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Optimization of V-Trough photovoltaic concentrators through genetic algorithms with heuristics based on Weibull distributions

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HIGHLIGHTS

- A study of genetic algorithms to optimize the parameters of photovoltaic V-Troughs.
- A new genetic algorithm with heuristics based on Weibull distributions.
- The new algorithm resulted significantly superior against standard metaheuristics.
- New indicators and indices were proposed as multi-objective fitness functions.
- Genetic optimization compared with an interactive software in a case study.

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ABSTRACT

Photovoltaic V-Troughs use simple and low-cost non-imaging optics, namely flat mirrors, to increase the solar harvesting area by concentrating the sunlight towards regular solar cells. The geometrical dispositions of the V-Trough's elements, and the way in which they are dynamically adjusted to track the sun, condition the optical performance. In order to improve their harvesting capacity, their geometrical set-up can be tailored to specific conditions and performance priorities. Given the large number of possible configurations and the interdependence of the multiple parameters involved, this work studies genetic algorithms as a heuristic approach for navigating the space of possible solutions. Among the algorithms studied, a new genetic algorithm named "GA-WA" (Genetic Algorithm-Weibull Arias) is proposed. GA-WA uses new heuristic processes based on Weibull distributions. Several V-Trough performance indicators are proposed as objective functions that can be optimized with genetic algorithms: (i) $\overline{C_e}$ (average effective concentration); (ii) *Cost* (cost of materials) and (iii) T_{sp} (space required). Moreover, from the integration of these indicators, three multi-objective indices are proposed: (a) I_{COE} ($\overline{C_e}$ versus *Cost*); (b) MI_{COE} ($\overline{C_e}$ versus *Cost* and $\overline{C_e}$ versus T_{sp} combined) and (c) MDI_{COE} (similar to MI_{COE} but with discretization considerations). The heuristic parameters of the studied genetic algorithms are optimized and their capacities are explored in a case study. The results are compared against reported V-Trough set-ups designed with the interactive software VTDesign for the same case study. It was found that genetic algorithms, such as the ones developed in this work, are effective in the performance indicators improvement, as well as efficient and flexible tools in the problem of defining the set-up of solar V-Troughs in personalized scenarios. The intuition and the more holistic exploration of a trained engineer with an interactive software can be complemented with the broader and less biased evolutionary optimization of a tool like GA-WA.

1. Introduction

The International Energy Agency estimated that almost one-fifth of the world's population, mostly from developing countries, lacks access to electricity [1]. This acute absence of basic living conditions contrasts with the rapid rate at which developing countries are becoming industrialized with fossil-fueled economies. Such scenario has taken the world to a point where "Developing nations are driving the ongoing increase in global CO_2 emissions"[2]. Most of these countries are located within the tropics [3], where there is higher solar insolation and hence, higher solar harvesting potential. However, the cost of residential solar Photovoltaic (PV) devices is still prohibitive for a widespread adoption [4–8]. Therefore, it is crucial to pursue solutions, from design and engineering, that might favor the transition of these nations towards sustainable solar energy.

In this regard, V-Trough concentrating devices present the

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opportunity to improve the cost-effectiveness of solar energy. They increase the energy that can be harvested with a solar absorber by means of low-cost non-imaging optics. These devices use flat mirrors, located on the borders of a PV absorber, in order to concentrate the sunlight from a greater effective solar-collecting area. As the flat mirrors and the additional supporting structure tend to be considerably less expensive than the PV material, V-Troughs have the potential to reduce the costs overall [9–11]. Moreover, the low concentration factors that they usually reach, mean that it is possible to use regular and widely available commercial solar cells [9,11–13]. V-Troughs are an effectively simple solar technology [6,14] compared to other concentration approaches, such as Fresnel lenses [15], solar power towers (heliostats) [16], high-concentration dishes [17,18] or parabolic troughs [19]. This simplicity is favorable in order to face the social-adoption barriers in developing countries because it can ease the manufacturing, installation, operation and maintenance processes [9,11,20].

The effectiveness of a V-Trough, to focus the sunlight, depends on several geometrical parameters: the lengths and angular positions of the mirrors, relative to the PV absorber, and the angular position of the device, relative to the sun. Since the sun follows an apparent path through the sky, such parameters can be dynamically adjusted in order to track the sun and enhance the harvesting effective area throughout the day. This can be achieved with automatized, yet technologically complex, solar tracking systems. On the other hand, to favor adoption among non-industrialized societies, it is worth exploring the potential of manually tracking the sun with a few adjusting steps along the day [21,22].

