Bui, T, Nguyen, TT and Hasegawa, H

Opposition-based learning for self-adaptive control parameters in differential evolution for optimal mechanism design

Article

Bui, T, Nguyen, TT and Hasegawa, H (2019) Opposition-based learning for self-adaptive control parameters in differential evolution for optimal mechanism design. Journal of Advanced Mechanical Design, Systems and Manufacturing, 13 (4). ISSN 1881-3054

Bulletin of the JSME Vol.13, No.4, 2019
Journal of Advanced Mechanical Design, Systems, and Manufacturing

Opposition-based learning for self-adaptive control parameters in differential evolution for optimal mechanism design

Tam BUI*,**, Trung NGUYEN** and Hiroshi HASEGAWA*
* Shibaura Institute of Technology
Fukasaku 307, Minuma-ku, Saitama-shi, 337-8570, Japan
E-mail: tambn@shibaura-it.ac.jp
** Hanoi University of Science and Technology
No.1 Dai Co Viet Road, Hai Ba Trung District, Hanoi, Vietnam

Received: 5 December 2018; Revised: 30 May 2019; Accepted: 26 September 2019

Abstract
In recent decades, new optimization algorithms have attracted much attention from researchers in both gradient- and evolution-based optimal methods. Many strategy techniques are employed to enhance the effectiveness of optimal methods. One of the newest techniques is opposition-based learning (OBL), which shows more power in enhancing various optimization methods. This research presents a new edition of the Differential Evolution (DE) algorithm in which the OBL technique is applied to investigate the opposite point of each candidate of self-adaptive control parameters. In comparison with conventional optimal methods, the proposed method is used to solve benchmark-test optimal problems and applied to real optimizations. Simulation results show the effectiveness and improvement compared with some reference methodologies in terms of the convergence speed and stability of optimal results.

Keywords : Optimization algorithm, Opposition-based learning, Differential evolution, Global search, Local search

1. Introduction

Opposition-based learning (OBL), a new searching principle in optimization, was first proposed by Hamid R. Tizhoosh (2005a), who discovered a better candidate solution by comparing the current particle and its corresponding opposition estimate. In the process of the evolutionary algorithm (EA), candidates are generated randomly in the search domain at the beginning of the process. After that, the EA estimates the new better candidate solution by searching the current individual's neighborhood. This principle depends on each kind of various metaheuristic algorithms, such as the Genetic Algorithm (GA) (Holland, 1992), Particle Swarm Optimization (PSO) (Kennedy and Eberhart, 1995), Differential Evolution (DE) (Storn and Price, 1997), Ant Colony Optimization (ACO) (Dorigo, 1992), Artificial Bee Colony (ABC) (Karaboga and Basturk, 2006), and Gravitational Search Algorithm (GSA) (Shaw, et al., 2012). The basic idea in OBL is that the searching neighborhood tries to discover a better particle by comparing an estimated particle and its opposite point. Experiments have shown that an opposition candidate solution might provide a higher chance of getting better solutions that are closer to the global optimal one.

S. Rahnamayan et al. (2008a) proposed an improvement of the DE algorithm in which the OBL principle was used to search for a new candidate during the algorithm. Experiment results showed that the proposed algorithm was more effective than the old one by changing from random initialization to OBL initial populations. Furthermore (Rahnamayan et al., 2007, 2008b), mathematically and experimentally proved this advantage as, when there is no prior knowledge of the candidate solution, it is impossible to make the best initial guess. In general, we should be simultaneously exploring all dimensions, and one of these works is expanding in the opposite direction. The gain of the OBL strategy over the random strategy is also shown more clearly, based on Euclidean distance to the global optimal solution; more details can be seen in (Rahnamayan et al.,2007).

Paper No.18-00526
[DOI: 10.1299/jamdsm.2019jamdsm0072]

In recent years, many proposed methods have discovered the advantage of applying the opposite particle in the population-initialization step and the generation-jumping stage to accelerate many kinds of metaheuristic evolutionary optimization algorithms, such as PSO (Wang, et al., 2011a), ABC (El-Abd, 2012), Harmony Search (HS) (Saha et al., 2013), DE (Wang et al., 2011b), and Gravitational Search Algorithm (Shaw et al.,2012). The OBL principle is also used to improve artificial-intelligence algorithms, including strengthening the learning process and back-propagation training in artificial neural networks (ANNs). Opposition-based reinforcement learning (ORL) was proposed by using the opposite-state and opposite-action functions (Tizhoosh, 2005b). Simulation results showed that ORL increases reinforcement learning. Similarly, by applying OBL to opposite weights and transfer functions, opposite-based ANNs were also proposed to strengthen their learning speed and stability (Ventresca and Tizhoosh, 2006, 2007, 2008).

Based on the theorem of No Free Lunch for Optimization, there is no optimal algorithm that can perfectly solve all kinds of objective functions. Its performance depends on the complexity of each problem, such as unimodal or multimodal, convex or nonconvex, and integer, real, or mixed variables. Therefore, we need to discover more methods to overcome this drawback. Inspired by the advantage of OBL, this paper presents applied OBL to improve the performance of self-adaptive control parameters in a differential evolution algorithm (Bui et al., 2013). The new proposed algorithm solved nineteen numerical optimizations in the literate benchmark test and four real-world optimal engineerings. Simulation results in the experiments showed effectiveness and improvement compared with the original DE and some reference algorithms. In the proposed OBL–self-adaptive control parameters in differential evolution (ISADE) algorithm, we apply the principle of OBL to both initialization populations and elite particles in the main process of DE.

The ISADE that automatically generate control parameters such as the Number of the Population (NP, NP), scaling factor (F), and crossover control (Cr) do not need to be tuned during the algorithm process. Experimental simulation results on benchmark-test problems showed that OBL-ISADE can perform outstandingly on many of the test problems in comparison with the original DE and other well-known algorithms.

The rest of this paper is organized as follows: Section 2 reviews the original DE, ISADE, and the theory of opposition-based learning. In Section 3, the proposed method is described. The experiments and simulation results are shown in Section 4. Section 5 concludes this paper.

2. Review of differential evolution and opposition-based learning

2.1. Review of differential evolution

DE, first proposed by Storn and Price (1997), is an optimization algorithm that belongs to the evolutionary-algorithm field. Similar to other evolutionary algorithms, DE tries to improve a candidate solution to the global optimum by using crossover, mutation, and selection operators at each generation. Algorithm 1 shows pseudocode DE algorithms.

