Solar Concentrator Layout Optimization: Metaheuristic Method Solution

Kung-Jeng Wang and Le Duc Dao
Department of Industrial Management, National Taiwan University of Science and Technology, Taipei 106, Taiwan, ROC
Email: kjwang@mail.ntust.edu.tw, ducdao92@gmail.com

***Abstract*—Solar energy is a potential project because it not only protects the environment, but also reserves the power for people to use in their daily life such as heating or lighting. This paper focuses on the natural sunlight saving system named solar concentrator layout. In our paper, we aim to bring the optimal profit for the firm when implementing the solar layout as well as helping a house get as much sunlight efficiency as possible for their using. We also consider some factors such as light reflection and light transmission loss to make the model more reliable. As for the economic scale, some constraints are added to make our study close to reality, such as the thickness of concentrator or the number of exits where a sunbeam is delivered to the main panel to enable energy transmission. To obtain a high brightness for the house, the firm would harm their profit. This study makes the balance between the conflict objectives to get a compromised solution. Finally, parallel-computing based genetic algorithm is introduced to accelerate the solution quality. To summarize, the result of our study will be the best strategy for the light efficiency to supply people and the profits that the firm earns for the job.**

***Index Terms*—genetic algorithm, multiple-objective optimization, solar concentrator layout**

I. Introduction

Nowadays, solar energy is known to be the potential energy for the future since the lack of other energy types, such as petroleum coal or gas. It has many benefits compared to other valuable powers because this is one of the promising solutions to protect the environment from the global warming problem. It is abundant, clean, and globally available and can be utilized anywhere in the world. Especially, solar power can create two to three times more jobs than money invested in coal or natural gas [1]. In many countries, government encourages their citizen to use the renewable energy especially solar energy since the benefit of them [2]. Some several papers prove that in recent year, the number of user-need for these types of energy increase annual and it will be the super-profit project for any firm who want to join to this potential market [3]. The last reason for producing solar energy comes from the human being. We recognize that people nowadays easily suffer from the disease such as cancer or many animals extinct through the dangerous viruslike Zika, Ebola appearing through the polluted environment formed by traditional energy such as gas or coal [4]. This is the emergency situation that we should take the action to rescue the earth [5].

However, solar system also has some drawback such that the sun does not remain 24 hours a day. In the night time, the solar system stops collecting the energy, and one must find alternative sources. In addition, how to efficiently collect solar energy infinite daytime becomes another important issue [6]. To conclude, although solar energy system possesses some advantages, a careful evaluation is required to invest it as competing to other energy systems.

II. Literature Review

Several research addressed how to increase the ability of receiving the light efficiency [7], [8] focusing on concentrator shape design to achieve the best sunbeam efficiency or new materials to make the good prism such as ideal prism concentrator [9], [10]. Some studies are related to the addressed study [11], [6]. For example, the model used in [11] applies GA to optimize the layout for light efficiency by 37%. Nevertheless, their study ignored such as the thickness of the concentrator, the number of exits, and conflict perspectives of users and manufacturers, which will dramatically influence to the economics of such systems. Actually, when the firm installs the layout for the house, the manufacturing firm will receive the profit while it costs by the establishment expenses such as materials and manpowers. In terms of the materials, the thickness of concentrator and the number of exits play the important role to affect the profit. As the rule, if once increases the number of exits, it usually raises the light efficiency, while costs more for installing them. How to balance these constraints/perspectives become one of the key issues.

III. Modeling of Optimal Sunlight Concentrator

Recall the model [11] which the objective function is to maximize the total light efficiency of the concentrator layout. The size of the panel is (10x11). They defined two exits, where the light beam is delivered to the main panel for later using with an 80% light transmission rate. In addition, when the light approaches air-gap, the efficiency reduces by Eq. (1).

Manuscript received February 25, 2018; revised July 20, 2018.

doi: 10.18178/ijoee.6.2.88-91

$$I_F = (I(x(i,j) \times LTR^A) \quad (1)$$

where I_F is the final light individual efficiency, $(I(x(i,j))$ is the initial efficiency of sunbeam when coming to the prism *x* at the position *i, j*, *A* is the total air gaps that light travels before reaching the final destination, and LTR is the light transmission rate.

