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An Approach to Optimal Architectural and Urban Design from the Energy Efficiency Point of View

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Abstract: This paper presents a new approach to architecture and urban design that results in an increase of the energy efficiency of buildings set close to each other, which is set as the optimization problem. The main goal is to maximize the sunlight impact on objects, in a way to minimize inter-object shading on each building. The problem is solved by the PSO (Particle Swarm Optimization) algorithm and its modifications, as well as the application of PSO algorithm with niches, which makes it possible to find a large number of local optima. It turned out that the PSO algorithm with niches is especially suitable for solving the described problems. The proposed methodology is illustrated by a few examples.

Keywords: Energy Efficiency, PSO algorithm, Multimodal optimization, PSO with niches.

1 Introduction

In recent decades, many are investing in the development of environmentally oriented technologies in almost all areas of application. Trend is to rationalize energy consumption and increase energy efficiency of the buildings. According to European Union research, the buildings are single largest consumer of energy, with a tendency of increase in line with population growth [1]. That is why energy efficiency in buildings is an area that has the greatest potential for reducing energy consumption. Establishing mechanisms to ensure that a permanent reduction in energy consumption in new buildings (new ways in design, use of new materials) and the proper reconstruction of existing buildings is the main goal of energy efficiency in buildings [2]. Strategies and techniques for the processing of solar energy are developing around the world. One way of production of electricity is by means of photovoltaic panels, which convert solar energy into electricity. Saving energy in buildings is carried out through the maximum advantage of natural light as well as the thermal energy of the sun.

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Insolation is part of solar radiation that reaches the Earth. It can be concluded that the insolation is an important factor in planning of urban settlements, which must be used appropriately in the winter as well in the summer. Proper orientation of the structure is an important prerequisite for the use of solar energy in order to reduce the energy needs of the building, achieve maximum solar insolation in winter and to reduce overheating in summer to a minimum. With a proper orientation and distance between structures, favorable insolation conditions within the same climatic conditions are achieved.

Therefore, the idea emerged to use optimization algorithms to organize objects within a limited space with the aim of objects less overshadowing each other. Numerous similar studies and pilot projects on this subject are conducted throughout the world [3, 4].

Solution presented in this paper is based on the use of particle swarm algorithm (PSO algorithm – Particle Swarm Optimization). PSO is an evolutionary optimization algorithm that was first proposed by Kennedy and Eberhart in year 1995 [5]. Their research was first focused on the simulation of the social behavior of birds during flock flights. Algorithm is then simplified and it was observed that it has the ability to perform optimization and multi-dimensional search space solutions. In the last two decades, the PSO algorithm is applied to solve a number of technical problems. Large number of applications caused the extensive theoretical research, for which reason large number of variations and modifications of the basic PSO algorithm are known [6 – 9].

Among these modifications the algorithm with time-varying acceleration coefficient TVAC PSO [6], an algorithm based on the convergence process CR-PSO [7], as well as the general PSO algorithm with parameters based on control theory GPSO [7, 8] stands out.

In addition to these algorithms depicted in this paper, algorithm based on particle swarm topology modifications that have caused change in the value of optimality criteria is revised in order to find the larger number of optimums, known in literature as a PSO algorithm with niches [9]. This algorithm is able to find multiple global and local optima. Some preliminary results are given in [10].

This paper is organized as follows: The second chapter describes the problem which is being dealt with. Also presented are the theoretical foundations and the idea of forming a shadow, and its behavior during the day, as well as laws by which this process occurs. The description of the specific problems is given in the form of mathematical formulations. Basics on the original PSO algorithm, and its modification along with algorithm with niches, and their most important properties that characterize it are given in the third chapter. The central results of the topic of this paper are presented in the fourth chapter. In this chapter, results of experiments that were created as a result of the implementation of the above mentioned algorithms to the problem described in the second chapter are analyzed. In the fifth chapter, certain conclusions about the obtained results and the performance achieved are given.