Algorithm 1: Differential evolution.

1: **Initialization :** Generate and randomly initialize all NP particles within the boundary.
2: **Mutation operation:** Compute mutation vector V using one of Eq. (1) to Eq. (3) depending on which mutation scheme is in this step.
3: **Crossover operation:** Compute trial vector U using Eq. (9).
4: **Selection Operation:** In this step, the fitness value is used to evaluate for trial vector U_i^G and target vector X_i^G. The better one is selected for reproducing new offspring by Eq. (10).
5: Repeat Steps 1 to 4 until the terminal condition.

Many experiment simulations (in the literature) show that DE algorithm is outstanding in terms of convergence speed, computation complexity, and robustness compared with many other metaheuristic approaches such as GA (Holland, 1992) and ACO (Dorigo, 1992). However, the effect of DE is mainly dependent on appropriately selecting the control parameters such as population size NP, scaling factor F, and crossover rate CR. Many aforementioned studies focused on finding suitable control parameters are given, and we know that it is important to set up the best DE learning strategies in DE and other DE control parameters. To overcome this difficulty, the author of this research (Bui, et al., 2013) proposed the improvement of self-adapting control parameters in differential evolution—a modification and improvement of DE. The main operations in ISADE are shown below:

Adaptive DE mutation-scheme operator: In this step, we automatically choose three kinds of mutation schemes based on the random section: The three DE mutation schemes to be selected are DE/best to 1 Eq. (1), DE/best to 2 Eq. (2), and DE/rand to best/1 Eq. (3). The two first schemes have good convergence (good at local search), while DE/rand to best/1 has good population diversity (global searchability). We apply the same probability to these strategies

($rand1 = rand2 = rand3 = 1/3$).

$$\textbf{DE/best to 1:}\ V_{i,j}^{iter} = X_{best,j}^{iter} + F * (X_{p_1,j}^{iter} - X_{p_2,j}^{iter}) \tag{1}$$

$$\textbf{DE/best to 2:}\ V_{i,j}^{iter} = X_{best,j}^{iter} + F * (X_{p_1,j}^{iter} - X_{p_2,j}^{iter}) + F * (X_{p_3,j}^{iter} - X_{p_4,j}^{iter}) \tag{2}$$

$$\textbf{DE/rand to best/1:}\ V_{i,j}^{iter} = X_{p_1,j}^{iter} + F * (X_{best,j} - X_{p_1,j}^{iter}) + F * (X_{p_2,j}^{iter} - X_{p_3,j}^{iter}) \tag{3}$$

Where X, current vector; V, mutation vector; X_{best}, best fitness of current vector; $iter$, number of iterations (generation); i, index of number of particles in population $i = 1, \cdots, NP$; j, index of the number of dimensions $j = 1, \cdots, D$; $p1$, $p2$, $p3$, and $p4$ are different elements chosen randomly from $[1, NP]$; and NP, D, number of populations and dimensions, respectively.

Adaptive scaling factor F: estimating scaling factor F is very important in DE and it greatly affects the nearby search of the current particles. We propose an adaptive form of this parameter to achieve better DE performance. From the experiment, we see that a large-value scale factor F at the beginning of the processing loop allows better exploration, and this value gradually decreases to the end of the loop to allow appropriate exploitation. This can be modeled by some mathematic equation such as linear function, sin or cosine function, hyperbolic tangent, and sigmoidal function. The sigmoid function is widely used in many nonlinear applications, for example, as a transfer function in artificial neural network, or to control the variable neighborhood range on APGA/VNC (Tooyama and Hasegawa, 2009). Inspired by the above ideas, ISADE uses a sigmoid function to calculate scaling factor F as shown in Eq. (4).

$$F_i = \frac{1}{1 + exp\left(\alpha * \frac{i - \frac{NP}{2}}{NP}\right)} \tag{4}$$

Where α is the parameter that controls the value of scaling factor F. We can see this more clearly in Figure 1.

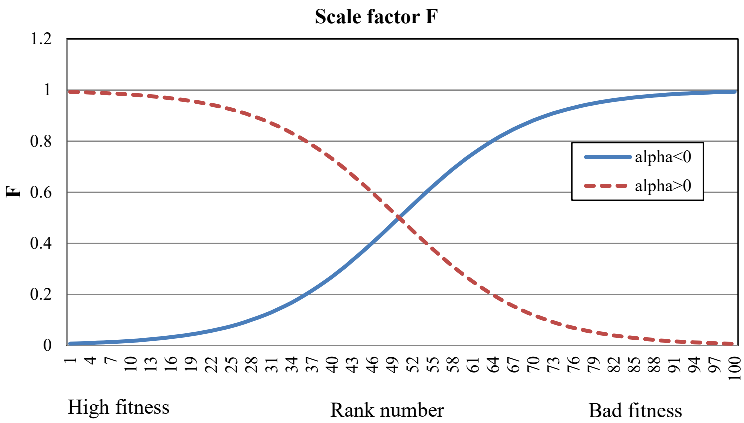

Fig. 1 Value of scale factor F depends on rank number i and α

.

$$F_{iter}^{mean} = F_{min} + (F_{max} - F_{min})\left(\frac{iter_{max} - iter}{iter_{max}}\right)^{n_{iter}} \tag{5}$$

Where F_{max} and F_{min} are the lower and upper limitation of F, respectively. From our experiment, it is recommended to use values of F_{max} and F_{min} 0.8 and 0.15, respectively. $iter_{max}$, and n_{iter} denote the maximum iteration, and the nonlinear modulation index as in Eq. (5); n_{max} and n_{min} are typically chosen in the [0, 15] range. Recommended values for n_{min} and n_{max} are 0.2 and 6.0, respectively.

The trend of scaling factor F_{iter}^{mean} mainly depends on nonlinear modulation n_{iter} and iteration number $iter$. We can see this more clearly in Fig. 2.

We separately calculate scale factor F for each particle in each iteration. The value of F_i^{iter} is the difference for all particles in the population. If we call F_i^{iter} an average value of F_i and F_{iter}^{mean}, we assign it to each iteration. Then, the suitable value of scale factor for each particle in every iteration is determined in Eq. (6):

$$F_{iter}^{i} = \frac{F_i + F_{iter}^{mean}}{2} \tag{6}$$

From now, we use particle scale factor F^i_{iter} in the proposed algorithm instead of general scale factor F in Eq. (1) to Eq. (3) for generating mutation vector V.

