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Optical simulation of a central receiver system: Comparison of different software tools

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ABSTRACT

Heliostat field layout design is a critical task in solar tower power plant construction due to its impact in the final plant efficiency and cost. The complexity of these systems and the high number of parameters to define during the field design stage demand the use of suitable simulation tools to compare different design options and evaluate the final performance of the heliostat field. This work concerns a comparison of some of the most common tools used for the heliostat field layout design and analysis, aiming to help Concentrating Solar Power researchers and industry by providing more information regarding the tools comparative results and features. A brief review of available tools is presented, including an extended description of some of them – Tonatiuh, SolTrace, TracePro and CRS4-2. A qualitative comparison of these four tools is performed focusing on functionality and usability. A quantitative comparison is done providing simulation results for a test-case, the SPSS-CRS facility located at Plataforma Solar de Almeria in Spain. In general, the results for total power and maximum irradiance are in good agreement across most tools. The total power values are very close for Tonatiuh, SolTrace and CRS4-2. Apart from the designer preferences, the choice of the most suitable tool depends on the specific application and requirements.

1. Introduction

Scientific research and technological development (RTD) enhances Concentrating Solar Power (CSP) systems, leading to improved efficiency and durability, and contributing to a decrease in CSP's levelized cost of electricity. Cost reductions coupled with CSP plants inherent capability to provide dispatchable power and ancillary services (by using thermal energy storage systems or through hybridization with other power sources [1]) are leading to an increased deployment of this technology.

Central receiver systems (CRS) are one of the main CSP technologies being deployed. Based on a matrix of flat or slightly curved reflectors, called heliostats, CRS concentrate the solar radiation onto a receiver placed on the top of a tower where it is absorbed and converted into heat [1–3]. An alternative configuration is the beam-down layout: where the heliostats focus the radiation on secondary optics, located on the top of a tower, which redirect the concentrated beam towards a receiver placed at the bottom of the tower [4–6].

Knowledge of the optical performance of the heliostat field is required for RTD activities and project development, from feasibility studies to detailed design. The total power incident on the receiver is one of the parameters required to characterize the heliostat field for research and during early stages of the project development, being used to compute heliostat field efficiency matrices used in plant performance simulations. Moreover it is also one of the relevant parameters during the detailed plant design, together with other information such as the maximum irradiance on the receiver surface and its position.

CRS optical design and simulation is complex and time-consuming, being a critical step to ensure the plant's feasibility and viability since the heliostat field represents a significant share of the plant's capital costs and energy losses [7].

Commercially available software packages for generic optical design, like Zemax/OpticStudio [8], TracePro [9], Code V [10], OSLO [11], ASAP [12] and others are conceived to simulate, develop and optimize optical components for disparate applications. Although the optical design of solar components can be one of such tasks, these

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software tools are not specifically developed to simulate solar plants, lacking dedicated methods for the design and optimization of CRS optical systems. The development of new software, to replace or complement the commercial packages, has the advantage of adapting the software to the needs of the solar plants optical design and optimization. However, this represents a considerable effort and resource consumption due to the complexity involved in creating an accurate and flexible tool suited to more than one application and configuration with all the needed functionalities, requiring a joint effort by a combined group of researchers and developers to be successful. It is also possible to develop simpler tools specific for a given application or configuration, however, such an approach will lead to the necessity for new developments every time a new configuration is to be simulated or a different analysis must be performed, increasing the amount of work and potentially leading to duplication of effort. Moreover, CSP technology is still not mature, with intense RTD activities underway, creating new requirements for the tools functionalities. Thus, software tools for optical design and analysis of CRS and other CSP technologies must be flexible and expandable since there is a strong drive for the development of new functionalities and demand for its application in new situations.

Over time, several tools have been developed by the CSP community, trying to achieve more accurate, faster and better suited tools to enable further development of this sector. Those efforts were (and to some extent still are) largely uncoordinated, arising from individual needs created by the research and development activities, having resulted in a large set of different software with distinct specificities and capabilities. A literature review, focused on publications where results from CSP RTD activities were presented, identified up to 37 different tools used for optical simulation of concentrating solar systems (see Table 1).

