Particle Swarm Optimization for Efficient Layout of Solar Streetlights in Dense Residential Roads

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Abstract: The study aims to design and test a Particle Swarm Optimization algorithm developed to provide the optimal placement of the solar streetlights in terms of spacing and mounting height which maximizes lighting efficiency while harnessing sufficient solar energy. Specifically, the study delves to show the effectiveness of the developed algorithm in terms of (1) providing solutions that satisfy the lighting and energy constraints, (2) providing solutions that give the optimal lighting efficiency in contrast to DIALux's optimization results, (3) solving in less computations or iterations, and (4) providing consistent solutions for a given sample. Test results for the PSO algorithm showed that it was able to position streetlights to meet lighting standards for all the roads tested, though it could not find layouts with sufficient energy generation for some roads with high buildings. On average the algorithm's computed lighting efficiency was 4.8 percent lower than DIALux's. The algorithm generated solutions in less iterations than DIALux's optimization method. The consistency test revealed that the algorithm provides relatively consistent results between trials with a standard deviation of 0.867. The initial results show that particle swarm optimization could be used to solve solar lighting optimization problems, but further work will have to be done to make the program feasible for public use.

Key Words: Particle Swarm Optimization; Solar Street Lighting; Residential Road Lighting, Lighting Efficiency

1. INTRODUCTION

1.1 Background of the Study

Proper lighting in roads helps deter crimes, lowers the incidence of accidents and helps provide people with a greater sense of safety (Welsh and Farrington 2008) However, streetlights that constantly draw from the power grid and the cost of keeping them powered puts strain on the government (Rabaza, et al, 2014). The introduction of solar powered streetlights could eliminate this issue and be beneficial to the environment at the same time.

Solar streetlights, however, present their own challenges. A recent attempt in India to install solar streetlights highlights these challenges (No solar streetlights for slums, 2015). Power generation relative to the position of these lights was not considered and as a result lighting was inconsistent. Also, congestion means that buildings could block sunlight from reaching a solar panel, and there is hardly any space for streetlights and this leads to ineffective illumination (Kulkarnil, 2014). Quite often, street lighting is poorly designed and inadequately maintained (USAID, 2010) which leads to not attaining the required lighting standards and consuming too much energy, hence making the installation inefficient. In the Philippines, Monsada (2017) stated that most streetlights consume excessive amounts electricity and this inefficiency harms the environment.

Despite its challenges, the researchers believe that solar street lighting remains the best option for lighting roads of densely populated residential areas. Hence, the study aims to develop an algorithm that uses particle swarm optimization (PSO) to determine the design of a solar streetlight system that maximizes its lighting efficiency while maintaining the ability to harness sufficient solar energy. The researchers decided to use the PSO algorithm because it is claimed that its calculation is very simple as it can be completed easily (Bai,2010). Likewise, PSO is preferred over other optimization techniques such as genetic algorithm for solving constrained optimization problems (Khare & Rangnekar, 2013), which will be useful to the present study as it will consider the requirements for lighting and energy as constraints.

2. METHODOLOGY

2.1 Research Design

The study uses the informal experimental design (after only with control) to test the performance of the algorithm developed. The experimental variable was the developed PSO algorithm by the researchers and the controlled variable is the optimize function (compute all possible combinations) of the DIALux, a free and widely used software for simulating and designing lighting systems such as solar streetlights (Bickford, 2008).

2.2 Sampling of Residential Roads

The study selected 15 residential roads in Metro Manila which were used as samples to test PSO algorithm. The roads were selected through convenience sampling and was based from the zoning map of Manila and Makati.

Table 1. Profile of roads sampled

Road	**Lighting Class**	**Required Average Horizontal Illuminance (lux)**	**Required Minimum Point Illuminance (lux)**
A. Roxas	P5	3.0-4.5	0.6
Agata	P5	3.0-4.5	0.6
Arellano	P4	5.0-7.5	1.0
Calatagan	P4	5.0-7.5	1.0
Dian	P3	7.5-11.25	1.5
Enrique	P3	7.5-11.25	1.5
Esmeralda	P2	10-15	2.0
Filmore	P2	10-15	2.0
General Luna	P3	7.5-11.25	1.5
Granate	P4	5.0-7.5	1.0
Inquimboy	P4	5.0-7.5	1.0
Lakas ng Bayan	P4	5.0-7.5	1.0
Real	P4	5.0-7.5	1.0
T. Ayala	P3	7.5-11.25	1.5
Victoria	P3	7.5-11.25	1.5

The roads sampled and their corresponding lighting class can be seen in the table above. Through Google Earth Pro, the researchers collected road data necessary for streetlighting which were: road width, road length, sidewalk width, road heading, layout of buildings adjacent to sidewalks, and traffic condition (specifically traffic speed, volume, composition, presence of parked vehicles and ambient luminance). The information gathered was used to determine the P lighting class of the various roads.

