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Review of software for optical analyzing and optimizing heliostat fields

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A B S T R A C T

Solar Central Receiver power facilities are complex industrial systems which require a very important initial investment. The heliostat field is a key factor for both the initial deployment costs and for taking the maximum benefit from the incoming solar energy. Consequently, numerous software packages have been developed through the years to help designers in the designing process of this kind of facilities. In this context, software packages are commonly divided into two main categories: (i) tools prepared for precise and deep optical performance analyses of given fields and, (ii) tools focused on proposing optimal heliostat field layouts according to particular requirements. Although there is a traditional and stable kernel of modeling tools dating from late seventies and eighties, this is an active field under continuous development. In this work, a review of existing software tools from this sector is done, ranging from the original ones (DELSOL, HFLCAL, *etc*), to some modern and powerful utilities (Tonatiuh, HOps, NSPOC *etc*). Additionally, some interesting ideas and algorithms are also commented as promising experimental tools and proofs of concept. The review shows the existence of mature and accessible tools for detailed optical analyses and a certain lack of modern open tools for field optimization.

1. Introduction

Solar Central Receiver Systems (SCRS) are promising power facilities that have been under continuous development since their initial implementations in 1965 [1, p. 618]. SCRS are one of the flagships of renewable energies based on solar energy concentration and they are considered as a viable option to replace traditional fossil fuel power facilities [2]. They are characterized by output stability, provided by heat storage systems, and operational efficiency, due to the overall mature status heat-related technologies.

From a simplistic point of view, these systems consist of a radiation receiver placed over a tower and a broad set of high-reflectance mirrors, known as ‘heliostats’, which track the apparent movement of the Sun, through the day, to concentrate solar radiation on the receiver. Therefore, the receiver is under a high-density radiation flux, and this energy is finally transfered to a working fluid which is in circulation in its interior and can then be applied in classic power steam cycles. At this point, it is important note that temperature gradients and flux distribution must be controlled to avoid damages in the receiver [3–6]. Some of the software packages reviewed in this work are also valuable tools for those control tasks as they are directly linked to the optical behavior of the field [4,6]. In Fig. 1, an overview of the main parts of SCRS is shown. Detailed information of this kind of systems can be found in [1,2,7–11].

The set of heliostats, with their properties and distribution over the SCRS land, forms what is known as ‘heliostat field’. This subsystem is of major importance for SCRS as it can represent approximately the 50% of the total initial investment and can generate up to 40% of energy losses in the power station cycle [12]. Consequently, the heliostat field must be carefully designed and optimized when deploying this kind of facilities. Therefore, specific software packages are valuable tools that can be used to simulate and analyze heliostat field designs in order to test their performance under different conditions and to generate new field designs focused on certain constraints and objectives. Optical efficiency, annual power output, cost of the produced energy and investment cost are some usual and non-exclusive objectives [13–19].

In this context, as commented by [20], two main categories of software tools can be found: on one hand, those prepared for precise optical performance analyses of given fields and, on the other hand, those focused on proposing optimal field layouts according to particular requirements such as land coverage, deployment costs and different combinations of them, but also requiring the evaluation of optical efficiency. The first class is mainly oriented to perform realistic solar flux calculations of defined heliostat fields by applying precise ray-tracing techniques. The second class, in an ideal world, would perform precise computations of the optical behavior of the field. However, as pointed out by most authors, this kind of precise

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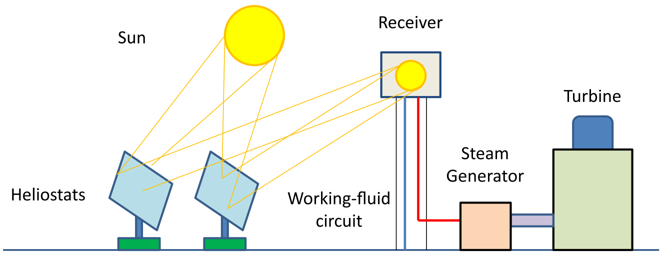

Fig. 1. Simplified scheme of an SCRS system.

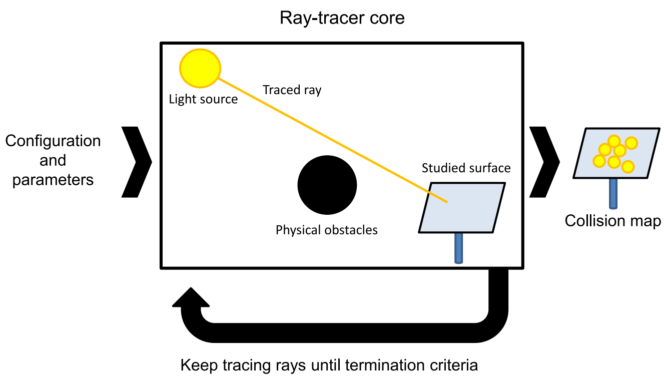

Fig. 2. General procedure of detailed optical analyzers.

