Street lighting efficiency with particle swarm optimization algorithm following Indonesian standard

M Eriyadi1,*, A G Abdullah2, S B Mulia1 and H Hasbullah2

1 Electrical Engineering Department, Politeknik Enjinering Indorama, Jatiluhur 41152, Purwakarta, Indonesia
2 Electrical Engineering Department, Faculty of Vocational Education and Technical, Universitas Pendidikan Indonesia, Bandung 40154, Indonesia

*mindit.eriyadi@pei.ac.id

Abstract. This paper aims the street lighting efficiency optimization of street lighting on Dr. Setiabudhi street, Bandung city. Particle Swarm Optimization (PSO) algorithm is used to get maximum lighting efficiency values with constraints in the form of lamp height, the distance between lights, lamp power, type/width of the street, the average illuminance and minimum illuminance according to Indonesian national standards (SNI) standards. Parameter optimization to obtain optimal values based on global standards and Indonesian national standards (SNI) has been done. PSO using MATLAB® (R2017a, MathWorks Inc, USA) has produced a street lighting optimization model with the level of lighting efficiency twice higher than the evaluation of existing conditions. Testing the results of the PSO algorithm shows a difference of 9.7% higher than the DIALux evo (8.0, Ludenscheid, Germany) software design. The test results show that the PSO algorithm can be used to obtain optimum lighting efficiency from a public street lighting system following SNI.

1. Introduction
Public street lighting provides benefits for lighting when driving, pedestrian lighting, and protecting pedestrians and motorists from crime [1]. Street lighting as part of building installed on the left or right or in the middle (median) used to light the street and the surrounding streets, including the intersection of streets, bridges and the underpass [2]. The rapid growth of cities in Indonesia is increasingly increasing the need for public street lighting [3-4]. Along with the rapid development of the city, the energy consumption in the public street lighting sector contributes greatly. Efforts have been made to efficiently consume public street lighting energy. Street lighting installations are characterized by geometric parameters as well as by the light [5]. Optimization using various algorithms is done to obtain maximum energy efficiency [1, 6-10]. Particle Swarm Optimization has been used to optimize lighting [7]. PSO that has been used by A. Castillo-Martinez et al uses Spanish standards [1].

This study fills the research gap in optimizing street lighting using PSO with one of the constraints being the minimum luminance limits based on Stanard Nasional Indonesia (SNI). This paper aims the street lighting efficiency optimization of street lighting on Dr. Setiabudhi street, Bandung city with Particle Swarm Optimization (PSO) algorithm based on SNI 7391-2008 [11], Commission International de l’Eclairage (CIE) 140 standard [12], CIE 115 standard [13], and EN 13201-5:2013 [14]. Validation of algorithm results is done with DIALux software that is already commonly used.
2. Methods

2.1. Street lighting system

A street lighting plan requires some supporting data, including the first is street data covering street class, street length, and street width, second illumination levels are needed, third level of uniformity is needed, while other data is the power of the lamp to be used, hanging height (mounting height) depends on the distance or space to be used and also depends on the width of the existing street [15]. SNI 7391:2008 standard, as it is shown in table 1 [11]. Light density or lumination is a measure of the density of light radiation that falls on a plane and is directed towards the eye so that the eye gets a bright impression. In other words, the density of light is the strong light or the size of the beam of light from a particular plane in the candela (cd) divided by the field of vision in m². The unit of light density (L) is expressed in candela/m² [12] shown in equation 1.

\[ E_{h} = \frac{(I(C, \gamma). \cos^3 e. \varnothing. MF))}{H^2} \]  

(1)

\( E_{h} \) is the horizontal illuminance at the point in lux, \( I(C, \gamma) \) is the luminous intensity in the direction \((C, \gamma)\) in \( \text{cd/klm} \), \( e \) is the angle of incidence of the light at the point, \( \varnothing \) is the initial luminous flux in klm of the sources in each luminaire, \( MF \) is the product of the lamp flux maintenance factor and the luminaire maintenance factor, and \( H \) is the mounting height in m of the luminaires above the surface of the street.