2.3 Programming the Algorithm

The PSO algorithm was programmed in the Unity game engine for its ease of use, ability to allow users to visualize the algorithm's results, and functions that are useful for simulating solar positions. The fitness function of the algorithm was the lighting efficiency defined by the equation:

$$\varepsilon = \frac{HI * (w * s)}{P}$$

where:

HI= average horizontal illuminance in lux
w= road width in meters
s= spacing between solar streetlights in meters
P= power consumption of light in watts

and the constraints were the required average horizontal illuminance and minimum point horizontal illuminance which are defined in CIE 115-2010: P lighting class, and the required annual energy input of the luminaire. The fitness function has been used in lighting standards such as EN 13201-5:2013 (Road Lighting - Performance Requirements) in European countries to define energy performance indicators for road lighting installations (Light Naturally, 2014). This equation is used in DIALux (reciprocal of the equation to be exact) and other lighting calculators for evaluating the light quality and efficiency of the proposed streetlight layout. Likewise, it has been used as a fitness function for optimizing streetlighting in the studies of Castillo-Martinez et al. (2017) and Gomez-Lorente, et al. (2013). It must be noted that the fitness function does not include the energy harnessed as a variable since it is set as a constraint which implies that it would not give a penalty nor a reward to the solution if it provides a higher or lower energy harness

In this study, the PSO algorithm was programmed to have 30 particles with two variables which are the spacing and mounting height. The personal and global weights were set to 0.75. The stopping criterion for the algorithm is when the value of the global best is consistent for 10 iterations or if it reaches the 100th iteration, whichever comes first.

Each particle will be computed for its fitness (lighting efficiency), average horizontal and minimum point illuminance, and harnessed solar energy. The equation for the horizontal illuminance is based from CIE 140-2000 which uses the point by point method. The equation of the illuminance at each point is:

$$E_h = \frac{I(C, y) cos^3 e \Phi MF}{H^2}$$

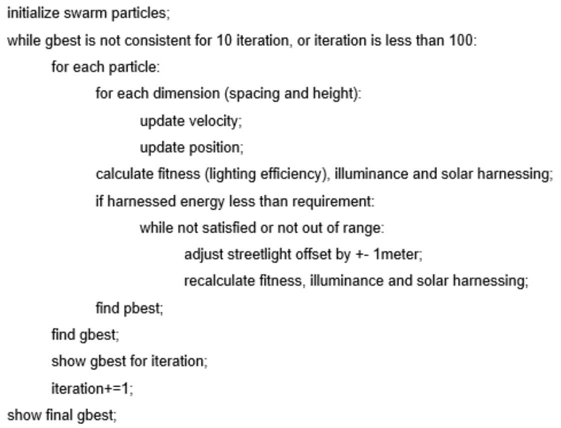
where:

Eh=horizontal illuminance at the point in lux
I(C,y)=intensity in cd/klm in the direction of the point;
e=angle of incidence of the light at the point
y=vertical photometric angle
H=mounting height in m of the luminaire
Φ=initial luminous flux in klm of the luminaire
MF= maintenance factor (set to 0.85 in this study)

the average of all the calculation points within the area of two luminaries with a defined spacing is the horizontal average illuminance and the minimum among the points is the minimum point illuminance. On the other hand, Unity's raycasting function was used to determine the frequency of each solar streetlight being shaded to further determine its annual energy yield. Data on the solar positions and solar insolation to be used in the raycasting function is based on NASA's Surface meteorology and Solar Energy data and the Energy3d software respectively. When a structure is located in the direction of the sun from the solar panel via raycasting, it detects how much, in percentage, of the solar panel is blocked and reduces the amount of energy generated by the blocked percentage.

