VTDesign: Implementation of a Direct Radiation Model in an Interactive Software for Designing V-Trough Photovoltaic Devices

Andrés Arias-Rosales*, Ricardo Mejía-Gutiérrez
Design Engineering Research Group (GRID). Universidad EAFIT, Cra. 49 N. 7 Sur 50, Medellín, Colombia.

* Corresponding author. Tel.: 57 3104693779; email: aariasr@eafit.edu.co
Manuscript submitted July 8, 2016; accepted August 1, 2016.
doi: 10.17706/ijcee.2016.8.5.288-293

Abstract: V-Trough concentrating devices with tracking strategies are considered to be a simple and low-cost approach to increase the solar harvesting area of photovoltaic energy conversion systems. Seeking to support the design and exploration of these devices, this work presents the development and exploration of the software “VTDesign”. The software was developed to guide a designer through the process of defining the geometrical parameters of a solar V-Trough based on the analytical assessment of direct radiation. VTDesign allows the user to rapidly iterate and compare diverse alternatives by means of a cost-effectiveness analysis and the visualization of the optical performance and geometrical representations. The capacities of the software in terms of interactive design are explored in a case study.

Key words: Energy conversion system, geometrical optics, interactive software, solar V-Trough.

1. Introduction

Among the energy conversion systems based on renewable energies, the V-Trough Photovoltaic (PV) devices are considered to be a suitable approach for the energy needs present in the developing countries which still experience limitations in purchasing power and technological capacities. These devices concentrate the sunlight with simple and low-cost flat mirrors located in the borders of a PV absorber. The lengths and angular positions of those elements can vary relative to each other and to the incident solar rays. Also, their angular positions can be dynamic, when solar tracking strategies are implemented, in order to effectively focus the rays towards the PV absorber as the sun moves throughout the day [1]. These variations can directly impact the optical performance of the device and imply several movements of the V-Trough's elements throughout the day, which in turn affects the cost-effectiveness and may have implications over the daily routines of the device's users.

The potential of V-Trough devices could be further explored and developed with new alternatives by focusing on simple user-oriented manual tracking strategies, personalized geometries and specific movements according to context requirements and the user's routine. The development of such new alternatives could be supported by empowering the designers to interactively simulate the optical and cost-effectiveness performance in successive iterations. In order to simulate the performance effects of different V-Trough geometrical set-ups, this work proposes an interactive software based on the analytical model of Arias-Rosales & Mejía-Gutiérrez [2]. This model was chosen because its conceptual definition is design-oriented and it allows a detailed description of the interactions between the direct solar radiation and the V-Trough's elements. The authors believe that the design-orientation capacities of the model can be further developed and explored by implementing it in a software capable of guiding a designer through the parameters definition process and providing a visualization of the modeling results. This work describes the development of such a software, so-called "VTDesign", and explores its capacities through a constrained case study.

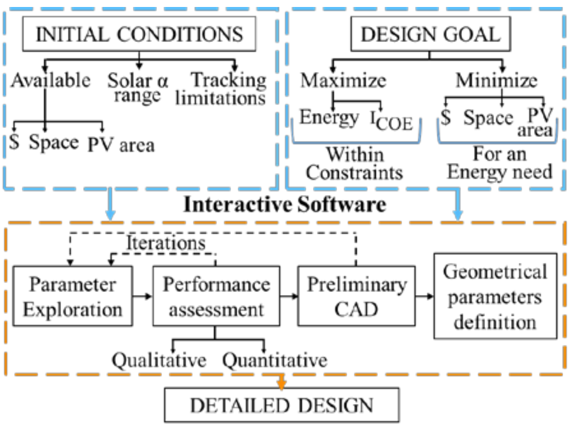
2. State of the Art

Several softwares were found which can be used to support the development and exploration of photovoltaic devices. For instance, PVsyst® is a widespread software used to support the development of new solar projects [3]. Nevertheless, it is too limited in terms of tracking and concentration for new devices. Other softwares offer more design flexibility by focusing on a detailed simulation of the optical performance of a solar device through ray-tracing methods, such as RaySim6®, Radiance®, Photopia®, LightTools® and TracePro® [4] [5]. From the analyzed softwares with radiation-modeling capabilities, SolTrace® [6] appears to be the most suitable for designing new photovoltaic devices such as the ones addressed in this work due to its geometrical flexibility for solar tracking and concentration. However, for these softwares to deliver useful modeling results, they must perform hundreds of thousands, or even millions of calculations, due to their numerical nature. The authors believe that a more effective approach to support V-Trough interactive design is through a dedicated interactive software based on an analytical core. Other authors have analyzed the optical performance of solar V-Troughs based on analytical models [1][7][8], but no software such as the one described has been found.

