones can be calculated as well as the radius for each radial zone centre. The main parameters to define the zone mirror density are the radial spacing between heliostat rows and the azimuth spacing between two heliostats in the same row. Once the density of the heliostat field zones is obtained, the No. of heliostats in the zone can obtained. Using this information, the number of heliostats per zone row, the No. of rows in each zone and the No. of heliostats in each row are calculated.

The Heliostat Minimum Radial Spacing presented in [9] has as main goal generation of heliostat field layouts that minimizes the shadowing and blocking losses in order to use the heliostat total reflective area and therefore collect the maximum solar radiation in the receiver. The radial spacing is defined as the critical value in the definition of the heliostats position because the azimuth spacing values does not vary too much in the field. The azimuth spacing, which is constant for the complete field, has to be provided in advance. This algorithm unlike the previous ones, takes into account the latitude of the plant location to calculate the value of the radial spacing. The input parameters for the algorithm are the location latitude, the list of heliostat cell centre position angles; the list of heliostat cells centre position radius, the heliostat dimensions a list of year days to calculate the radial spacing and the daily operation time. This algorithm calculates specific radial spacing for a number of different cells defined by the user via the list of heliostat cell centre positions.

The main objective of the MUUEN algorithm, a radial staggered algorithm presented in [4], is the generation of fields avoiding blocking between heliostats. This algorithm divides the field in different zones, with different angular and radial spacing to increase the efficiency of land use. The input parameters of the algorithm are: heliostat dimensions, ratio of reflecting area to total heliostat area, height of the heliostat centre from heliostat base, heliostats aiming point height, receiver height, heliostats separation distance, terrain inclination angle, minimum radius of the first row in the field, maximum radius of the last row in the field, and field maximum angular direction. The core of this algorithm is to calculate the best radius for the next heliostat row in the layout in order to avoid blocking. Each time a new radius is calculated, the algorithm checks if it is better, from a land usage point of view, to add a new row to the current zone (with the current angular spacing) or to start a new zone (updating the angular spacing). If the zone continues, it grows with a classical radial staggered configuration, keeping the same angular spacing.

The Campo algorithm presented in [11] and [1] consists on a set of algorithms to create improved radial staggered layouts. As a first approach, an algorithm to define Dense Radial Staggered layouts is presented. In these layouts the radial spacing between adjacent rows is constant and azimuth spacing is calculated for each heliostat zone. Then, an azimuth expansion and radial expansion is proposed to alleviate the heliostat density and obtain fields with higher annual energy. The input parameters of the algorithm are the heliostat dimensions, the radius of the first row in the field, an additional separation distance between the center of two adjacent heliostats, and a reference blocking factor. The basic procedure defined in Campo places the first heliostat of even rows in the north axis (Y axis). The second heliostat of these rows is placed at distance of ΔAz from the first one in clockwise direction. The same procedure is used for the rest of the heliostats in the row. The odd rows' first heliostats are placed at $\Delta Az/2$ from the Y axis (N) and subsequent heliostats are placed at distance of ΔAz from the previous one.

The Fermat´s Spiral algorithm presented in [12] generates heliostat fields based on spirals, as they have a continuous density function. Fermat spiral function represents the spirals shown in sunflowers. The position of a heliostat is defined as $\theta_k = 2\pi\, \varphi^{-2} k$ for the angular position and $r_k = a\, k^b$ for the radial position. Therefore, this algorithm requires a linear Fermat's spiral parameter (a), a power Fermat's spiral parameter (b), the heliostat dimensions, a security distance between heliostats, the heliostat minimum radial distance to the tower and the total number of heliostats as input parameters.