Their computation result showed that with 80% light transmission rate, the improvement of light efficiency is 31% in comparison with existence patent showed in Fig. 1. However, one issue comes in this case, which is related to the number of exits where total light is obtained and transformed to other channels. As more number of exits is defined, our experiment showed that the total light efficiency significantly increases to 4,044 units in comparison with the original 3,812. Based on the empirical result (Table I), we conclude that if we increase the exits, we can increase the benefit of the house while the cost will be increased also. To solve this issue, the optimal number of exits for sunlight will be searched to help a house receive the optimal light at a reasonable cost.

TABLE I. COMPARISON OF LIGHT EFFICIENCY WITH DIFFERENCE NUMBER OF EXITS

The model	The number of exits	Light efficiency
Existing Patent	2	2,905
Wang et al. 2014	2	3,812
	3	4,044

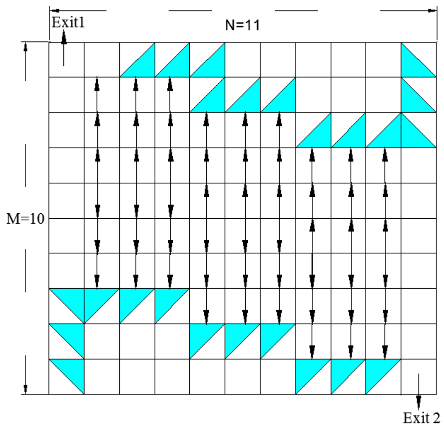

Figure 1. The existence layout (generated [11], LTR=0.8, TTE=2905)

IV. OBJECTIVE FUNCTION AND CONSTRAINTS

In this model, we concern the profit and show the firm the best deal with the house of its service Eq. (2).

$$Profit = Revenue - Expenses \quad (2)$$

where *Revenue* is the money the house owner pays for the firm; *Expenses* is the cost of buying concentrators and the cost of guiding fibers (the number of exits).

Notations are defined as following:

$x(i,j)$: The concentrator type at the position (i,j)

M: The vertical size of the layout

N: The horizontal size of the layout

C_c: The unit cost of a prism

C_E: The unit cost of a exit

P: The profit that the firm receives when installing the layout

U: The maximum number of exits in a concentrator

T: The number of concentrator type using in the study (1-4 and 9 are the guiding fiber, 5-8 are the receiving material)

TTE: Total light efficiency of the layout

k^*: The benchmark concentrator thickness presented in [11]

k: The concentrator thickness in our study

Decision variables are defined as following:

E: The number of exits

Q: The number of prisms

The objective is to maximize the profit of the firm when doing their jobs (Eq. (3)).

Maximize:

$$\sum_{i=1}^{M}\sum_{j=1}^{N} TTE(x(i,j),E) \times P - Q \times C_c - C_E \times E \quad (3)$$

where $x(i,j)$ is the component number at a checked location (i,j), E is the exit for sunlight, $TTE(x(i,j))$ calculates the light efficiency after the sunlight passes through the receiving fiber, then it goes into guiding fiber and ends the particular exit, This function returns a value of zero when sunlight is unable to arrive the exit. $\sum_{i=1}^{M}\sum_{j=1}^{N} TTE(x(i,j),E) \times P$ is the revenue that a firm will gain after implementing the layout, $Q \times C_c$ is the cost of buying prism material, and $C_E \times E$ is the cost of exits

Subject to

$$1 \le x(i,j) \le T,\ x(i,j) \text{ is integer variable} \quad (4)$$

$$1 \le i \le M,\ 1 \le j \le N \quad (5)$$

$$1 \le E \le U \quad (6)$$

where Eq. (4) is the types of prisms (T= 9 as referring to Appendix). Eq. (5) is the location to put the prism and it must be inside of the concentrator layout. Eq. (6) is the number of exits. The maximum quantity exits should not excess of the predefined number *U*.

V. SOLUTION APPROACH

This research will use two methods to optimize the layout to get the result. Firstly, the genetic algorithm is applied to optimize the Eq. (3) and give the firm the optimal layout with the reasonable cost. Then, to illustrate the trade-off between the light efficiency and cost, we will use NSGA II to solve this issue. The detail of GA and NSGA II can be seen in [12], [6] respectively. Especially, the same operators of two algorithms are adopted with the model which generated by [11] such that mutation with uniform {0.03}, crossover {0.85}, population {1000} and generation {200}. This paper also includes the light efficiency of [11] to our model. The result of two papers will be compared through the experiments. The algorithm is implemented by the Matlab optimization toolbox ([13], [14]) The parameters is shown in Table II. In addition, There are two components at work when sunlight reaches a prism. The first is the optical component, which uses to receive sunlight and then transmit it to the next prism.