2 Problem Description

In this paper discussed was the problem of redistribution of specific, known number of objects of known shape within pre defined parcels in order to minimize the total level of shade on the south side of the building during the day. Minimization of the level of shade on south side of the building maximizes the energy efficiency of the building which results in maximizing the potential of solar gain and maximizes the amount of solar energy that could be derived by installing solar panels on that side of the building. In order to solve the original problem it is necessary to analyze the patterns by which the shadow is created along with the movement of shadow, as well as to organize the objects within the parcel in order to gain as little overshadowing of the objects as possible. In order to simplify the analysis, the observed objects are rectangular in shape. The problem is set as an optimization problem.

2.1 Shadow

Shadow of the objects or beings is an area on a surface to which light from a source can not pass from the objects or beings and manifests darker in color than the rest of the area that is lightened. In this way, the shadow is always the same shape as the object blocking the light, but as a reverse projection, except the case when illuminated area is uneven. If the shadowed area is obscured by a plane or some other object, a transfer of the shadows on the other object occurs. Equations used to calculate the position and intensity of the shadows have been taken from [3, 4].

Shadow depends on the maximum angle of elevation in the solar noon for which parameter $v_0 \in (0,1)$ is introduced, which contains information about that angle [12]. Denote by t normalized time of the day, suh that t varies from 0 at dawn to π at dask. According to this, the vector of direction of the sun can be described by the following equation [4]

$$\begin{gathered} vsun(t) \in \left(v(t)\cos(\pi - t), v(t)\sin(\pi - t), -v_0 \sin(\pi - t)\right), \\ v(t) = \sqrt{1 - v_0^2 \sin^2(\pi - t)}. \end{gathered} \tag{1}$$

During the day the sun constantly shifts its position relative to the earth, which leads to variation of its strength in different periods of the day and this is described by the following equation [4]

$$\rho(t) = \rho_0 \sin(\pi - t), \tag{2}$$

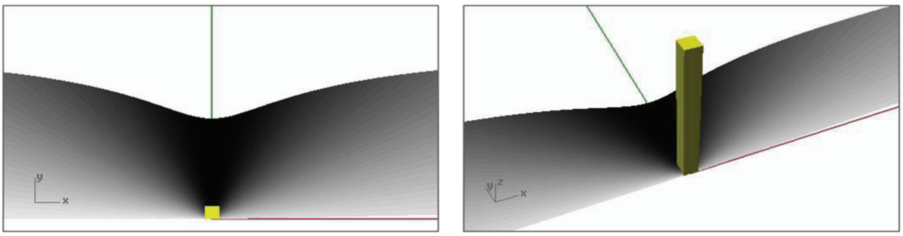
where ρ_0 is the coefficient of insolation.

Therefore, if there is a thin vertical prismoid structure which height is given with h_0, its position in the coordinate system is (x_0, y_0, 0), and using direction of sunlight ray (1), then the coordinates of its shadow in x–y plane in specific moment of time t are calculated by the following equations [4, 11]

$$\mathrm{x} = \mathrm{x}_0 + \frac{h_0}{v_0} v(t) \cot(\pi - \mathrm{t}), \tag{3}$$

$$y = y_0 + \frac{h_0}{v_0} v(t). \tag{4}$$

Shadow of a stick is represented on the Fig. 1.



(a) *Top view* (b) *Perspective view*

Fig. 1 – *Shadow figure.*

2.2 Encryption of solution and search space

Search space is an area within which buildings should be positioned. Potential solution should consist of three parts: a number that describes how many buildings is to be distributed, the scheme that describes how the buildings are spread out and the third part of solution contains information about each building separately [3, 4]. The building is described with position, height, width and length. The building dimensions are marked with two radius R and r and height of h, and position using x, y, z coordinates, while the dimensions of the location are given with L_1 (width) and L_2 (length). Thus, the set of possible solutions are ξ's which are presented as a series in the form

$$\xi = (n, L_1, L_2, B_1, ..., B_n). \tag{5}$$

In (5) n is the number of objects, and B_1, B_2,...,B_n are the parameters of each object

$$B_k = (x_k, y_k, z_k, h_k, R_k, r_k) \tag{6}$$

The main task is determining coordinates x and y, while the other parameters are known. Their value is limited by the dimensions of the space within which objects are allocated and should be in the range of $[-L_1/2, L_1/2]$ for x and $[-L_2/2, L_2/2]$ for the y coordinate. So, if we spread the n objects of fixed size, the dimensions of the search space will be $2n$.