Adaptive crossover control parameter: ISADE can automatically detect the Cr value. The large value of Cr is used if the test problem is dependent (nonseparable functions), while a small value of Cr is suitable for independent problems (separable functions). A minimum base for Cr around its median value is incorporated to avoid stagnation around a single value. Figure 3 shows this approach, so we propose the ideas behind this adaptive mechanism for crossover control parameter Cr, which is assigned as in Eq. (7).

$$CR_i^{iter+1} = \begin{cases} rand_2 & \text{if } rand_1 \leq \tau \\ CR_i^{iter} & \text{otherwise.} \end{cases} \tag{7}$$

where $rand_1$ and $rand_2$ are generated randomly in $\in [0, 1]$, and τ represents probabilities to adjust Cr, which is also updated using Eq. (8).

The value of CR is adjusted as in Eq. (8).

$$CR_i^{iter+1} = \begin{cases} CR_{min} & \text{if } CR_{min} \leq CR_i^{iter+1} \leq CR_{med} \\ CR_{max} & \text{if } CR_{med} \leq CR_i^{iter+1} \leq CR_{max}\ . \end{cases} \tag{8}$$

where Cr_{min}, Cr_{med}, and Cr_{max} are the small, median, and large value of crossover parameter Cr, respectively. From our experimentation, we suggest using the values of $Cr_{min} = 0.05$, $Cr_{med} = 0.50$, $Cr_{max} = 0.95$, and $\tau = 0.10$.

Crossover operation: In this process, current vector X and mutation vector V are used to generate a trial vector U as in Equation (9).

$$U_i^{iter} = \begin{cases} V_{i,j}^{iter} & \text{if } rand_j \leq CR_i^{iter} \text{ or } j = j_{rand} \\ X_{i,j}^{iter} & \text{otherwise.} \end{cases} \tag{9}$$

Where j_{rand} is a random integer number in $[1, D]$, and $rand_j(0, 1)$ is a uniform random real number in $[0, 1]$. Because of using j_{rand}, trial vector U differs from target vector X.

Selection operation: The better fitness between target vector X and trial vector U are selected for the next generation.

$$X_i^{G+1} = \begin{cases} U_i^{iter} & \text{if } f(U_i^{iter}) \leq f(X_i^{iter}) \\ X_i^{iter} & \text{otherwise.} \end{cases} \tag{10}$$

We propose adaptive particle scaling factor F and adaptive crossover control parameter Cr in this research. Therefore, a user has no need to tune the suitable values for both of F and Cr. Therefore, the new proposed algorithm is simpler and less time-consuming than the original DE algorithm. It is easier for a user to apply this modified DE to real-world problems.

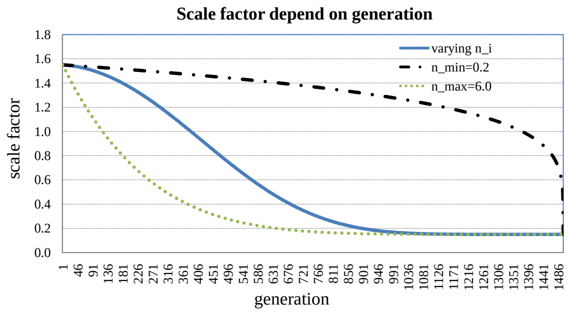

Fig. 2 Scale factor depending on generation.

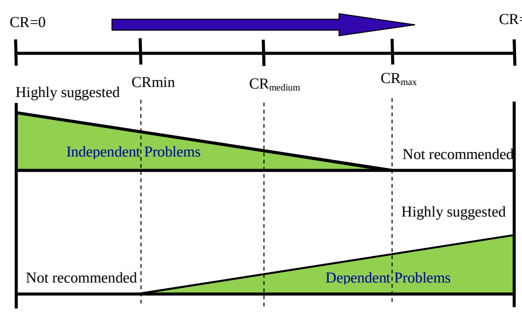

Fig. 3 Suggested to calculate CR values

2.2. OBL review

Opposition-based learning, first proposed by Hamid R. Tizhoosh (2005a), tries to get a better candidate solution by comparing the current particle and its corresponding opposite estimate. This technique provides a new way to find a better solution that can reach the global optimum. Some definitions of opposition-based learning are introduced that include opposition number in mathematics and opposite particle in evolutionary optimizations, as follows:

Definition of opposite number in mathematics: If variable x is a real number within its boundary [lb,ub], the opposition of x is ox, where $ox = lb + ub - x$. We can extend the concepts of the opposite number to the multidimension.

Definition of opposite particle in evolutionary optimization: given $p\,(x_1, x_2, \ldots, x_D)$ be a particle in D-dimensional space, where $x_1, x_2, \ldots, x_D$ are real numbers and $x_i \in [lb_i, ub_i]$. Then, the opposition of particle $p\,(x_1, x_2, \ldots, x_D)$ is defined as in Eq. (11).

$$ox_i = lb_i + ub_i - x_i \tag{11}$$

where lb_i and ub_i are the lower and upper boundary of x_i.

Figure 4 illustrates an example of an opposite number and its corresponding opposition in both one- and two-dimensional spaces.

Opposition-Based Learning: In OBL, both the particle and its corresponding opposition point are simultaneously evaluated based on their fitness value. The better one in term of fitness wins and is selected for reproduction in the next generation. Let $f(x)$ be the objective function and $fit(x)$ be the fitness function. If particle $p \in [a, b]$ is the current one in the searching population and op is its corresponding opposition, then in every generation of the evolutionary algorithm we compare the fitness value between $fit(p)$ and $fit(op)$. If $fit(p) \geq fit(op)$, then particle p wins over op and continues to the next generation for the production new candidates; otherwise, with op.

3. Proposed new evolutionary algorithm based on OBL

In this section, we proposed two schemes of using OBL to improve the performance of the modified DE. The first scheme is jumping OBL (JOBL-DE), and the other one is elite OBL (EOBL-DE).

3.1. Proposed JOBL-DE

We enhance two main core impotence steps in ISADE, namely, the initialization population and reproducing new candidates for the next generation by evolutionary operators such as mutation, crossover, and selection. In the first step, OBL is applied for all particles (100%) at the initialization population. Different from the first step, in the second step, each particle has a chance to generate its opposition if a random number in [0, 1] is less than jumping rate (Jr). The new proposed JOBL-DE implementation process is as in Algorithm 2.