Street lighting standards in Indonesia use the SNI 7391: 2008 [11]. In the SNI 7391: 2008 the standard types or classifications of streets, the average illuminance, the uniformity illuminance, the average luminance, the uniformity luminance, and the glare limit are shown in table 1.

| Type/street classification | Illuminance | Luminance | Glare limits |
|----------------------------|-------------|-----------|--------------|
|                           | E average (lux) | Uniformity | L average (cd/m²) | Uniformity | G | TJ (%) |
| Collector street:         |             |           |               |            |   |        |
| - Primary                 | 3 - 7       | 0.14      | 1.00          | 0.40       | 0.50 | 4 - 5 | 20 |
| - Secondary               | 3 - 7       | 0.14      | 1.00          | 0.40       | 0.50 | 4 - 5 | 20 |

The SNI standard in table 1 above will be a constraint in compiling the PSO algorithm for street lighting efficiency. The parameters are used for type/street classification, average illuminance, and luminance uniformity. Street lighting efficiency uses a formula shown in equation 2. The fitness function has been used in lighting standards such as EN 13201-5:2013 (Street Lighting - Performance Requirements) in European countries to define energy performance indicators for street lighting installations [14].

\[ \varepsilon = \frac{(HI. (w. s))}{P} \]  

(2)

\( \varepsilon \) is the lighting efficiency, \( HI \) is the average horizontal illuminance in lux, \( w \) is the street width in meters, \( s \) is the spacing between solar streetlights in meters, and \( P \) is the power consumption of light in watts.

2.2. Evaluation of existing street lighting

Research to evaluate street lighting in Jalan Dr. Setiabudi, Bandung has been done. All the street lights along the 4,980 kilometers, as many as 114 lights have been measured. Street lighting evaluations carried out included typical types and power of the lights that were installed, the height of the light pole, the level of illumination on the waypoints and the width, length, class of the street. The results of the street lighting evaluation that have been carried out are divided into seven street sections as shown in table 2.


Table 2. Existing conditions of street lighting.

| Width of the street (meter) | Distance per poles (meter) | Poles Height (meter) | Average illuminance (lux) | Power (watt) | Lighting efficiency |
|-----------------------------|----------------------------|----------------------|---------------------------|-------------|--------------------|
| 6                           | 78,9                       | 9,19                 | 12,5                      | 250         | 23,67              |
| 7                           | 45,599                     | 9,16                 | 5                         | 250         | 6,38               |
| 8                           | 129,629                    | 7,17                 | 5                         | 250         | 20,74              |
| 9                           | 45,649                     | 10,36                | 5                         | 125         | 16,43              |
| 10                          | 68,591                     | 8,32                 | 16,5                      | 250         | 45,27              |
| 13                          | 34,217                     | 8,14                 | 5                         | 125         | 8,90               |
| 13,9                        | 24,002                     | 10,05                | 7                         | 125         | 18,68              |

2.3. **PSO algorithm for lighting efficiency**

The PSO algorithm includes steps to generate the initial position of a number of particles at the same time as their initial velocity randomly as shown in equations (3) and (4).

\[ X_i(t) = x_i1(t), x_i2(t), \ldots, x_iN(t) \]  

\[ V_i(t) = v_i1(t), v_i2(t), \ldots, v_iN(t) \]  

Where \( X \) is the position of the particle, \( V \) is the velocity of the particle, \( i \) is the particle index, \( t \) is the t-iteration, and \( N \) is the measure of the dimensions of space.

The fitness evaluation of each particle based on its position. Determine the particle with the best fitness, and set it as Gbest, the initial Pbest will be the same as the starting position for each particle.

Using the existing Pbest and Gbest, update the speed of each particle using equation (5) then with the new speed obtained, update the position of each particle using equation (6).

\[ V_i(t) = \omega V_i(t - 1) + c1r1 \,(X_i^L - X_i(t - 1)) + c2r2\,(X_i^G - X_i(t - 1)) \]  

\[ X_i(t) = V_i(t) + X_i(t - 1) \]  

Where \( X_i^L \) = \( X_{i1}^L, X_{i2}^L, \ldots, X_{iN}^L \) represents the local best of the particle \( i \). Whereas \( X_i^G = X_{i1}^G, X_{i2}^G, \ldots, X_{iN}^G \) represents the global best of all herds. Whereas \( c1 \) and \( c2 \) are positive constants which are usually referred to as learning factors. Then \( r1 \) and \( r2 \) are random numbers of values ranging from 0 to 1.

Inertia weights \( \omega \) are used to reduce speed during iterations, allowing the birds to converge the target points more accurately and efficiently [16]. Equation (3) is used to calculate the new particle speed based on the previous speed, the distance between the current position and the best position of the particle (local best), and the distance between the current position and the best position of the herd (global best). Then the particles fly to a new position based on equation (4). After the PSO algorithm is run with a certain number of iterations until it reaches the dismissal criteria, a solution will be found that lies in the global best. Evaluate the fitness of each particle, determine the particle with the best fitness, and set it as Gbest. Determine Pbest by comparing the current position with Pbest from the previous iteration for each particle. Check to stop criteria, if filled stop but if not, go back to the beginning.