techniques are not generally suitable for a deep optimization procedure because of their time and computational power requirements [7,14,16,20–25] and they often apply simplified convolution methods [20,26]. In fact, optimization procedures usually require to evaluate the optical field efficiency, but they tend to take the liberty of applying numerous simplifications to the problem. In this line, it is interesting to note that proposing new approximated ways of evaluating the optical performance of heliostat fields is a very active area of work. It is specially focused on reducing the computational cost of evaluating shading and blocking relations between heliostats, which is one of the most computational demanding processes [14]. This is usually achieved by choosing reduced sets of shading and blocking candidates for each considered one (as done in [14,21,23]) and also by working with analytical simplifications and projecting simple geometrical figures (as done in [21,23,25,27,28]) and surface tessellation (as proposed in [14,29]). Additionally, it is important to highlight that high performance computing techniques are also starting to be seriously taken into account for both categories in order to be able to solve larger problems and to reduce the need of problem level simplifications as proposed in [19,28,30]. In Fig. 2, a simplified flowchart of detailed analysis tools is shown. In general terms, they generate light rays and track their trajectory and interaction with the physical environment. Similarly, in Fig. 3, a simplified flowchart of optimization-oriented tools is included. As can be seen, these utilities try to alter a defined set of design parameters along to achieve certain objectives, what usually includes optical performance. Additionally, this classification is depicted and summarized in Fig. 4 while also including their development lines, i.e., research in methodologies and technological exploitation.

In this work, a review of some existing codes for the heliostat field design and optimization is done. It ranges from the initial and more iconic tools to the new ones. The main purpose of this review is to update previous and very interesting works, such as [20,31,32], with new items and comments from the authors' perspective. The optical performance analysis involving the solar flux calculation of the field is generally kept as the fundamental review criterion for tools, as done in [20]. However, for the sake of completeness, this review also highlights some specially interesting approaches and methodologies related to heliostat field optimization and fast optical performance evaluation.

In the next section the selection of software is presented and exposed in depth. Special attention is payed to the particularities of each tool according to what has been considered to be most important to be mentioned. Then, some points and guidelines are commented about software selection. Finally, conclusions are drawn and some comments with perspective of future are made.

2. Main reviewed codes

There are numerous software tools intended to assist the designer during the process of studying and designing the heliostat field of an SCRS facility. This area has been under development since the first generation of codes appeared at late seventies. Then, the basis of the sector was established with tools such as DELSOL and MIRVAL, which are still of interest nowadays [20,31]. This kind of utilities has been progressively updated with new versions of the previous software, some totally new tools, and numerous new partial models and ideas which are applicable to both heliostat field optical performance analysis and optimization. The set of codes exposed herein is not intended to be extensive but to include the most known ones while also describing some new and promising tools. Despite not being separated into two different sections, features of each code are commented paying special attention to whether they are focused on precisely computing the solar flux distribution, they target heliostat field optimization or they can be applied to both objectives. The alphabetical order has been chosen for the list of tools. In Table 1, a summary of the commented codes, their availability and their references are shown in a similar manner as done in [31]. The first column includes the name of the tools while the second one is for the main organization related to each one. The third column classifies the software according to its main purpose where 'OS' stands for 'Optical Simulation' and 'FO' for 'Field Optimization'. Additional comments are given in the fourth column. Finally, the fifth and the sixth columns are reserved for the availability and the most interesting references of each software respectively.

2.1. ASAP

ASAP, whose name stands for 'Advanced Systems Analysis Program', is a commercial multi-purpose non-sequential ray-tracing software tool. Therefore, it can also be applied to precise heliostat field modeling and optical performance analysis. It has been actively developed by Breault Research from 1982 to nowadays. In fact, its last version is from 2015. It is able to simulate the interaction of light with mechanical and optical structures taking into account the most important physical phenomena related to light such as reflection, refraction, diffraction, etc. in a very realistic way.

ASAP has several interesting features such as a user-friendly GUI (Graphical User Interface), detailed plotting 2D and 3D, realistic light sources, interoperability with SolidWroks and CAD formats. The tool is compatible with script interaction by using its own scripting language as well as other popular ones such as Python, VBScript and JavaScript. Furthermore, ASAP is also equipped with an easy to use optimization toolbox that can be applied to optimize optical systems featuring algorithms like Simulated Annealing and Downhill Simplex. However, it is important to note that these optimization capabilities are not intended to cover full complex heliostat fields but specific reflecting surfaces and designs, as it could be the design parameters of a parabolic collector for instance.

In spite of being a multi-purpose tool which is not specifically oriented to solar applications (not being 'solar friendly' as commented in [46]), this tool has been chosen to be included because of its long trajectory and continuous improvement. In fact, it was already selected as an interesting heliostat field optical performance analyzer at [32]. Its applicability in this context is also commented in [42] and specially in [50], where it is used to accurately simulate the heliostat field energy losses (cosine, blocking, shadowing, attenuation, and reflective losses,