In the selection of the personal best (pbest) of each particle and gbest of the iteration, it would first check if it satisfies the constraints on the light requirements, then it compares from the previous pbest/gbest if it has a higher fitness. In case that no particle that satisfy the constraints (usually during the first iteration), the particle whose deviation to the minimum or maximum value of the constraint is smaller is the fitter/fittest pbest and gbest

The pseudocode of the algorithm is shown below.



```
initialize swarm particles;
while gbest is not consistent for 10 iteration, or iteration is less than 100:
    for each particle:
        for each dimension (spacing and height):
            update velocity;
            update position;
        calculate fitness (lighting efficiency), illuminance and solar harnessing;
        if harnessed energy less than requirement:
            while not satisfied or not out of range:
                adjust streetlight offset by +- 1meter;
                recalculate fitness, illuminance and solar harnessing;
        find pbest;
    find gbest;
    show gbest for iteration;
    iteration+=1;
show final gbest;
```

Figure 1. Pseudocode of PSO algorithm

2.4 Testing

The researchers would like to determine if the developed PSO algorithm (1) provides solutions that satisfy the constraints, (2) provides solutions that are optimal, (3) solves in less computations or iterations, and (4) consistent in providing a solution.

Five runs were conducted for the PSO algorithm per road (total of 75 runs) while DIALux was run only once per road (total of 15 runs. A consistency test was also conducted where a single road (Enrique) was run 30 times through the program and the standard deviations of its results (lighting efficiency) were calculated.

For each road sample, the researchers inputted the road data, lighting requirements and annual energy requirement which is at 411kwh; given that the luminaire of the solar streetlight used was the "GE lighting 16777_ODL-3-F-T-94-4-2_EU", that consumes 94 W and emits 9299 lumens, and the solar panel used has a size of 0.99mX1.96m with a cell and inverter efficiency of 19% and 98% respectively.

3. RESULTS AND DISCUSSION

The effectiveness of the PSO algorithm in generating an optimal solution was verified by running 75 tests with 15 different road samples, and 30 tests for one road sample.

Table 2. Number of runs satisfying the constraints

Required Hor. Ave. Lux	**Required Min. Pt. Lux**	**Energy Requirement**
75	75	43
Total Runs	75	

As shown from the table above, all 75 test runs had generated a solution that satisfies the required average horizontal illuminance and minimum point illuminance (both in lux) for their respective P lighting class. However, 32 of the 75 runs were not able to position the solar streetlights so that they could harness solar energy to meet their annual energy input of 411kwh. Losses in energy harnessing depends on the infrastructure near the sidewalks where the solar streetlights are to be placed, hence it is likely that no solar streetlights would attain the required energy input when the area is surrounded by high buildings.

Table 3. Comparison of the optimal lighting efficiency solved by PSO algorithm and DIALux

Road Sample	**Average Lighting Efficiency per Road Sample (5 runs each)**			
Road Name	**PSO**	**DIALux**	**Diff.**	**% Diff.**
A Roxas	24.25	25.64	-1.39	-0.054
Agata	18.11	18.18	-0.068	-0.0037
Arellano	41.67	42.01	-0.34	-0.0082
Calatagan	28.73	29.41	-0.68	-0.023
Dian	32.67	32.68	-0.014	-0.0004
Enrique	34.79	35.71	-0.92	-0.026
Esmeralda	34.08	35.71	-1.63	-0.046
Filmore	33.58	35.71	-2.14	-0.060
Gen. Luna	34.74	34.48	0.26	0.0075
Granate	25.04	25	0.038	0.0015
Inquimboy	11.15	11.91	-0.76	-0.064
L. Bayan	13.26	13.70	-0.44	-0.032
Real	34.50	37.04	-2.54	-0.069
T. Ayala	26.60	28.5	-1.90	-0.067
Victoria	34.94	34.48	0.46	0.013

Average % Diff. of all 75 runs	**-0.048**

Table 4. Summarized results of paired t-test

Two-Tail Test	
Null Hypothesis (Two-Tailed Test)	LEalgo-LEDia=0
Level of significance	0.01
Sample Size	75
S_D	1.5454
Standard Error	0.1784
t Test Statistic	-4.5096
Lower Critical Value	-2.6439
Upper Critical Value	2.6439
p-Value	0.0000
Reject the null hypothesis	

The Two-tailed test able to reject the null hypothesis which imply that either the PSO algorithm or DIALux has a significantly higher computed lighting efficiency, hence the computed lighting efficiency of the algorithm is significantly less than the computed lighting efficiency of DIALux. A lower lighting efficiency compared to DIALux, however, is not necessarily negative. This can be explained by the fact that the algorithm takes solar insolation in to consideration, while DIALux is focused solely on lighting efficiency. However, on average, the algorithm's lighting efficiency value was 4.8 percent lower than DIALux's lighting efficiency value.