Brief descriptions and comments regarding the main characteristics and functionalities of several tools can be found in the following review papers [7,12,21,31]. These works result from a qualitative analysis of the software, performed by the authors based on their personal usage of the tools, literature review and a user/developer survey. Garcia et al. [21] surveyed the developers or heavy users of six of the most used tools at the time, presenting the main characteristics and features of the tools, dividing them between optimization and performance analysis codes. Moreover they quoted new generation codes that were under development. This article is still relevant since several of the reviewed tools are still being used today, ten years later. Cruz et al. [7] is built upon the work of Garcia et al. [21], presenting and briefly analyzing the features of a large subset of the available tools, reviewing the key aspects and availability of 18 software tools, categorizing them in two groups: precise-analysis tools and optimization-oriented tools. Additionally they present summarized information regarding “valuable discontinued tools, proofs of concept (even if they may not be used as stand-alone software) and not widely used/described tools that could also be of interest.” Ho [12] presents a general overview of the available software tools for the analysis of concentrating solar thermal systems, encompassing a wide range of tasks and technologies, including six tools for the optical design and performance assessment of heliostat fields. Bode and Gauché [31] briefly summarize and compare the main characteristics of ten tools.

None of these articles delves into an in-depth comparison of the software features, no one performs any kind of comparison of the results. However, comparative analysis of tool functionalities and simulation results are extremely relevant to the CSP community, namely to its researchers and engineers, who must choose the most suitable tool for their tasks in order to achieve fast and accurate results. The chosen tool can be different depending on the task at hand. For example, simulation or performance analysis requires tools able to perform accurate and precise simulations, representing as close as possible the real system. However, for optimization purposes it may be best to sacrifice some accuracy to achieve greater computational speed. Other authors [7,12,21] briefly discussed the choice of a suitable tool. Garcia et al. [21] present the choice problem from an industrial project point of view, suggesting two approaches for the CRS design. The first is a two steps approach, starting with the determination of the general layout of the plant from key parameters using an optimization code, followed by a detailed analysis with a performance analysis code. The second consists in using solar field efficiency matrices, obtained with one of the analyzed codes, in thermal performance simulations of the CRS system. Bode and Gauché [31] discuss this subject from the South African researcher point of view, defending the development of their own tool considering the mathematical models and algorithms already available and described in the literature. Garcia et al. [21] stress the need to separate from detailed heliostat field analysis and optimization when choosing a tool and to evaluate tool availability, support, documentation and expansion capabilities. For detailed optical analysis activities they recommend to consider first SolTrace, Tonatiuh and a commercial tool like STRAL. However, for heliostat field optimization there is no clear recommendation.

Considering that a large number of tools are available, it is necessary to know how the tools compare for a given application in order to help the users to decide which tool to use for each type of task. Moreover, these comparisons help to identify the requirements for further improvement of the tools and to understand which tools should be chosen for additional development, signaling to the community the best tools to develop, i.e., the ones where resources for improvement should be focused, helping to achieve a coalescence around a smaller set of tools in order to reduce dispersion of efforts while increasing the resource pool available for each tool.

Very few articles present direct comparisons of simulation results obtained using different software tools. One exception is [44] that presents a comparison between Tonatiuh and SolTrace for different solar concentration systems. However, this comparison was carried out

Table 1
Non exhaustive list of software tools used for optical simulation of concentrating solar systems.

Software	Reference	Software	Reference	Software	Reference
ASAP	[12]	LightTools	[27,28]	SolTrace	[36]
CAMPO	[13]	mcm3d	[20]	SOLVER	[31]
CAVITY	[14]	MIRVAL/SPRAY	[29]	SORISM	[23]
CIRCE	[15]	NSPOC/CAVISOL	[30]	STRAL	[37]
COSAC	[16]	OPTEC	[31]	Tonatiuh	[38,39]
CRS4-2	[17,18]	OptiCAD	[32]	TracePro	[9]
DELSOL/winDELSOL	[19]	Radiance	[33]	VeGas	[40]
EDStar	[20]	RADSOLVER	[14]	WELSOL	[41]
Fiat Lux	[21]	Raytrace3D	[34]	WISDOM	[42]
HELIOS	[22]	RCELL/TieSOL	[31]	Zemax/OpticStudio	[8]
HFLCAL	[23,24]	SCT	[31]	Tracer	[43]
HFLD	[25]	SENSOL	[31]		
ISOS	[26]	SoFiA	[35]		