2.3 Criteria optimum

We are analyzing the building with the coordinates of the central position (x_0, y_0, 0), the height h_0, width and length R_0 and r_0, respectively, in a fixed moment of time t_0. To form the shadow of the building, we have defined edge of the building [3]

$$\Theta_0 = (x_0 - 0.5R_0, x_0 + 0.5R_0) \times (y_0, y_0 + r_0) \tag{7}$$

Then, we apply equations (3) and (4) at all points along the edge of the building, and thus the edge of the shadow is determined as a function of χ_{Θ_0}. If there is another building in a shadows created by a building with a height h_1, central position (x_1, y_1,0), width R_1, length r_1, we need to calculate the level of shade on the south side of the other building. Area of the other building exposed to the shadow is defined as

$$D_1 = (x_1 - 0.5R_1, x_1 + 0.5R_1) \times (y_1, y_1 + h_1) \tag{8}$$

Accordingly, quantity of shade received by the second building is

$$R_s(1,0) = \iint_{D_1} \chi_{\Theta_0} \rho(\mathrm{t}) \, \mathrm{d}x \, \mathrm{d}y \tag{9}$$

Therefore, the total shadow of all buildings, i.e. impact of shade on buildings affected in an given moment of time t is described by the formula

$$R_s(\xi) = \sum_{\substack{i,j=1 \\ i \neq j}}^{n} \iint_{D_{(\mathrm{i})}} \chi_{\Theta_{(\mathrm{j})}} \rho(t) \, \mathrm{d}x \, \mathrm{d}y \, . \tag{10}$$

Because of the need to monitor the movement of the shadows during the entire day, the total value of individual criteria functions is calculated by the equation

$$R_u(\xi) = \int_t R_s(\xi) \, \mathrm{d}t \, , \tag{11}$$

where t describes the movement of the sun during the day and takes values from the interval (0, π).

It is now clear that the minimization problem is find ξ from the set of possible solutions that have minimum values of a $R_u(\xi)$. This function is called the criteria optimum, meta function or a function of energy.

3 PSO Algorithm

PSO (Particle Swarm Optimization) algorithm is a modern optimization technique that has found its basis in interactions of flocks of birds and swarms of insects.

3.1 The original PSO algorithm

This algorithm is described in detail in the literature [5]. Its main goal is to search the area using groups made of particles. A set of particles makes swarm, which is identified with a population in evolutionary terms. Each particle has its position and speed. Speed is the difference between the current and previous positions. Particle "remembers" its best position in the history of the search while "swarm" remembers best global position. The basic idea of the PSO algorithm is that the particles move guided by the personal best and global best position, while calculating a new value of speed in each iteration and the particle is moved to a new position which is described by the following expressions

$$\begin{gathered} v[k+1] = w \cdot v[k] + cp \cdot rp[k] \cdot (p[k] - x[k]) + cg \cdot rg[k] \cdot (g[k] - x[k]) \\ \mathrm{x}[k+1] = x[k] + v[k+1]. \end{gathered} \tag{12}$$

The parameters *w*, *cp* and *cg* define inertial, cognitive and social component. Their value is changed in order to improve performance which led to different modifications of the PSO algorithm [6 – 9].

3.2 Modifications of PSO algorithm

Inertial factor *w* is characterizes stability. This factor influences the way in which particles "fly over" the search space and thus can be adapted to the performance of the algorithm. Frequently it is recommended that the value of inertia factor varies linearly in the range of from 0.9 at baseline to 0.4 at the end of the search. Acceleration coefficient *cp* is characterized by the degree of individuality of individuals, i.e. a higher value *cg* gives stronger emphasis on the best solution in perspective of a collective, and thus provides a more detailed study of the environmental solution. Ratnaweera and associates [6] have suggested that cognitive coefficient *cp* should range in the interval [2.5, 0.5], while *cg* is to be increased in the interval [0.5, 2.5]. This modification of the algorithm is known as TVAC PSO (PSO with time varying acceleration coefficients).

In addition to this modification of the original PSO algorithm there is also PSO algorithm with parameters based on the convergence of the process CR – PSO (Convergence Related Particle Swarm Optimization) [7], which analyzes the convergence process, and based on it introduces a new set of parameters (w, ξ, η).