3. Development of the Software

Fig. 1(a) contextualizes the main goals of the software within a design frame. According to the specific design application there are several initial conditions to consider, such as tracking limitations defined from the number of times that a user is willing to move the device, for instance. There may also be limited economical or space resources as well as limited range of *solar angular elevation* (α [deg]), constrained by the characteristics of the surrounding horizon and nearby objects.

In terms of the main V-Trough design goal, there may be two perspectives: To maximize the daily energy output or the *cost-effectiveness of the device* (I_{COE}) given certain limitations; or to meet a certain energy need while minimizing the cost, the PV area or the area needed for the whole device. From the initial conditions and a stated design goal, the software intends to interactively guide the designer throughout the process of defining the static and dynamic geometrical parameters of the device, which lays the foundation for the successive detailed design stages.



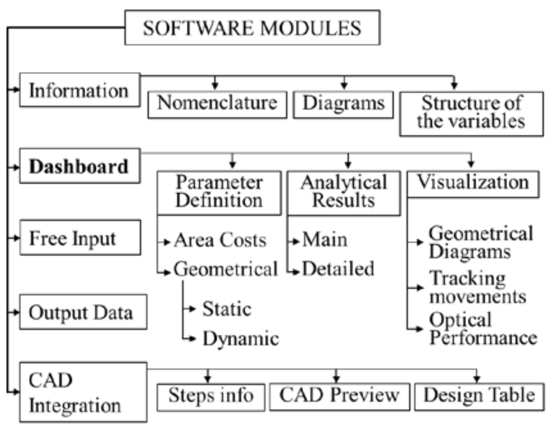


Fig. 1. Conceptual structure where the proposed software is contextualized and defined.

Fig. 1(b) illustrates the way in which the modules and sub-modules of the software were structured hierarchically. This structure served as a guide to design in detail the elements of each module and their interactions. The software's modules were programmed with Visual Basic® in Microsoft Excel® seeking a highly interactive application. The main module is the Dashboard, where the designer can define the main geometrical parameters while visualizing the V-Trough's proportions, movements and performance in terms of optics and cost-effectiveness. The Dashboard also shows a representation of the needed space in the floor to allocate the device and shows the PV area reduction achieved as compared to a reference. The module of CAD Integration is where the parametric exploration process is integrated with the software SolidWorks® for a 3D visualization of the geometries and tracking movements. This module includes a design table in which the user can define parameters for 3D considerations, such as thickness and depth dimensions. The integration with the CAD software allows the designer to explore in detail the implications of the V-Trough device in four different configurations, corresponding to four solar elevations α defined for visualization. For a detailed explanation of the relevant variables and the mathematical model behind the software, refer to the published and corroborated model which VTDesign uses for its simulations [2].

4. Case Study: The energy needs of a family in a developing country

The case study is framed within the following design brief: A family with a daily energy need of 1495.4 Wh has an available solar elevation range of $0° \leq \alpha \leq 160°$, an average Irradiance of $354.2\ W/m^2$ and they are willing to manually move the V-Trough system twice a day, i.e., at 10 a.m. and at 2 p.m. Their solar cells have an efficiency of 15% and $0.024\ m^2$. The system has 16% efficiency losses and the mirrors have an index of reflection of 0.85. The area costs of the PV absorber, the mirrors and the supporting structure are 600, 13.33 and 62.23 $[USD/m^2]$, respectively. This design problem was approached from three different design perspectives where an initial intuitive set-up was defined for every perspective and then the parameters were interactively iterated with VTDesign. The inputs for the simulations were: the left and right mirror lengths (LL and LR respectively) as proportions of the length of the PV absorber; the inclination of both mirrors (ψL and ψR); the *initial angular position of the device* (β_i); the *solar angular step between tracking steps* ($\beta_{\alpha S}$); and the *tracking angular variation per step* (β_S).

4.1. Results and Discussion

The most interesting simulations from the case study are summarized in Table 1 and the behaviour of their *optical effective concentration* (C_e) is shown in Fig. 2.