3. **Results and discussion**

3.1. **Algorithm experiment**

The proposed PSO algorithm is tested in this section. To improve its performance, it is necessary to set the parameters which determine the best algorithm configuration in order to improve its lighting efficiency in optimizing a given problem. To obtain the best configuration, the following parameters were modified. The inertial weight: 0.9 to 0.4 proportionally decreases each time the update uses equation (7) where \( i \) is the iteration

\[ \omega_i = \omega_{\text{max}} - ((\omega_{\text{max}} - \omega_{\text{min}})/i_{\text{max}}) \cdot i \]
acceleration factors \( c1 \) and \( c2 \) are 2 to 2.5, population size is between 20 to 500, maximum iteration is between 100 and the initial velocity is 10\% of the position. Testing the algorithm is done 10 - 50 times to get the best parameters for the algorithm. The constraint used is the minimum illumination value limit and the average available in SNI. The test results show an evolutionary comparison between the number of runs with a population size of 100 and PSO convergence characteristic as shown in figure 1.

Figure 1. (a) Lighting efficiency with iterations for 10 runs (b) PSO convergence characteristic.

Table 3 shows the maximum lighting efficiency and iteration convergence obtained for each configuration based on the width of street and population size. This result was obtained using MATLAB® R2017a software.

| Width of Street (m) | Population Size |
|---------------------|-----------------|
| 20                  | 40-50           |
| 40                  | 40-50           |
| 100                 | 20-30           |
| 150                 | 40-50           |
| 300                 | 50-60           |
| 500                 | 50-60           |
| Lighting Efficiency ε | 25.2         |
| 29.4                |
| 33.6                |
| 37.8                |
| 42.0                |
| 54.6                |
| 58.3                |

3.2. Comparison, validation dan discussion
The design with DIALux evo 8.0 has been completed using optimal parameters obtained from the results of testing the algorithm using LED Philips BGP383 1xGRN160 / 830 DK lights with 126 watts of power with the luminance diagram as shown in figure 3. LED technology has been the right choice in the replacement project of street lighting because it reduces cost, consumes less power, and has a longer life cycle [17]. The design results in the form of isoline with DIALux evo 8.0 are shown in figure 2.
Figure 2. (a) Design isoline for 13.9 m, (b) Luminance, (c) polar LDC, (d) linear LDC diagram of LED.

The use of DIALux software is commonly used for lighting design. The results of the DIALux design compared to the PSO algorithm are shown in table 4. The comparison between the lighting efficiency of the existing conditions and the efficiency of the results of the optimization using PSO shown in the final stage of this paper.

Table 4. Comparison of the lighting efficiency of the DIALux and the PSO algorithm.

| Width of Street (m) | Lighting Efficiency ɛ | Differentiation % | Existing conditions | PSO algorithm | Differentiation % |
|--------------------|-----------------------|--------------------|--------------------|----------------|--------------------|
| 6                  | 37.03                 | 25.2               | 11.83              | 23.67          | 25.2               | 1.53               |
| 7                  | 38.46                 | 29.4               | 9.06               | 6.38           | 29.4               | 23.02              |
| 8                  | 41.7                  | 33.6               | 8.1                | 20.74          | 33.6               | 12.86              |
| 9                  | 43.47                 | 37.8               | 5.67               | 16.43          | 37.8               | 21.37              |
| 10                 | 45.45                 | 42.0               | 3.45               | 45.27          | 42.0               | -3.27              |
| 13                 | 50                    | 54.6               | -4.6               | 8.90           | 54.6               | 45.7               |
| 13.9               | 50                    | 58.3               | -8.3               | 18.68          | 58.3               | 39.62              |
| Average Diff       | 0.097                 |                    |                    |                |                    | 20.12              |
| % Average Increase | 100.5                 |                    |                    |                |                    |                    |

The widths of streets 10, 13 and 13.9 with a population size of 300 also produce the same number of iterations. PSO algorithm produces a value of 150 for the distance between poles and 12 for the height of the pole with a minimum illumination constraint according to SNI 7391: 2008 for primary collector paths worth 3 and illuminance averages 3 to 7. But this result will be different for each case depending on the existing conditions of each street being evaluated.
4. Conclusion
The results of the PSO algorithm test show that the most efficient population to produce converging iterations is 40 with the number of iterations between 10-20 for all street widths. Comparison of the results of street lighting efficiency using the PSO algorithm with DIALux has indicated by the average difference of 9.7% greater than DIALux. The results of comparison with existing conditions show that the PSO algorithm is able to produce an increase in street lighting efficiency twice from existing conditions. But this result will be different for each case depending on the existing conditions of each street being evaluated.

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