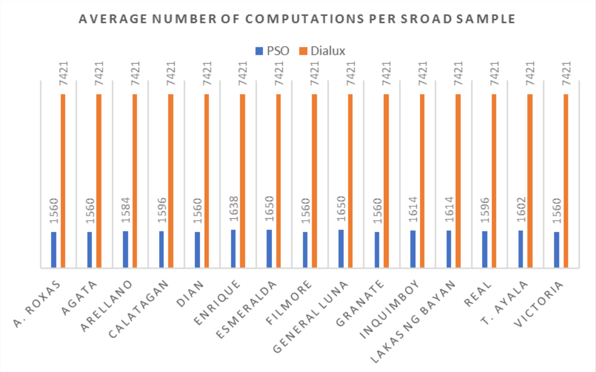


Figure 2. Comparison of PSO algorithm and DIALux's optimization in terms of algorithm cost in average no. of computations

Another important aspect of the algorithm is that it requires less computations than DIALux's method of optimization which computes for all possible combination for a given search space and resolution. The algorithm, with 30 particles, computes for the design within 52 to 67 iterations which result to a total of 1560 to 1650 average computations as compared to the 7421 computations of DIALux, assuming that it would also calculate for solar energy harnessing similar to that of the developed algorithm. This has a significant implication when time and Random Access Memory (RAM) are considered given that more design parameters and constraints, which are not included in this study, are considered leading to more computations.

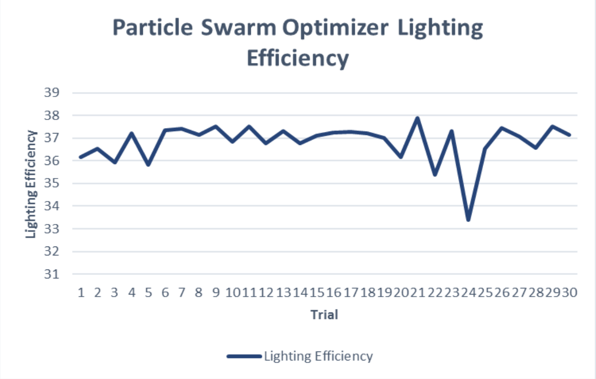


Figure 3. Lighting efficiencies of solved solar streetlight setup in 30 test runs

It is important to take note the consistency of the algorithm in providing its result because it gives assurance that the result solved in the first run is near the optimal, and would not require another run for confirmation. In the consistency test, it was revealed from the 30 test runs that the results are relatively consistent with a standard deviation of 0.867.

4. CONCLUSIONS

The algorithm was able to compute for feasible streetlight layouts in less iterations than existing market software (DIALux) while also considering solar energy harnessing requirements. Programs that solve for the most efficient lighting layout already exist, as do programs that solve for solar energy that can be harnessed at particular locations, but the program is unique because it solves lighting efficiency and solar energy harnessing at the same time. The algorithm calculated lighting efficiency averaged 4.8 percent less than DIALux, but this is not necessarily a bad result as the algorithm also adjusted streetlight positions to harness enough solar energy while DIALux only dealt with lighting efficiency. The algorithm also appeared to provide consistent results between trials as it had a standard deviation of 0.867. The algorithm was capable of finding a streetlight layout that met lighting requirements for all the roads it was tested on, but it was not always able to find a layout that could generate enough solar energy, though this can be attributed to some roads being unsuitable for solar lighting due to factors like high buildings. The researchers believe that the algorithm has the potential to make the installation of solar streetlights easier and more likely to be able to run once installed. Further improvements like the separation of luminaire and solar panel height, increasing the lighting table resolution, and the addition of other solar streetlight factors like panel and luminaire angles and boom length will also be worked on.

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