Also applied in this work is the PSO algorithm with parameters based on control theory GPSO (Generalized Particle Swarm Optimization) which was presented in [7, 8]. The authors have identified particles with swarm dynamical system of second order and then analyzed its stability.

3.3 PSO algorithm with niches

The main disadvantage of PSO algorithm is the difficulty of finding multiple optima. This is compensated by using PSO algorithm with niches. This algorithm is used when functions of optimality criteria is non-linear and has more than one optimum value. Suppose that the function has assessable amount of vertices (optimum), where all vertices have a minimum distance between them , and we want to find all the peaks [9].

Let P be the population of particles ξ_i, where i represents the index of the particles. The population is divided into niches where j denotes the niche index . Let η_j stands for the size of sub-populations, i.e. size of the niche j, and let $f(\xi_i)$ be the value of criterion function. Suppose that ξ_i, ξ_j are two particles whose distance can be defined by

$$d(\xi_i, \xi_j) = \text{Euclidian distance between } \xi_i, \xi_j. \qquad (13)$$

To define a niche we need to define niches diameter, i.e. the maximum distance between any pair of particles that belong to that niche.

Then the degree of membership of the particles to a niche is defined with

$$dm(\xi_i) = \begin{Bmatrix} \dfrac{d(\xi_i, \xi_j)}{\text{niche diameter } j}, & \text{if } \xi_i \text{ belongs to niche } j \\ 1, & \text{if } \xi_i \text{ resides outside of niche } j \end{Bmatrix}. \qquad (14)$$

While a modified value of the criterion function, and the particles is described in the following manner

$$df(\xi_i) = \frac{f(\xi_i)}{dm(\xi_i)}, \qquad (15)$$

thus modifying the value of criterion function. If a particle is closer to the existing optimum, then the value of the fitness function changes, otherwise it remains unchanged. In this way, we can find all the local optimum. This is a dynamic process because the niches dynamically change during the evolution process.

The development of the population in practical terms is achieved by dynamically dividing the population into several sub-populations. In the first step of the PSO algorithm will be applied over the entire population. Then the process of evolution would begin. When it finds an optimal solution of the whole population, it is placed in a niche set of cores. In this niche core is the best solution that is found within this niche, and the niche core is a collection of optimal solutions and niche. Then the number of desired niches needs to be set. Then we re-start the process of setting a new niche core and sub-populations. If a particle diameter is within a niche of a niche of cores from the set , then the value of the criterion function changes according to (14) and (15). The process continues until a new optimal solution is found, and it is added to the set of cores or revoked if it doesn't meet some pre-defined conditions.

4 Experiment Results

In this section, some of the experimental results obtained are presented. They were created as a result of the application of optimization algorithms to the problem of mutual glare reduction on facilities.

Experiments have been performed over the set of 21 buildings. In the first set of experiments it was selected that the space within which the buildings are to be concentrated has the dimensions of 1400*m* x 1000*m*. Different schemes of parameter settings are used which summary is presented in **Table 1**.

Table 1

Scheme of parameter settings.

Scheme	Values of algorithm parameters		
	w	*cp*	*cg*
TVACPSO	0.9→0.4	2.5→0.5	0.5→2.5
	w	ξ	η
CRPSO	0.9→0.4	0.5	1/ 2.5→2.5
	ρ	ζ	c
GPSO1	0.95→0.6	-0.9→0.2	0.8→0.2
GPSO2	0.95→0.6	-0.9→0.6	0.8→0.2

In addition to the various schemes for setting the parameters, the number of particles in the swarm and the number of iterations of the process execution was also altered. It was noticed that increasing the number of particle swarm contributes to faster convergence of process, as well as that increase in number of iterations provides the solution to move closer to the global optimum. The best results were obtained using the generalized PSO algorithm, i.e. using GPSO2 scheme parameter setting. Number of swarm particles at the beginning of the experiment was 30, and then increased to 50 and 70. Search is carried out in 300 iterations. The results are shown in **Table 2** and Fig. 2.

Table 2

Experiment results.