The HGM methodology proposed in [13] uses tower height and receiver dimensions already optimized and generates a heliostat field with a higher degree of freedom than the previous algorithms. The HGM methodology uses yearly normalized energy surface (YNES) maps to select the field position in a heliostat field with the highest value of optical efficiency. It places a heliostat in this position and recalculates the YNES map to include the losses related to shadowing and blocking due this heliostat and repeat this process until the desired field size is achieved. The list of input parameters for the HGM Methodology comprises the plant location, the Typical Meteorological Year, the tower height, the receiver dimensions and the heliostat dimensions. The first step in the heliostat field generation procedure is to build the initial YNES. Then, the position with the highest energy value is selected to place the first heliostat. Once the first heliostat is placed, yearly normalized shadowing and blocking effects due to this heliostat are included to build the second YNES map. Then the new best position is selected to place an additional heliostat and the updated YNES map due to this new heliostat is calculated. These steps are repeated until the complete field is generated.

Very similar to the previous algorithm, Carrizosa et al. presented the Greedy algorithm, where the heliostats are placed using a growth method [14]. The algorithm only uses two constraints to generate the heliostat field layout, the heliostat field shape and the heliostat centre constrains.

Table 1: Summary of the parameters optimized in each of the compared algorithms

	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12
Place	Tamanrasset (22.7833º N; 5.51667 E),											
Atmospheric attenuation model	2.93+27.48 R-3.394 R^2											
Tower height	50 m	50 m	50 m	50 m	70 m	70 m	70 m	70 m	100 m	100 m	100 m	100 m
Acceptance Angle	180º	165º	360º	90º	180º	165º	360º	90º	180º	165º	360º	90º
Heliostats size	7 m^2 / 140 m^2											
Heliostat reflectivity (incl. soiling)	0.88											
Design Point	21st March (noon) – Irradiance: 950 W/m^2 – Field power: 50 MWth											

Table 2: Summary of the parameters optimized in each of the compared algorithms

Algorithm	Input parameter	Description
DELSOL	NRad	Number of zones in radial direction
	fExpansion	Expansion factor for radial spacing
	gapBetweenZones	Distance to increase for rows of adjacent zones
MUUEN	dsep	Security distance between heliostats.
Campo	dsep	Security distance between heliostats.
	fbref	Reference blocking factor
Fermat Spiral	a	Fermat's spiral 'a' parameter.
	b	Fermat's spiral 'b' parameter.
	dsep	Security distance between heliostats.

The distance between two heliostats must be higher than a safety distance in order to avoid collisions. This algorithm places the heliostats freely, without using a pattern. This algorithm uses the annual energy as objective function to be maximized and the heliostat cost doesn't depend on the position of the heliostat in the field.

In summary, 8 algorithms were reviewed and have been explained; however, the following comparison is made for the most promising ones based on patters, since they are more likely to be implemented in real plants according to the bibliography. The compared algorithms are the DELSOL, MUUEN, Campo and Fermat's Spiral.

2. Methods

2.1. Algorithms comparison methodology

The optimization of the solar field for each algorithm is needed to ensure a fair comparison between algorithms. The solar field layouts resulting from the different algorithms have been compared for different scenarios to cover a relatively wide range of applications. For each of the scenarios, the algorithms are compared in terms of annual efficiency of the optimum solar field resulting from the algorithm. Therefore, the solar field layouts from the different algorithms have been compared for 12 different scenarios. The scenarios have been selected according to the characteristics of the research concept and focus of the EUROSUNMED project. Besides, the comparison is carried out both for small heliostats (7 m^2) and for large heliostats (140 m^2). For each of these heliostat sizes, the scenarios used for the comparison are summarized in Table 1.

Hence, for each algorithm, the compared solar field is the one resulting from an optimization procedure that finds the optimum values of each input parameter and maximizes certain objective function. In this way, each solar field is the best field that can be generated by a particular algorithm provided a scenario. The input parameters to be optimized for each algorithm prior to their comparison are shown in Table 2.

In this study the objective function to be maximized for the solar field optimization is the annual optical efficiency of the field. The annual optical efficiency of the solar field is calculated as the ratio of the field annual energy at the receiver aperture to the total incident energy in the solar field. Both the total incident energy in the solar field and the energy at the receiver aperture are calculated by summing up the contribution of each heliostat in the field.

To calculate the energy provided by each heliostat, the instantaneous optical efficiency is calculated for each heliostat. Then, by using the incident radiation data and the heliostat area, the energy provided by a heliostat to the receiver can be calculated for one time instant and, summing up for the complete year, the annual values can be computed.