To get the most out of the V-Trough technology, the parameters that define the geometrical features of a V-Trough, and the way in which they are to be adjusted for manual tracking, can be tailored to the specific conditions and priorities of a given family. Personalized V-Trough set-ups can be interactively explored and evaluated with "VTDesign", a generative software developed by Arias-Rosales and Mejía-Gutiérrez [23]. VTDesign is based on a computationally-inexpensive, yet flexible, geometrical and analytical model [24]. This model can be used to simulate the interactions between the V-Trough's elements and the solar beam radiation, which is typically taken as 90% of the global radiation on average [25].

Nevertheless, a tool such as VTDesign may require the intuition of an engineer trained in V-Trough technology and may be susceptible to human bias. This may, in turn, limit a widespread exploration and implementation of V-Trough personalized solutions. Accordingly, optimization methods may be used to converge into satisfactory set-ups without requiring a deep understanding of the optical phenomena behind the simulations. However, the broad space of possible solutions renders optimization methods like exhaustive-search impractical. Despite the simplicity of these devices, there is a vast amount of possible configurations of V-Trough dynamic geometries. Moreover, a V-Trough analytical model such as the one used by VTDesign [24] is not a continuous function, so it cannot be optimized with derivatives. Other simpler analytical models [26] could be optimized in such a way, but they lack the parametric flexibility needed for a broad exploration.

When more traditional methods are not applicable, Genetic Algorithms (GAs) can be an effective way to navigate an extensive space of possible configurations looking for an optimal (or near-optimal) solution in design and engineering matters [27–31]. GAs are based on the biomimicry of Darwinian evolution principles [29]. Following this biological metaphor, V-Trough devices can be regarded as animals whose DNA (genetic information) determines the geometrical parameters of their mirrors and the PV absorber and the way in which they move in reaction to the solar apparent movement. Within a genetic algorithm, these "V-Trough beings" would be arranged in a diverse population where every individual may have a different physiology (set-up). By means of a series of processes, inspired by sexual reproduction and biological mutation, this population can evolve throughout a given amount of generations. This evolutionary progression seeks to converge into the best-explored solution in terms of a given objective function. GAs, as opposed to VTDesign and other optimization methods, offer the opportunity to overcome possible design biases, find non-intuitive solutions and to converge effectively and consistently for personalized scenarios without the need of a solar-qualified engineer behind a software.

This work studies genetic algorithms as tools for determining the V-Trough's geometrical set-up in scenarios which are personalized in terms of the context conditions, the performance priorities and the user's routine. The developed GAs can be used to optimize the system's performance regarding the effective optical concentration, the cost of materials, the space occupied and the multi-objective cost-effectiveness from several perspectives. Among the GAs studied, a new genetic algorithm is proposed based on Weibull frequency distributions; named as "GA-WA" (Genetic Algorithm-Weibull Arias). GA-WA is a general-purpose genetic algorithm and, therefore, it can be used in other design-engineering problems. However, it is believed to be of special use in the V-Trough design problem. Its performance is compared in a V-Trough case study against more traditional genetic algorithms and previously published results achieved with VTDesign [23]. To the best of the authors' knowledge, the following are the contributions of this work to the state of the art:

- Unprecedented flexibility in the multi-parameter optimization and geometrical exploration of V-Trough solar devices (Sections 3 and 4.2).
- New indicators and indices proposed as fitness functions for assessing a V-Trough's performance in terms of the space required and the cost-effectiveness from various multi-objective perspectives (Section 3).
- First evaluation of genetic algorithms as heuristic tools for determining the V-Trough parameters in personalized scenarios.
- Introduction of a new genetic algorithm, GA-WA, with the novel heuristic capabilities of initializing the first population around intuitive values, implementing various stagnation strategies and a greater control and flexibility regarding random processes in mutation and elitism (Section 4).
- First optimization of the heuristic parameters of three genetic algorithms in the V-Trough engineering problem, assessing the effect of each heuristic parameter on the optimization performance (Section 5).
- Applied case study were both GA-WA and the software VTDesign are evaluated and compared from the perspective of three different design goals (Section 6).

2. Literature review

This section seeks to address what has been done in the literature concerning the optimization of V-Trough solar devices. Heuristic optimization methods are presented as a suitable approach, in particular, genetic algorithms, which are classified as metaheuristics. As follows, there is a review on GAs implementations in solar matters and specific genetic heuristics which are of interest for this study. As defined by Pearl [32], "heuristics stand for strategies using readily accessible information to control problem-solving processes in man and machine". Regarding optimization, metaheuristics can be seen as general algorithmic frameworks that select among different heuristic strategies and can be applied to a wide set of different design/engineering problems [33].

In the majority of the V-Trough studies found, the optimization is based on performance curves obtained numerically [34,35,9,12,10,36–41]. In this approach, a given geometrical