Algorithm 2: JOBL-DE.

1: **Initialization—Opposition-Based Learning operation:** Generate and randomly initialize all NP numbers of populations within the boundary. After that, calculate their corresponding opposition. We have a total of 2NP number of populations.
2: **Evaluate and rank population:** Evaluate and rank all populations by their fitness value. After that, select first best NP particles for the next generation.
3: **Adaptive scaling factor:** Calculate adaptive scale factors F as in Eq.(4) to Eq. (6).
4: **Mutation operation:** Apply adaptive selection learning strategy to create mutation vector V in Eq. (1) to (3).
5: **Adaptive crossover control parameter** Cr: Calculate adaptive crossover rate Cr in Eq. (7) and Eq. (8).
6: **Crossover operation:** Trial vector U is computed in this step using Eq. (9).
7: **Selection Operation:** In this step, the fitness value is used to evaluate for trial vector U_i^G and target vector X_i^G. The better one is selected for reproducing new offspring by Eq. (10).
8: **Jumping Opposition-Based Learning operation:** Each particle is selected randomly to perform opposition-based learning. After that, both the particle and its estimate opposition are compared to each other, and the better one in term of fitness value survives and Is selected for the next generation. Different from opposite-based learning of initialization, the detail about this step can see in the procedure of EOBL-DE Fig. 6.
9: Repeat Steps 2 to 8 until terminal condition.

3.2. Proposed EOBL-DE

To increase local searchability, we applied OBL to the top elite particles after evaluating the fitness of all particles. Therefore, the best nearby elite particles can be discovered and a new better candidate is selected for the next generation. In Fig 5, the position of the elite particle (blue circle symbol) and its corresponding opposition (**red star symbol**) can be seen. By applying OBL to elite particles (top best particles with the highest fitness value), we can enhance local searchability in this strategy. The new proposed EOBL-DE implementation process is presented as Algorithm 3.

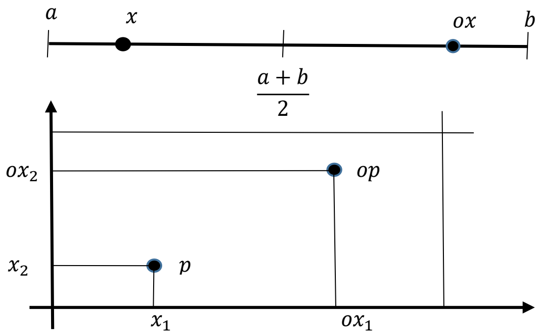

Fig. 4 Illustration of opposition theory.

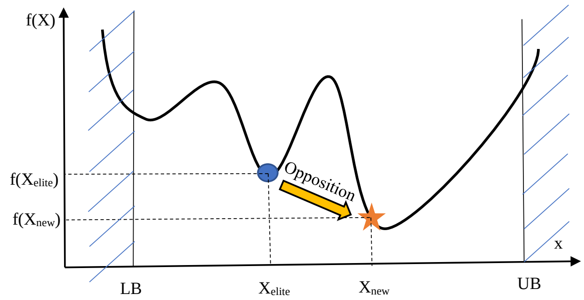

Fig. 5 Elite strategy-based opposition.

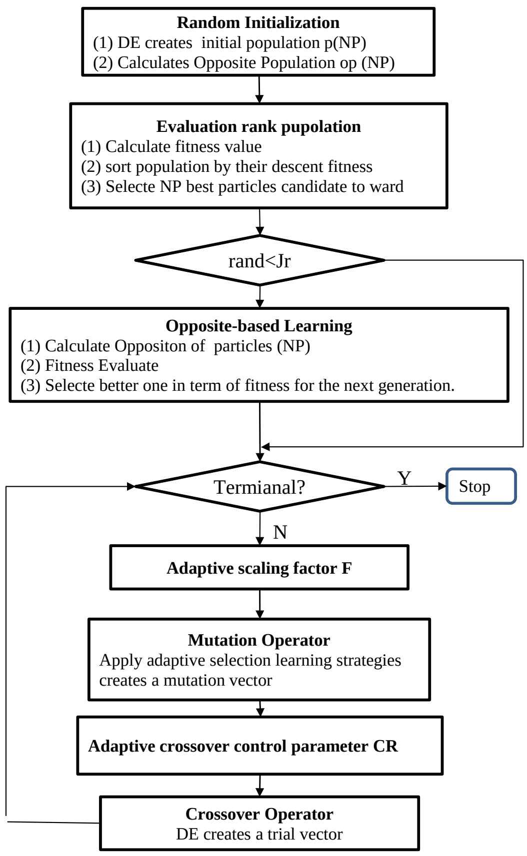

Fig. 6 Jumping OBL (JOBL-DE) procedure.

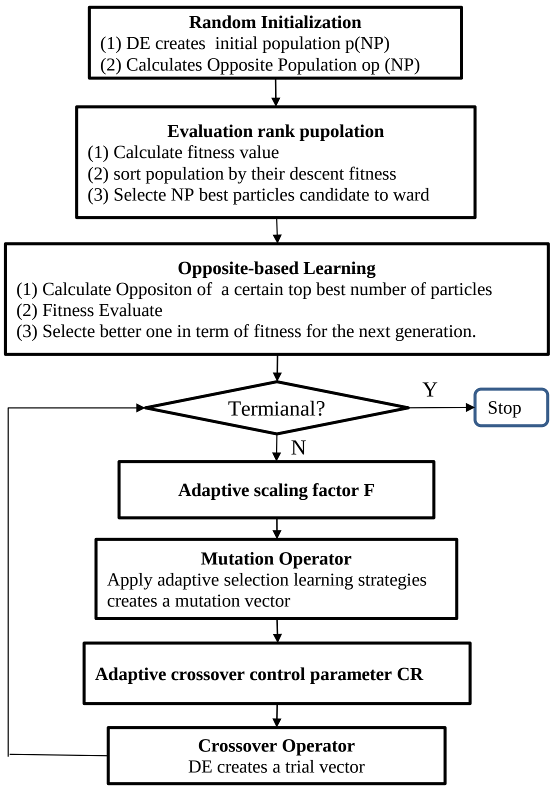

Fig. 7 Elite OBL (EOBL-DE) procedure.

Algorithm 3: EOBL-DE.