- Design Perspective I: The goal was to minimize the cost while fulfilling the given energy need. The strategy was therefore to maximize the *cost-effectiveness index* (I_{COE}) presented by the software. The selected set-up was Ia, which achieved the lowest cost. The set-up Ib presented a higher I_{COE} but it resulted in a higher cost than Ia. This can be explained from the fact that the PV cells have discrete areas and thus, the *number of cells* ($nPVC$) must be a whole number and this in turn forced Ib to generate more energy than needed when the minimum $nPVC$ was defined.
- Design Perspective II: The goal was to maximize the energy within $10\ m^2$ and with 80 cells available. The strategy was to maximize the *average optical effective concentration* ($\overline{C_e}$) by taking full advantage of the available space through concentration and tracking. The set-up IIa was selected since it achieved the highest energy output.
- Design Perspective III: The goal was to minimize the *Space* needed to allocate the device while fulfilling the energy need. The strategy was to maximize $\overline{C_e}$ by focusing on tracking and minimizing the area of the mirrors. The selected set-up from this perspective was $IIIa$.

Table 1. Summary of the most interesting simulations.

Set-up	LL	LR	ψL	ψR	β_i	$\beta_{\alpha S}$	β_S	$\overline{C_e}$	I_{COE}	$nPVC$	$Space$	$Cost$	$Energy$
Ia	0.8	0.8	25°	25°	60°	60°	-56°	1.403	1.716	92	$4.77m^2$	$1753.4USD$	$1495.4Wh$
Ib	1	1	24°	27°	59°	60°	-57°	1.463	1.723	89	$5.46m^2$	$1761.6USD$	$1508.1Wh$
IIa	2.35	2.35	20°	20°	60°	60°	-56°	1.678	1.58	80	$9.95m^2$	$1980.7USD$	$1554.8Wh$
$IIIa$	0	0	0°	0°	60°	60°	-56°	0.96	1.389	135	$3.29m^2$	$2175.7USD$	$1501.6Wh$
$IIIb$	0	0	0°	0°	10°	60°	0°	0.702	1.015	184	$4.39m^2$	$2965.3USD$	$1496.3Wh$

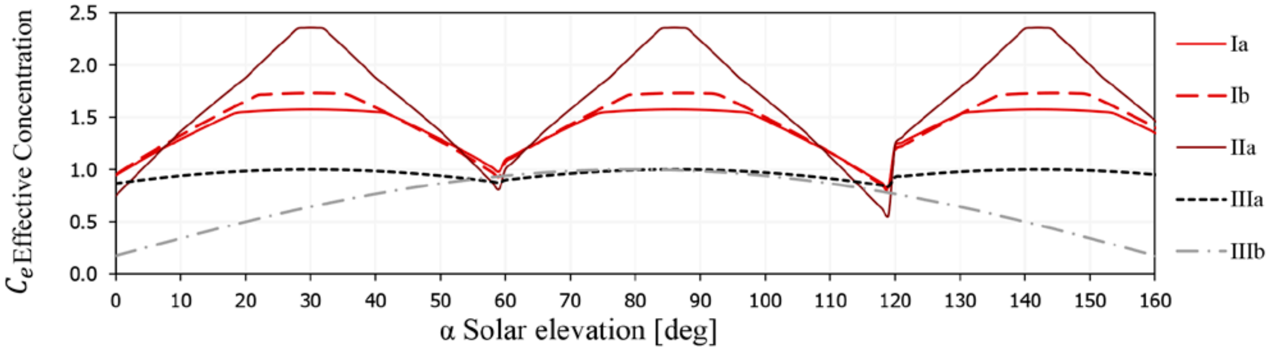


Fig. 2. Optical effective concentration C_e of the most interesting simulations.

The visualization provided by VTDesign was crucial for analyzing each set-up in detail. Fig. 3 presents such geometrical and numerical visualization by taking the set-up Ia as the most representative example. Fig. 3(a) illustrates the tracking movements in function of α. Fig. 3(b) shows the main optical performance; including the *effective concentration* (C_e), the *incident optical concentration* (C), the *effective concentration due to the PV absorber* (CPV_e), the *effective concentration after one bounce off the mirrors* (CM_{PV}), the *effective concentration after two bounces off the mirrors* (CM_{MPV}) and the *effective concentration of a reference cell with no mirrors and no tracking* (C_eReference). Fig. 3(c) graphically shows the achieved reduction in the needed PV area as compared to a reference cell. Fig. 3(d) shows the positions which occupy more horizontal length. Fig. 3(e) presents the preliminary CAD obtained from the integration between VTDesign and SolidWorks® and it is shown for 4 different solar elevations. Finally, Fig. 3(f) shows a more detailed design of the same V-Trough system contextualized in the design scenario.