Once the objective function is defined, the goal is to find the set of input parameters for each algorithm that maximizes the annual field efficiency. A number of optimization procedures and algorithms have been proposed in the literature that can cope with this task. In this study, an evolutionary algorithm "Backtracking Search Optimization Algorithm" (BSA) [16] has been used.

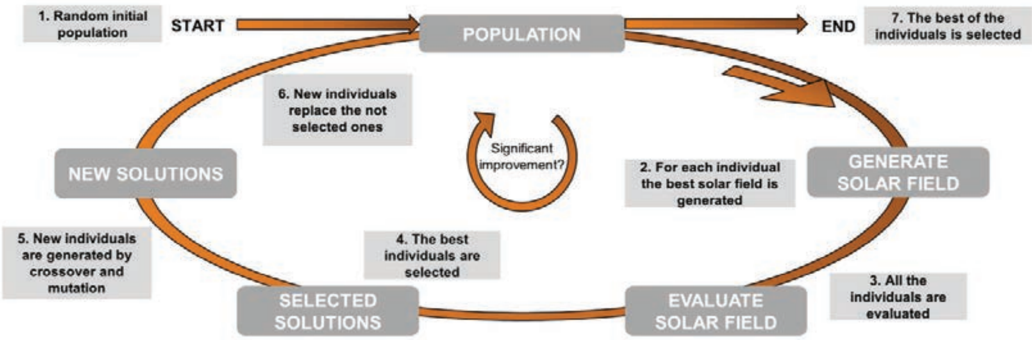

Fig. 1. Schematic representation of the solar field layout algorithms optimization procedure based on the “Backtracking Search Optimization Algorithm” (BSA) [16].

In the evolutionary algorithms, a set of possible solutions, called population, is stored. This population is formed by a number of so-called individuals. In this study, an individual is a set of input parameters for the algorithm that leads to a specific solar field and value of the objective function. In the evolutionary optimization process the input values of the existing solutions are mixed to create new individuals and evaluate again to verify if these new individuals improve the previous ones. If this is the case, the new individuals replace the previous ones. In this study, new individuals correspond to new sets of input parameters for an algorithm and are created as a combination and mutation of the input parameters already existing in the population. These new sets of parameters lead to new solar fields with different values of the objective function. If the new solar fields are better than the previous ones, they replace the existing ones and the procedure continues. Two criteria are used in this study to decide if the optimization has finished: maximum number of iterations in the optimization process and maximum number of iterations without a significant improvement in the solution. Once the process is finished, the best set of input values are selected as optimum solution. This procedure is graphically shown in Figure 1.

There are two critical parts in this procedure, the generation of the solar field and the evaluation of its performance. The procedure used to generate a specific solar field layout according to a specific algorithm for a particular scenario, given a set of input parameters to the algorithm, is as follows:

- First, a very large solar field (very large number of heliostats) is generated by applying the algorithm with the given input parameters.
- Secondly, a complete year simulation of the solar field is performed with a detailed optical simulation program. This simulation program uses the position of each heliostat, its geometric and optical characteristics and the meteorological data of the location to assess the annual energy provided by the field and by each of the heliostats.
- Then all the heliostats are sorted by annual energy provided to the receiver, i.e. the first heliostat is the one providing larger annual energy (best one) and the last heliostat is the one with minimum annual energy contribution (worst). A synthetic clear sky day meteorological data set is used for the simulation, to prevent the sorting of the heliostats from being affected by local climate effects (what would lead to non-symmetrical solar fields) and focus exclusively in the algorithm effects.
- A second simulation is performed for the design point (one time instant) and the power provided by each of the heliostats is computed.
- Finally, the solar field is defined as the minimum number of heliostats required to provide the design power taken from the beginning of the heliostat list sorted by annual energy yield. This means, that the solar field is composed by the best heliostats in annual performance that deliver the required power at the design point.