1: Steps 1–7 operations are the same as **Algorithm 2**.
2: **Elite Opposition-Based Learning operation**: The top best particles (elite particles in the populations) are selected after ranking all populations by their fitness value. After that, we apply OBL to these elite particles in this step. Both the particle and its corresponding opposite point are evaluated and compared to each other; the better one in term of fitness is selected for the next generation. As a difference from opposite-based initialization learning, there is only some certain amount of best fitness whose opposition is calculated. Details about this step can be seen in the procedure in Fig. 7.
3: Repeat Steps 2 and 3 until terminal condition.

Figure 7 shows the procedure of elite opposition-based learning for modified differential evolution. By considering to use opposite-based learning to our optimization algorithm, the searching process benefits more in terms of convergence speed, stability, and less time consumption. During the simulation, we ran some benchmark tests and real engineering applications to verify the robustness of the new proposed algorithm.

[DOI: 10.1299/jamdsm.2019jamdsm0072]

4. Numerical experiment simulation

In this section, to show the effects of the proposed method in terms of convergence speed (time consumption), stability, and accuracy, we compare our new method with other methodologies, including the original DE and an improved version of DE for the robustness of optimization processing.

4.1. Benchmark-test problems

To evaluate the convergence speed and stability of each method, 19 well-known benchmark-test problems were used. These benchmarks are multiple dimensions (Molga, 2005) that contain multidimensional unimodal and multimodal functions: Sphere or first De Jong (f1), the Rosenbrock function known as "Banana" (f2), Griewank (f3), Rastrigin (f4), Ackley (f5), Ridge or Schwefel's Problem 1.2 (f6), Levy (f7), Schawefel or Schwefel function 2.22 (f8), Schaffer function (f9), Alpine function (f10), Pathological function (f11), Axis Parallel Hyper-Ellipsoid (f12), Sum of Different Power (f13), Zakharov Function (f14), Exponential Problem (f15), Salomon Problem (f16), Bent Cigar Function (f17), Expanded Schaffer's F6 Function (f18), and Schwefel Function (f19). The details of all benchmarks are summarized in Appendix A.

All benchmark-test functions are continuous. They can be divided into groups as follows:

Group 1: Unimodal, convex, and multidimensional.

Group 2: Multimodal, nonconvex, multidimensional, with a few local optimums.

Group 3: Multimodal, nonconvex, multidimensional, with many local optimums.

Group 4: Independent functions: If the function is independent, each variable x_i can be optimized independently. Functions of this category are easy to solve.

Group 5: Dependent functions: If the function is dependent (nonseparable), then all its variables have a strong relationship with each other and cannot be independently optimized. Such functions are relatively difficult to solve.

All benchmark tests are formulated hereinafter as minimization problems, but this does not lose generality that can also be applied for maximization problems by the simple converting sign of the objective function.

4.2. Comparing the robustness of the new proposed algorithm and reference approaches

We compare the robustness of the two new proposed algorithms (JOBLDE and EOBLDE) with the original DE (Storn and Price, 1997) and reference methods ISADE (Bui et al., 2013) by measuring the number of function evaluation calls (FE) and the success rate. The number of FE is the most popular parameter that is used to evaluate the convergence speed of an optimization method. The smaller the FE is, the higher the convergence speed is. The second parameter that is used to show the stability of each algorithm is success rate (SR); one simulation is a success ($SR = 1$) if it can reach the termination-error value (ϵ) before reaching FE_{max}. Each test function is used to calculate both SR and FE. Terminate before reaching FE_{max} if the error in the function value is $\epsilon = 10^{-8}$ or less.

In the experiment, we set a parameter such as number of dimensions $D = 30$, number of populations $NP = 100$, accurate $\epsilon = 10^{8}$, and maximum number of function evaluation calls $FE_{max} = 10000 * D = 300000$ for a fair performance comparison. We also used F = 0.5 and Cr = 0.9 for the original DE algorithm. Our decision for using those values was based on proposed values from the literature DE (Storn and Price, 1997) and ISADE (Bui et al., 2013). All simulations were independently given 50 runs per test function. We used the same uniform random initialization for comparison pairs. This can be achieved by using a fixed seed for a random-number generator in MATLAB software.

The simulation results of the two new proposed algorithms (JOBLDE and EOBLDE) with the original DE and reference method ISADE to solve all benchmark problems are given in Table 1 and Figure 8. As can be seen, ISADE, JOBLDE, and EOBLDE could reach the global optimal solutions for all benchmark-test problems except for f10, the success rate equaled 100%, and DE was not stable to reach the termination-error value ($\epsilon = 10^{-8}$). The success rate of DE was equal to zero on test problems f2, f4, f9, f16, f18, and f19. Therefore, we can say that the new methods, JOBLDE and EOBLDE, were more stable than DE and ISADE.

In terms of comparing number of function calls FE, JOBLDE and EOBLDE also reached the global solution at fewer function calls than the reference in all benchmark functions except test function f10. From the above comparisons, comments, and evaluations, we can see that the proposed methods could reach the global optimal optimum with fewer function evaluation calls than of the reference. With the nine benchmark tests, f4, f5, f8, f9, f11, f14, f16, f18 and f19, new approaches are much robust. Convergence speed to the global optimum solution can be significantly improved than that in EAs for the same termination-error value.

Table 1 Results for comparing robustness of the new proposed algorithm.

Function ID	DE		ISADE		JOBLDE		EOBLDE		
	SR	FE	SR	FE	SR	FE	SR	FE	IR
f1	1.00	35688	1.00	34163	1.00	39255	1.00	**16222**	54.54%
f2	0.00	300000	0.84	179307	1.00	193766	1.00	**176237**	41.25
f3	0.34	38641	0.50	49687	1.00	40759	1.00	**22064**	42.90%
f4	0.00	300000	1.00	144068	1.00	107351	1.00	**85710**	71.43%
f5	0.82	54385	1.00	58290	1.00	46712	1.00	**22047**	59.46%
f6	1.00	126046	0.96	138338	1.00	42267	1.00	**14995**	88.10%
f7	0.76	33618	0.94	46556	1.00	37269	1.00	**17972**	46.54%
f8	1.00	57898	1.00	95701	1.00	68416	1.00	**25377**	56.17%
f9	0.00	300000	0.00	300000	1.00	99038	1.00	**85059**	71.65%
f10	1.00	**58682**	0.98	132938	0.58	186813	0.62	135331	-130.62%
f11	0.00	300000	0.00	300000	1.00	112790	1.00	**90963**	69.68%
f12	1.00	33614	1.00	46457	1.00	37413	1.00	**15102**	55.07%
f13	1.00	8322	1.00	9644	1.00	10181	1.00	**4610**	44.61%
f14	1.00	182620	1.00	172252	1.00	39307	1.00	**13932**	92.37%
f15	1.00	24942	1.00	42009	1.00	31603	1.00	**12198**	51.09%
f16	0.00	300000	0.00	300000	1.00	108121	1.00	**85172**	71.61%
f17	1.00	61828	1.00	113429	1.00	75826	1.00	**25981**	57.98%
f18	0.00	300000	0.00	300000	1.00	112636	1.00	**88738**	70.42%
f19	0.00	300000	1.00	94849	1.00	112648	1.00	**84745**	71.75%