No. of particles	No. of iterations	Parameter scheme	Duration (seconds)*	Best score
30	300	GPSO2	10715	189.3868
50	300	GPSO2	7936.7	0
70	300	GPSO2	24514	27.9995

*simulation is carried out on Intel(R)Pentium(R)CPU G630@2.7 GHz RAM 4 GB PC

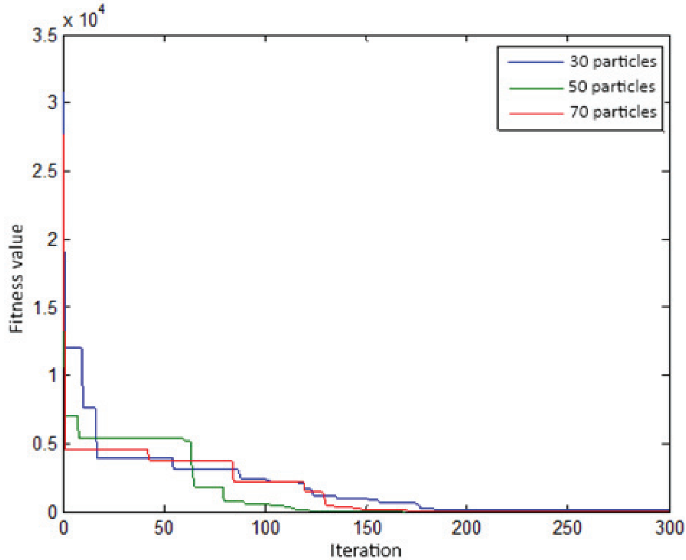


Fig. 2 – *Value of optimization criterion for* GPSO2 *parameter setting.*

This procedure was the only one able to find one of the global optimum. Conclusion that this really is global optimum is derived from the fact that the value of the optimality criterion is zero. The time during which the procedure converged to the global optimum is acceptable. Scheme of arrangement of buildings for finding the global optimum is shown in Fig. 3.

In the next set of experiments testing of the PSO algorithm with niches was carried out. It was decided that the space within which the building needs to be spread is to be lower than in previous experiments that would indicate the efficiency of the procedure and its dimensions are 1000×1000 [m×m]. GPSO2 scheme parameter setting was selected. The number of niches alternated. The best results were obtained using the PSO algorithm with five niches. Diameter of the niche is set so that the maximum distance between the same two buildings of different particles within a niche is 250 m. Behavior of value criterion function through niche is shown on Fig. 4.

Results are given in **Table 3**.

The success of this test is reflected in finding more solutions whose value criteria is small, i.e. intensity of mutual glare on groups of close building is small. This means that 21 building could be deployed in a number of ways in an area of 1 km^2, and at the same time the impact of solar energy is maximized. The best result was obtained in a niche 2, and how the buildings were arranged in such a solution is illustrated in Fig. 5.

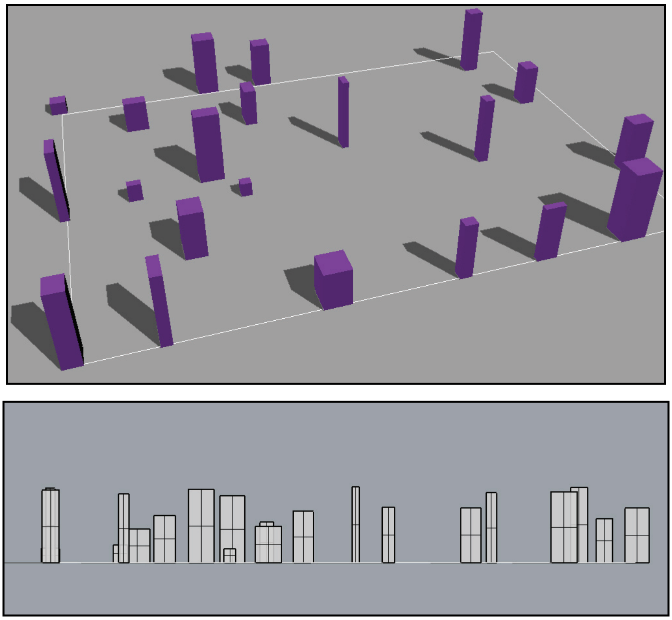


Fig. 3 – *Arrangement of buildings within the parcel resulted from the first set of experiments.*