To compare the solar fields generated by the different algorithms and, as stated before, also to generate these solar fields, yearly (and design point) energy simulation of the solar fields is required. This simulation should take a complete one-year meteorological data set (only Direct Normal Irradiation values are needed) and evaluate for every hour in the year the optical performance of the solar field and the energy delivered (into the receiver) by each single heliostat and the complete field. Summing up along the year the annual energy output of the solar field and of each heliostat can be then calculated. The evaluation of the solar field performance includes, for each heliostat, the calculation of the cosine effect, shadowing and blocking losses with all its neighbours and atmospheric attenuation. These calculations are performed through detailed mathematical, empirical and geometrical models. Worth mentioning is that in this particular case, the spillage losses have not been considered/included in the calculation, since these losses strongly depend on the receiver geometry, which has not been defined. If spillage was to be considered, the receiver geometry should vary from one scenario to other and should be also optimized for each particular case, leading to an unaffordable computational and design effort which makes no sense for comparing the layout generation algorithms. To make simulations more computationally efficient, the performance of the solar field is not calculated for each of the hours in the year, but an efficiency matrix depending on the sun position is created. This matrix is created for specific values of sun azimuth and elevation covering the complete range of possible sun positions. During the yearly simulations, the sun position for each hour is computed and the solar field performance is obtained via interpolation in the efficiency matrix. For the purpose and methodology of this work, this efficiency matrix is required and thus created for each of the heliostats in the solar field instead of being a single whole solar field matrix (more common in simulation programs). The simulation program and methodology previously depicted has been analysed to check the associated precision and results show errors smaller than 1% when compared to optical simulations with a very detailed and precise ray tracer simulation program, Tonatiuh [17].

3. Results and discussion

The main results obtained from the algorithm comparison are presented in Figure 2. In this figure, the annual efficiency obtained for each of the algorithms once optimized for each of the considered scenarios is shown.

The results show that the differences in annual efficiency reached by the optimized solar fields according to the different algorithms are very small. In fact, these differences are in most cases within the accuracy of the method and models used for the analysis. Only for the scenarios with a very narrow North field configuration (acceptance angle of 90º) the DELSOL algorithms seems to deliver better results than the rest, while the Fermat Spiral seems to be worse. As a reference, the detailed results obtained for Scenario 6, consisting of a 70 m tower and an acceptance angle of 165º are shown in Table 3.

To check the consistency of the comparison approach, it was decided to apply the same comparison considering large heliostats. In this comparison, the expected differences were higher than for small heliostats, since larger heliostats will produce larger blocking for the same tower height and then the positioning algorithm becomes somehow more relevant. The results obtained are shown in Figure 3. Even if the results showed that larger heliostats lead to slightly larger differences in the performance of the algorithms, the differences were also very little. This way, the results obtained show that the driving parameter is most probably the plant size, in such way that all the algorithms behave in a rather similar way for small towers.

4. Conclusions

After a deep review of the existing layout algorithms, a comparison of their performance for several scenarios has been carried out. Even if both options seem to deliver reasonable results, the comparison of the algorithms has been limited to the algorithms based on patters, since they are more likely to be implemented in real plants. These algorithms have been compared for different scenarios covering a range of tower heights, heliostat sizes and acceptance angles (defining to what extent the resulting field is North configuration or surrounding). All the

Table 3: Results obtained for the 6th scenario corresponding to a 70 m high tower and an acceptance angle of 165^{o}.

	Parameters			Number of heliostats	Annual Energy (GWth)	Annual Efficiency (%)	Difference (% points)
DELSOL	nRad=23	fExp=1.13	gap=6.00	576	114.94	59.59	---
MUUEN	dsep=10.80			602	113.03	56.06	-3.55
Campo	dsep=0.89	fbref =0.93		578	112.87	58.31	0.31
Fermat S.	a=1.96	b=0.87	dsep=1.98	584	114.51	58.55	0.73