In the final review of the result, the last column of Table 2 shows the improvement rate of EOBLDE over reference DE. EOBLDE could improve the convergence speed by more than 40% of the improvement rate (IR) for all benchmark functions except test function f10. Comparing between the two new proposed algorithms (JOBLDE and EOBLDE), EOBLDE converged faster and more stably than JOBLDE.

Figures 9 to 14 show the behavior of all algorithms for six test problems, f2, f3 f5, f7, f12, and f13. The horizontal axis presents the number of iterations, while the vertical axis presents the function value. These graphs show that our algorithms (EOBLDE and JOBLDE) converged to the global optimum minimum value with accurate $\epsilon = 10^8$ at fewer iterations than the renaming reference algorithms.

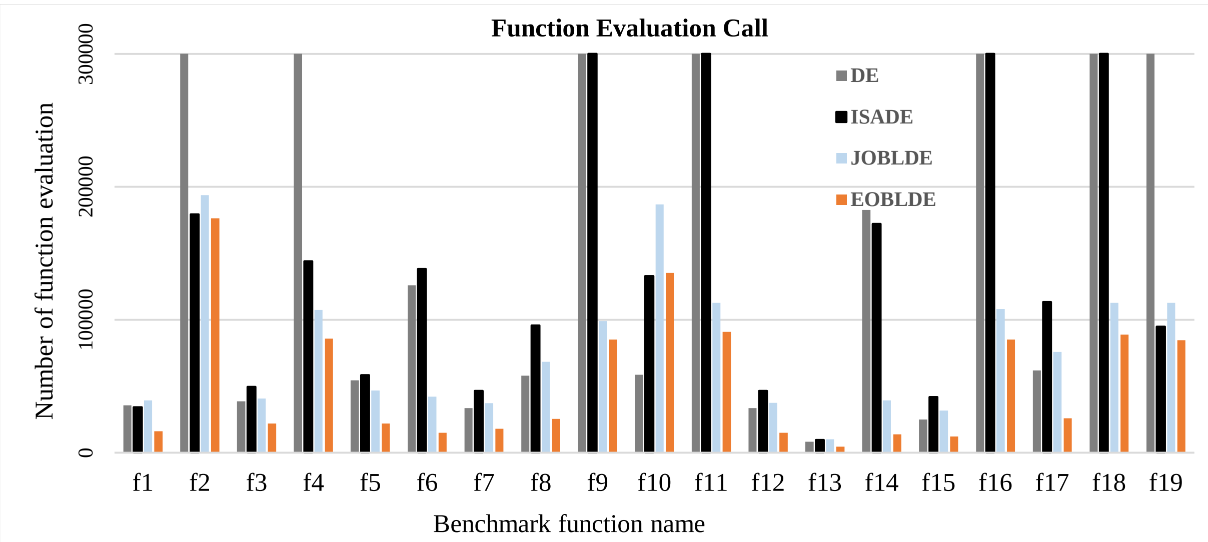

Fig. 8 Comparison of function calls and success rate on all benchmarks.

Last consideration in this section is the contribution of opposition-based learning in the EOBLDE; we used OBL at two different processes: the first is the creation of the initial population and the other is the creation of new particles during the evolution of the ISADE algorithm. To see the contribution of each process in the EOBLDE, we investigated which one is important to improve computational performance. In order to do that, we separated the two processes into two cases: in the first case, EOBLDE only uses OBL in the initial population and is called EOBLDE1; in the second case, EOBLDE only uses OBL in the main process to create new particles and it is called EOBLDE2. All sets of benchmarks

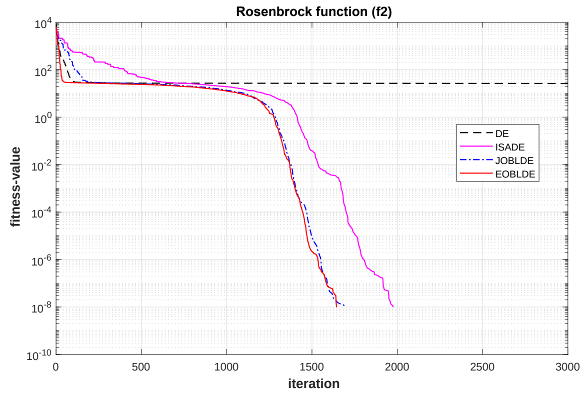

Fig. 9 Convergence graph for f2.

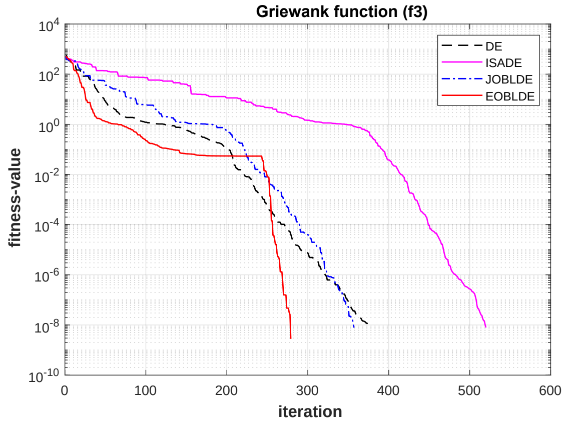

Fig. 10 Convergence graph for f3.

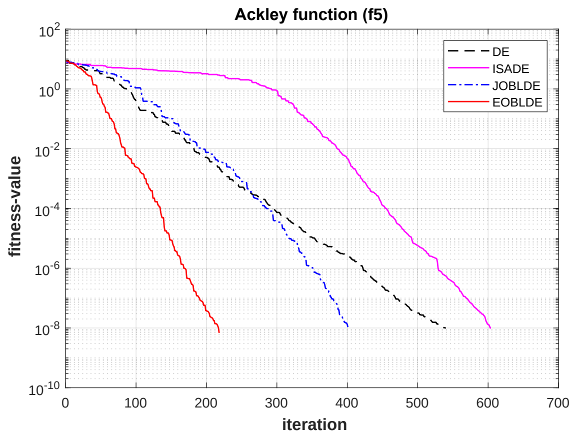

Fig. 11 Convergence graph for f5.