Meanwhile, the second components play as the role of guiding sunlight to the exits. The detail of the light direction referred in [6].

TABLE II. MODEL PARAMETER SETTING

Parameter	Value
Q = M x N	110
P	100 NTD /1 unit of light efficiency
C_c	1,000 NTD
C_E	10,000 NTD
LTR	80%

VI. EXPERIMENT

A new layout is searched when using the same number of prisms with [11]. Firstly, by executing the GA, setting up the same parameters with Tables II. Using the same concentrator size of [11] the optimal layout is depicted in Fig. 2. By increasing the number of guiding fibers (exits) to 7, the firm gets the optimal profit (260,812 NTD) and the house gets a reasonable light efficiency 4.108 NTD to supply for their need.

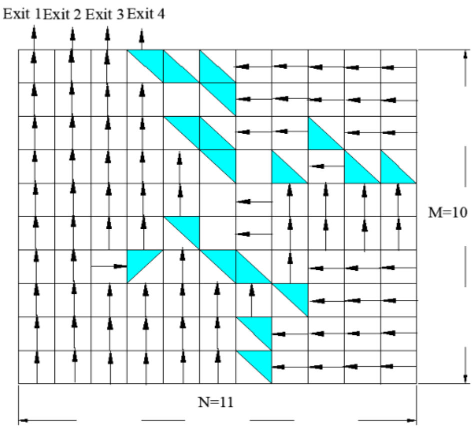

Figure 2. The proposed optimal solution (LTR=0.8, TTE=4,108, k=k*)

To compare with the layout by [11], the light efficiency and profit of our paper are measured. By increasing the number of exits, the light efficiency and profit generated by our proposed model are improved by 3.82% and 7.76%, respectively. The improvement of profit is in Fig. 3. And the comparison is in Table III.

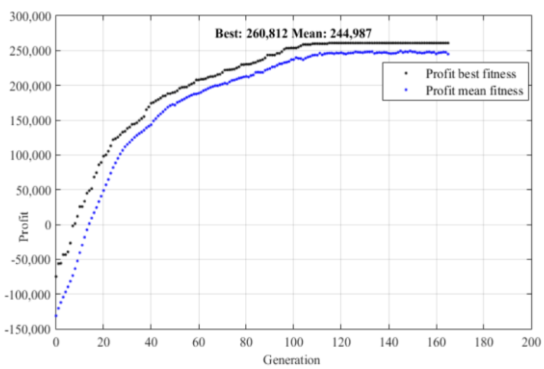

Figure 3. The profit evolution

TABLE III. THE COMPARISON RESULT (WITH A TRANSMISSION RATE OF 80%, $k = k^*$)

Factors	Result of this study	Result of PLGA layout (Wang et al. 2014)	Gap
Number of exits	4	2	
Net Profit (NTD)	260,812	251,200	3. 82%
Total light efficiency	4,108	3,812	7, 76%

k^* The concentrator thickness in Wang *et al.* (2014)

The other new layout is searched when we use the same size of concentrator but decrease the thickness (as well as the height at the same proportion) of the prism to the half size of [11] and run again our model. However, since the size of the thickness is decreasing to the half and the layout is fixed, the specific location can include four prisms instead of one and the size of exits is assumed to be double the thickness of prism. For more specific, we need 440 prisms to fulfill the optimal layout in Fig. 4. The detail is in Table IV.

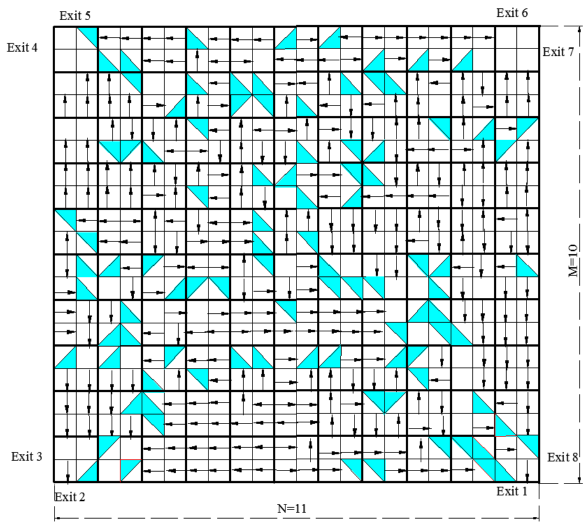

Figure 4. The proposed optimal solution (LTR=0.8, TTE=12,460, $k = 0.5 \times k^*$)