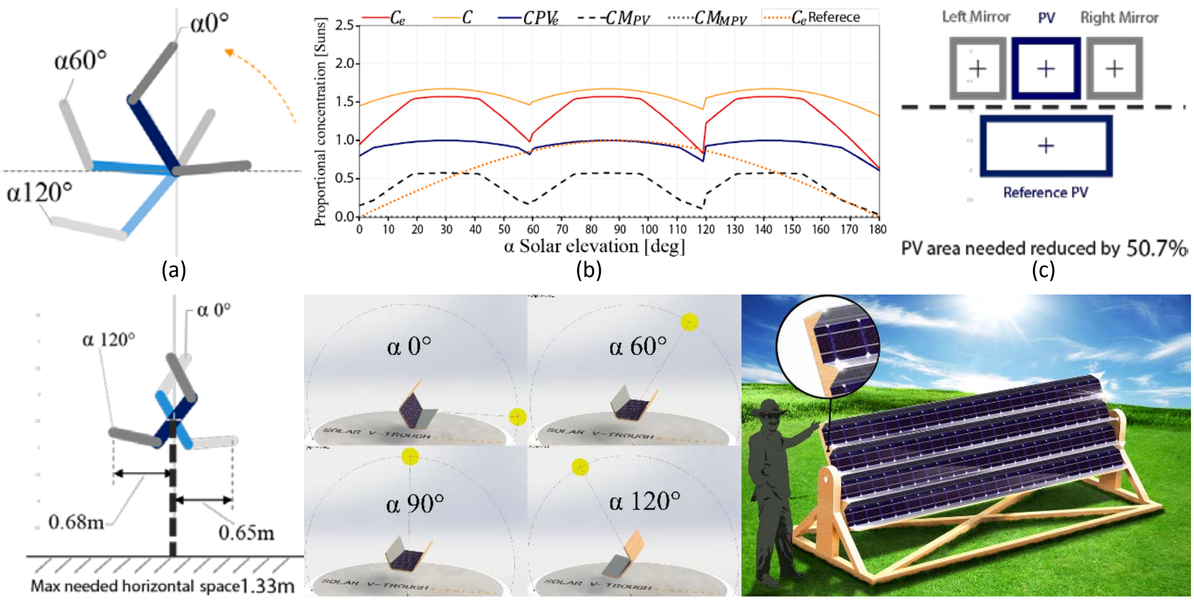


Fig. 3. From VTDesign: Optical performance, geometrical diagrams and CAD evolution of the set-up Ia.

5. Conclusion

A highly specific and constrained design brief was approached from three different perspectives in terms of the design goal. This was made possible by the parametric flexibility of the proposed software and the results of the simulations that it provided in a numerical and graphical manner. The design exploration was performed by interactively iterating the input geometrical parameters and analyzing the real-time simulations, which favored an effective and sufficiently informed decision-making process. The diagrams provided by VTDesign supported an intuitive understanding of the geometrical implications arising from the input parameters. Moreover, the numerical results guided the design exploration towards 3 different selected set-ups; one for every design perspective established.

The software proved to be useful for personalized design scenarios, since it was possible to achieve set-ups with superior performance than the base set-ups, which were designed from intuition. For instance, the most intuitive angular position for the mirrors would commonly be 30°, but the simulations (Ia, Ib, IIa) showed that, under the specific design frame of the case study, a better performance may be achieved with different inclinations which can be maximized according to the tracking strategy and the lengths of the mirrors. The total cost of Ia was 3.7% less than the starting intuitive base set-up (base set-up for perspective I: $LL = LR = 1$; $\psi L = \psi R = 30°$; $\beta_i = \beta_{\alpha S} = -\beta_S = 60°$). The energy output of IIa was 19.1% greater than the base set-up, which was the same intuitive starting point as the one for perspective I. In the third selected set-up $IIIa$, the needed space to allocate the whole device was 27.8% less than the base set-up for that design perspective (base set-up for perspective III: $LL = LR = 0$; $\beta_i = \beta_{\alpha S} = \beta_S = 0°$). By comparing Ia and Ib it was also found that, for a minimum given energy need, a greater index of cost-effectiveness I_{COE} does not necessarily mean a lower total cost, since the needed PV area is comprised of several cells with discrete areas and this can lead to additional costs for unnecessary extra PV area.

References

[1] H. M. Bahaidarah, B. Tanweer, P. Gandhidasany & S. Rehman. (2015) A Combined Optical, Thermal and Electrical Performance Study of a V-Trough PV System—Experimental and Analytical Investigations. *Energies*, *(8)4,* pp. 2803-2827.