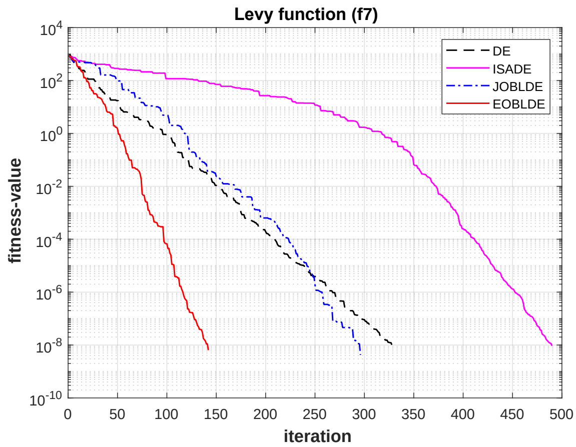

Fig. 12 Convergence graph for f7.

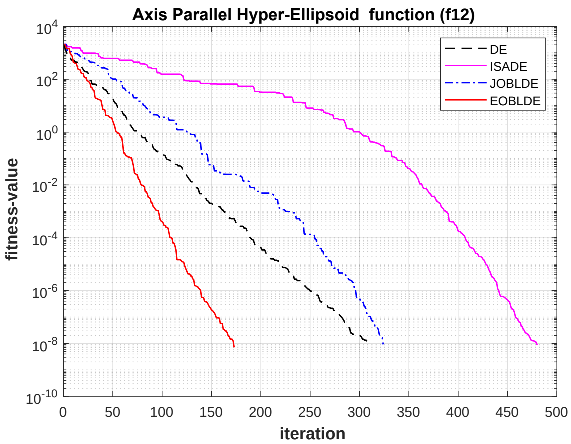

Fig. 13 Convergence graph for f12.

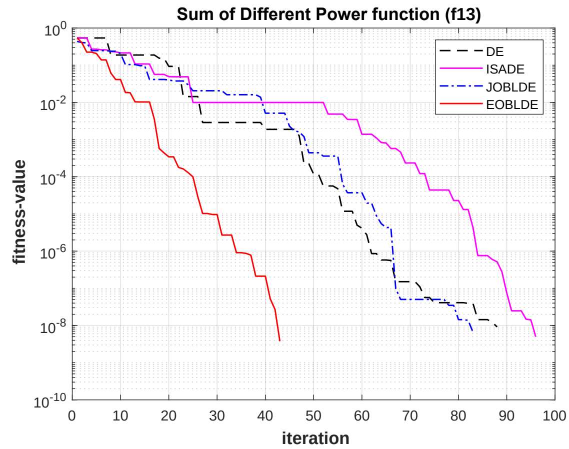

Fig. 14 Convergence graph for f13.

and parameters, same as above, are used to perform simulations for ISADE, EOBLDE1, EOBLDE2, and EOBLDE. Table 2 shows the improvement-rate (IR), function-evaluation-call (FE), and success-rate (SR) values obtained by all algorithms in 50 runs for each function.

As shown in Table 2, both EOBLDE1 and EOBLDE2 could improve computational performance compared with the reference IASDE, but EOBLDE2 was much better than EOBLDE1 in terms of average improvement rate (IR), that is, 56.07% compared with 0.35%. We also see that EOBLDE was better than both EOBLDE1 and EOBLDE2, so using opposition-based learning at two different processes of EOBLDE was the best choice in this study.

[DOI: 10.1299/jamdsm.2019jamdsm0072]

Table 2 Results of comparing EOBLDE1 and EOBLDE2.

Function ID	ISADE		EOBLDE1			EOBLDE2			EOBLDE		
	SR	FE	SR	FE	IR	SR	FE	IR	SR	FE	IR
f1	1.00	34163	1.00	33768	1.16%	1.00	16531	51.61%	1.00	16222	52.52%
f2	0.84	179307	0.90	176733	1.44%	1.00	175134	2.33%	1.00	176237	1.71%
f3	0.50	49687	0.44	49456	0.46%	1.00	25268	49.15%	1.00	22064	55.59%
f4	0.00	144068	1.00	144494	-0.30%	1.00	90112	37.45%	1.00	85710	40.51%
f5	0.82	58290	1.00	58186	0.18%	1.00	22839	60.82%	1.00	22047	62.18%
f6	0.96	138338	1.00	135260	2.23%	1.00	15223	89.00%	1.00	14995	89.16%
f7	0.94	46556	0.98	46800	0.12%	1.00	16028	65.57%	1.00	17972	61.40%
f8	1.00	95701	1.00	97648	0.06%	1.00	25558	73.29%	1.00	25377	73.48%
f9	0.00	300000	0.00	300000	0.00%	1.00	90140	69.95%	1.00	85059	71.65%
f10	0.98	132938	1.00	131928	0.76%	0.68	143576	-8.00%	0.62	135331	-1.80%
f11	0.00	300000	0.00	300000	0.00%	1.00	96681	67.77%	1.00	90963	69.68%
f12	1.00	46457	1.00	46549	-0.20%	1.00	15202	67.28%	1.00	15102	67.49%
f13	1.00	9644	1.00	11297	0.48%	1.00	4119	57.29%	1.00	4610	52.20%
f14	1.00	172252	1.00	171098	0.67%	1.00	13314	92.27%	1.00	13932	91.91%
f15	1.00	42009	1.00	42151	-0.34%	1.00	12214	70.93%	1.00	12198	70.96%
f16	0.00	300000	0.00	300000	0.00%	1.00	91156	69.61%	1.00	85172	71.61%
f17	1.00	113429	1.00	113770	-0.30%	1.00	26038	77.04%	1.00	25981	77.09%
f18	0.00	300000	0.00	300000	0.00%	1.00	94055	68.65%	1.00	88738	70.42%
f19	1.00	94849	1.00	94639	0.22%	1.00	91639	3.38%	1.00	84745	10.65%
Average	0.75	-	0.75	-	0.35%	0.98	-	**56.07%**	0.98	-	**57.29%**

4.3. Applying newly proposed method for solving real-world applications

To show the ability of the newly proposed method, some real-world constrained problems were used in this section. EOBLDE is very robust compared with JOBLDE and other methods.