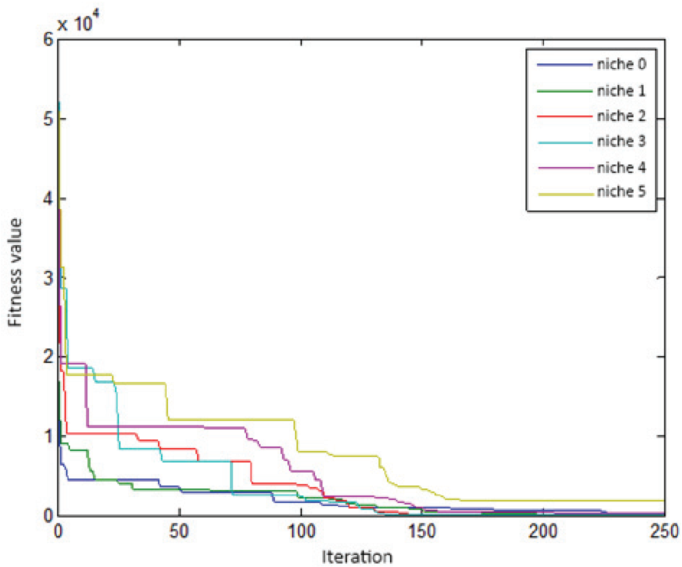


Fig. 4 – *Value of optimization criterion during calculations with PSO algorithm with niches applied.*

Table 3
Experiment results.

Niche No.	Best score	Duration
0	220	16h 29min 22 s*
1	70.411	
2	39.7293	
3	121	
4	264	
5	1874	

*Intel(R)Pentium(R)CPU G630@2.7 GHz RAM 4 GB PC

It is noticeable that duration of search procedure in PSO algorithm with niches is much longer than with the other optimization algorithms, but this allows for better search space solutions and finding multiple acceptable solutions.

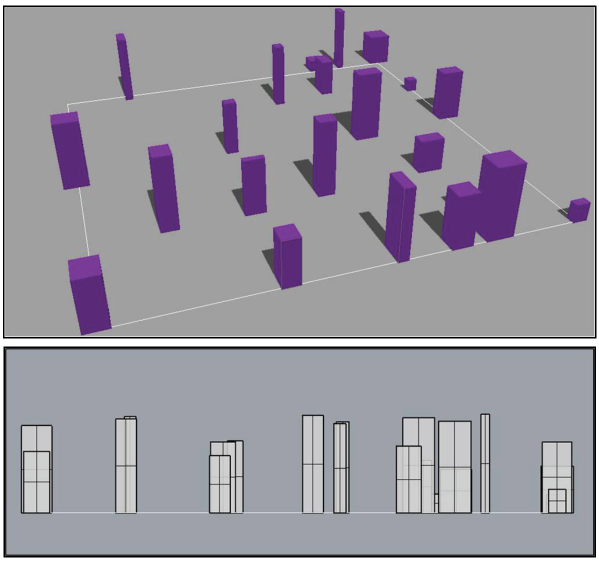


Fig. 5 – *Arrangement of buildings within the parcel resulted from the second set of experiments.*

5 Conclusion

This paper presents a way of solving the problem of utilization of sunlight energy and increasing energy efficiency in buildings. The goal was to position the objects so that during the day they are completely lightened and exposed to solar energy. This is achieved by the use of optimization algorithms. The optima criterion of algorithms was overall level of shade on buildings during the day. Paper presented original and modified versions of the PSO algorithm that have been applied to solve the aforementioned problems. New modifications of PSO algorithm, which introduces different parameterization algorithms, have a better performance compared to the traditional version of the PSO algorithm. The best results were gained by using generalized PSO algorithm (GPSO). As the issue of the building arrangement may have more than one solution, PSO algorithm with niches has been used that enabled finding more satisfactory solutions.

Paper analyzed level of shade on the south side of the building received from other buildings, and with further development of the algorithm, other sides of the building will be considered. All experiments were conducted under the assumption that the observed parcel had no existing buildings on its surface or in the immediate vicinity of the parcel that throw shadows on it. Therefore, the algorithm could be improved by making it possible to define the existing immovable object as initial constraints in the algorithm.

Optimization algorithms may have broad application to other problems in architectural and urban design, which can result in increased energy efficiency in buildings. This will be the topic of further research.

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