TABLE IV. THE COMPARISON RESULT (WITH TRANSMISSION RATE OF 80%, $K = 0.5 \times K^*$)

Factors	Result of this study	Result of PLGA layout (Wang et al. 2014)	Gap
Number of Exits	7	2	
Net Profit (NTD)	726,051	251,200	1 89%
Total light efficiency	12,460	3,812	2 26%

k^* The concentrator thickness in Wang *et al.* (2014)

A. Trade-off between Profit, Cost and Light Efficiency

In the previous section, we stand on the firm viewpoint to design solar concentrator layout with the optimal profit. As for the consumer, they do not have any interest in the purchase decision, but how to optimize the light efficiency, which the objective is conflict to the firm perspective. Therefore, in this part, we assume limited budget is allocated (300,000 NTD), and a deal for sunlight efficiency and profit is made to satisfy both sides of view. In this case, we keep the size of the concentrator as the same with [11]. It is clear that the more light efficiency to enhance our life will likely lead to less profit for the firm illustrated in Fig. 5.

From the perspective of the house owner:

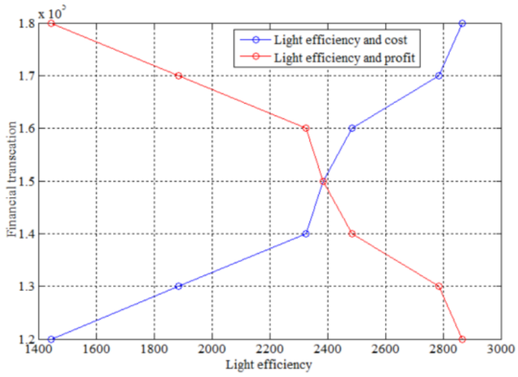

Figure 5. The sensitivity analysis between the light efficiency and cost

VII. Conclusion

Our research proposed the solar concentrator layout model, which is set up on the house's roof. The sunlight will be received and transmitted through this system before coming to the main panel, which later forms the new energy channels. To be more precise, nine types of prism, including receiving and guiding material are used. Various studies have already approached to design the number and the position of each prism to satisfy both stakeholders need such as the profit and brightness. Firstly, we will stand as the firm's viewpoint to maximize their profit and help consumers to enjoy the acceptable light efficiency. Our research also concerns some flexible variables, which ignored in [11] like the number of guiding fibers (exits) or the thickness of the concentrator. After running the model, our result performs better than [11]. In addition, the conflict between two objectives of the firm and the house owner has been solved by NSGA II. The model starts with the non-domination sorting concept for population, then converts the multi-objective optimization to the single objective function, and finally addressed by GA. In addition to the "crowding distance sorting" algorithm, it used to assist NSGA II in the process of selection mechanism and a Pareto optimal solution creates the trade-off between two stakeholder's perspectives. In Fig. 5, it illustrates that if firm expects to get higher profit they must provide the poor quality of the light efficiency to house owner.

VIII. Future Research

We can extend to several directions. For instance, we can optimize the light efficiency by transmitting it among houses against energy imbalance and consider stochastic energy demands. The authors might carry our result and set it to the capacity planning stochastic model. This could illustrate the prism manufacturing system, including many types of solar concentrators to set on the house roof. We can also develop the algorithm NSGA II to get a better Pareto-optimal solution.

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Professor Kung Jeng Wang is serving in the Department of Industrial Management, Taiwan Tech after getting the Ph.D. degree of industrial engineering in the University of Wisconsin at Madison, 1993-1997. His research focuses on The Supply Chain Management, Service Science and Innovation, Technology and Operations Management, Computational Intelligence in Production Economics. He has published more than 60 referred journal paper including 40+ SCI/SSCI paper (IEEE Transaction on System, Man, and Cybernetics IIE transaction, European Journal of Operation research etc. He also achieves many valuable honors & Awards of Taiwan Tech University, e.g., Outstanding research, NTUST excellence teaching, especially CIEE paper award.

Mr. Le Duc Dao is currently the Ph.D. candidate in the Department of Industrial Management, Taiwan Tech. He gets the bachelor degree of Industrial System Engineering in Ho Chi Minh City University of Technology Vietnam, 2010-2015 and Master degree of Industrial Management in Taiwan Tech, 2015-2017. His research is solar energy focusing on the solar concentrator layout design and multiple objectives regardless of balancing between the energy production and environmental impact. He attended some internship programs in Vietnam and attended the conference in Singapore: ICIEA 2018.