[2] A. Arias-Rosales & R. Mejía-Gutiérrez. (2016). Cost-effectiveness analysis of Low Concentration Photovoltaics (LCPV): Modelling of direct solar radiation for the design and simulation of V-Trough devices with Tracking. *International Journal on Interactive Design and Manufacturing (IJIDeM), (10)3,* 257–273.

[3] B. S. Kumar & K. Sudhakar. (2015). Performance evaluation of 10 MW grid connected solar photovoltaic power plant in India. *Energy Reports, 1,* 184-192.

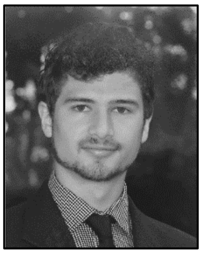
[4] J. Cotter. (*2005).* RaySim 6.0: a free geometrical ray tracing program for silicon solar cells. *Conference Record of the Thirty-first IEEE Photovoltaic Specialists Conference, 2005,* 1165-1168.

[5] T.-K. Yew, K.-K. Chong & B.-H. Lim. (2015). Performance study of crossed compound parabolic concentrator as secondary optics in non-imaging dish concentrator for the application of dense-array concentrator photovoltaic system. *Solar Energy, (120),* 296-309.

[6] W. Le Roux. (2016). Optimum tilt and azimuth angles for fixed solar collectors in South Africa using measured data. *Renewable Energy, (96),* 603-612.

[7] G. Tina & P. Scandura. (2012). Case study of a grid connected with a battery photovoltaic system: V-trough concentration vs. *Single-axis Tracking. Energy Conversion and Management, (64)*, 569–578.

[8] N. Fraidenraich. (1992). Analytic solutions for the optical properties of V-trough concentrators. *Applied Optics, (31)1,* 131-139.



Andrés Arias-Rosales was born in Medellín, Colombia, in 1991. He graduated with honors from the B.A. in Product Design Engineering from *Universidad EAFIT* (Colombia, 2014). Arias is currently in the final year of the Master of Science in Engineering, *EAFIT*. His major field of study are renewable energies.

In 2013, he joined the Design Engineering Research Group (GRID) in *EAFIT* as a Research Assistant Intern, where he participated in the development of the first Colombian solar car. In the same group, he worked as a graduate Research Assistant in 2015 in the field of wind energy. He then became an Adjunct Professor during 2016. Nowadays, he has a grant within GRID to pursue his work in wind energy. He is the corresponding author of "Nominal energy optimisation method of constrained battery packs through the iteration of the series-parallel topology" (Wiley Online Library, 2017) and the first author of "Modelling and simulation of direct solar radiation for cost-effectiveness analysis of V-Trough photovoltaic devices" (Springer, 2016).

Mr. Arias-Rosales was acknowledged with two undergraduate Honor Scholarships; with the Award for Outstanding Undergraduate Students for their Involvement in Research, by the Medellin's Major; with the Postgraduate Studies Scholarship due to Research Recognition, EAFIT; and with the Best Presentation Award 2016 3rd International Conference on Mechanical, Materials and Manufacturing.

Ricardo Mejía-Gutiérrez was born in Medellín, Colombia, in 1976. He holds a PhD in Mechanical Engineering from *École Centrale de Nantes* (France, 2008); a M.Sc. in Manufacturing Systems from *Tecnológico de Monterrey* (Mexico, 2003) and a BSc in Production Engineering, graduated with honors, from *Universidad EAFIT* (Colombia, 2000). His current research interests include: sustainable design, electric mobility, knowledge management and engineering, integrated product development, numerical techniques for design, collaborative/concurrent engineering, product lifecycle management and manufacturing technologies.

He is Full Professor at EAFIT University since 2009 and the Director of the Design Engineering Research Group (GRID). He previously worked from 1999 to 2008 in recognized research centers, such as LIPSI/ESTIA in France, Fraunhofer-IPT in Germany and CIDyT/ITESM in Mexico, as well as in the company Technosoft Inc. He has co-authored more than 28 scientific articles in international journals, 61 articles in international conferences, as well as 9 book chapters.

Dr. Mejía-Gutiérrez is Associate Editor of the Springer's International Journal on Interactive Design and Manufacturing (IJIDeM). He participated in the "EPM-EAFIT Solar Car" project to develop the first Colombian solar car; which was a project awarded with the National Engineering Award 2014, by the Colombian Society of Engineers (SCI), the Antioquia's Engineering distinction 2014 from the Antioquia's Society of Engineers (SAI) and with the EAFIT University Best Research Award in 2013.