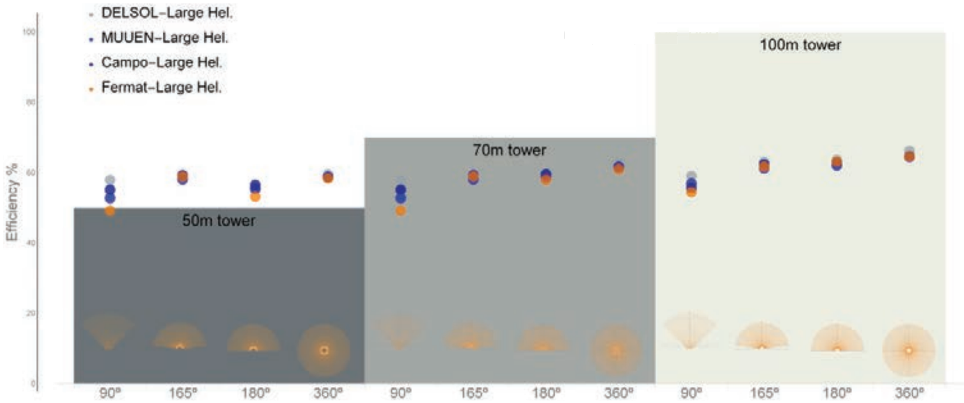

Figure 2: Annual efficiency of each algorithm for each scenario (90, 165, 180 and 360 Degree solar field acceptance angles and 50, 70, 100 m tower heights) for 140 m^2 heliostats.

scenarios are related to a single location in the MENA region and to small fields/powers, according to the goals of the research topics being carried out within the EUROSUNMED project.

For the present study, a robust methodology has been developed, which ensures a fair comparison of the algorithms by analysing the performance of optimized solar fields according to each layout generation method. For this, all the input parameters of each layout generation algorithm are optimized for each scenario prior to compare the solar field performances. The main conclusion is that all the analysed layout generation algorithms lead to similar solar field efficiencies when compared for the scenarios considered in the study and once they are optimized for each scenario. It is worth noting that the slight differences obtained in the simulations are within the expected accuracy of the models used for optimizing and evaluating the algorithms.

In the present analysis, different tower heights, acceptance angles (field shapes) and heliostat sizes have been used for the algorithm comparison, while the plant location, solar field power at design point and other parameters have been kept constant. Therefore, further work is required to check if the algorithms also show similar efficiencies, or to what extent they are similar, when different locations and field powers are considered. Also, more detailed or complete simulation models could be used to double-check this analysis prior to considering this as a final conclusion, since some of the simplifications made could influence the results to certain extent. These additional analyses will be considered within the EUROSUNMED project as a continuation of the current work. Note that, if this conclusion is supported by additional analyses for wider scenarios, the decision on which algorithm is better will most probably be based in other technical and economic considerations rather than in the solar field efficiency.

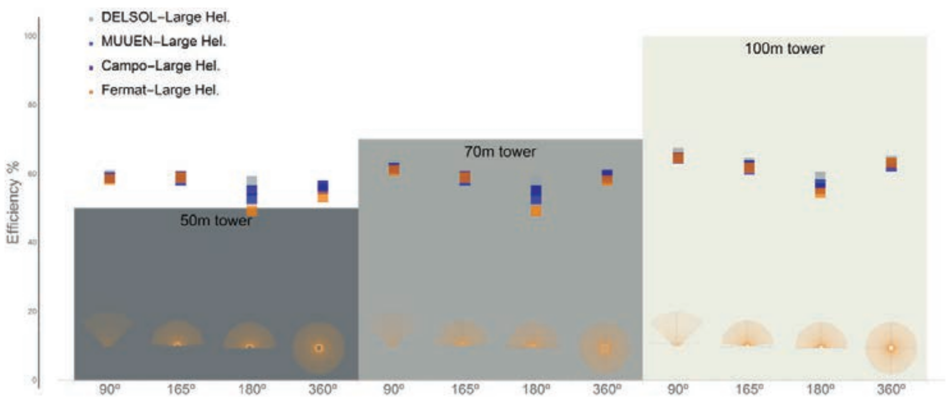

Figure 3: Annual efficiency of each algorithm for each scenario (90, 165, 180 and 360 Degree solar field acceptance angles and 50, 70, 100 m tower heights) for 140 m^2 heliostats.

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