A set of four well-known mechanical-design optimization problems were selected in this experiment. A more detailed description of these constrained engineering-design optimization problems is presented in Appendix B. These test problems have previously been used to evaluate the efficacy of many other methodologies in the optimization literature.

Some parameters were set for all experiments: number of population $NP = 8 * D$, and the terminal stopped at maximum function evaluations FE_{max}. All simulations were independently given 50 runs per test problem.

To handle the constrained optimization problems, we first applied penalty methods (Alice and David,1996) to convert a constrained optimization problem to unconstrained problems. The basic formulas are shown below:

Constrained objective function: Minimize $f(X)$

Where $X \in D$ is a vector of design variables of dimension D, and f is a scalar objective function.

- Inequality constraints: $g_i(X) \leq 0$ $i = 1 \ldots q$
- Equality constraints: $h_j(X) = 0$ $j = q + 1 \ldots m$

Where q is the number of inequality constraints, $m - q$ is the number of equality constraints, $g_i(X)$ and $h_j(X)$ are the functions of inequality and equality constraints.

Boundary on variables: $LB \leq X \leq UB$

Where LB and UB are the lower and upper boundary of the variable

Unconstrained objective function: Minimize $F(x) = f(X) + cP(X)$

Where c_i is a positive constant, and term $P(X)$ is the penalty function as in Eq. (12).

$$P(X) = \frac{1}{2}\sum_{i=1}^{m} max\{0, g_i(X)\}^2 \tag{12}$$

Experiment results for the Welded Beam problem (E01): Some methods are given for making comparisons for this problem, such as the coevolutionary differential evolution method (CDE) (Huang et al., 2007), coevolutionary particle-swarm optimization (CPSO) (He and Wang, 2006), the GA-based coevolution model (CGA) (Coello, 2000), and study method EOBLDE. The best solutions found by the above methods are listed in Table 3, and their statistical objective values are shown in Table 4. From Table 3, it can be seen that the best solution found by EOBLDE was the best between those of all methods. From Table 4, we can see that the average searching quality of EOBLDE and the standard deviation of the objective function were also better than those of the others.

Experiment results for the Pressure Vessel problem (E02): We continued applying the methods of CDE, CPSO, CGA, and our EOBLDE to this problem. The best solutions obtained by the above approaches are listed in Table 5, and

Table 3 Best solutions found for the Welded Beam.

D.V	CDE	CPSO	CGA	EOBLDE
x_1	0.203137	0.202369	0.208800	0.205729
x_2	3.542998	3.544214	3.420500	3.470488
x_3	9.033498	9.048210	8.99750	9.036623
x_4	0.206179	0.205723	0.210000	0.205729
g_1	-44.57856	-12.83979	-0.337812	-1.4790E-7
g_2	-44.66353	-1.247467	-353.9026	-1.8863E-7
g_3	-0.003042	-0.001498	-0.001200	-9.7584E-11
g_4	-3.423726	-3.429347	-3.411865	-3.432983
g_5	-0.078137	-0.079381	-0.083800	-0.080729
g_6	-0.235557	-0.235536	-0.235649	-0.235540
g_7	-38.02826	-11.68135	-363.2323	-4.4691E-8
$f(X)$	1.733462	1.728024	1.748309	**1.724852**

Table 4 Statistical results for the Welded Beam.

Methods	Best	Mean	Worst	Std
CDE	1.733461	1.768158	1.824105	0.022
CPSO	1.728024	1.748831	1.782143	0.013
CGA	1.748309	1.771973	1.785835	0.011
EOBLDE	1.724852	1.724856	1.725001	**2.131E-5**

their statistics of objective-function values are shown in Table 6. From Table 5, it can be seen that the best solution found by EOBLDE was the best between those of all approaches. From Table 6, it can be found that the average searching quality of EOBLDE was also better than those of reference methods.

Table 5 Best solutions found for the Pressure Vessel.

D.V	CDE	CPSO	CGA	EOBLDE
x_1	0.812500	0.812500	0.812500	0.812500
x_2	0.437500	0.437500	0.437500	0.437500
x_3	42.098411	42.091266	40.323900	42.098445
x_4	176.637690	176.746500	200.000000	176.636595
g_1	-6.677E-07	-0.000139	-0.034324	-1.1102E-16
g_2	-0.035881	-0.035949	-0.052847	-0.035800
g_3	-3.683016	-116.382700	-27.105845	-2.3283E-10
g_4	-63.36231	-63.253500	-40.000000	-63.363400
$f(X)$	6059.7340	6061.0777	6288.7445	**6059.7143**

Experiment results for the Speed Reducer problem (E03): Some well-known methods are given for making comparisons for this problem, such as the Adaptive Penalty Method, include AIS-GAH and APMbc (Bernardino et al., 2008), the simple real-coded steady-state genetic algorithm APMrc (Afonso et al., 2010), and our method EOBLDE. Table 7 shows the best solution found by our proposed algorithm and others from the literature, and their statistical objective-function values are shown in Table 8. In these experiments, we set the maximum number of function evaluations to 36,000. From the test result, we can observe that all methods could essentially reach the same optimal design variables. The best value was found by our EOBLDE, APMbc, and APMrc, the same at (2996.3480). Table 7 shows the final values of the objective function for 50 independently runs (all solutions were feasible). As seen in Table 7, the best solution found by our method EOBLDE was the same as those found by the reference methods. The comparison of the statistical results of the different methods in Table 8 shows that the average searching quality of EOBLDE was also better than those of the other methods, and even the worst solution found by EOBLDE was better than the best solution found by the references.

Experiment results for Tension/compression Spring problem (E04): The four methods applied to this problem were CDE, CPSO, CGA, and our study method EOBLDE. The best solutions obtained by the above approaches are listed in Table 9, and their objective-function value is shown in Table 10. From Table 9, it can be seen that the best solution found by EOBLDE was the best among those of all approaches. From Table 10, it can be found that the average searching quality of EOBLDE was also better than those of others.

[DOI: 10.1299/jamdsm.2019jamdsm0072]

Table 6 Statistical results for the Pressure Vessel.

Methods	Best	Mean	Worst	Std
CDE	6059.7340	6085.2303	6371.0455	43.013
CPSO	6061.0777	6147.1332	6363.8041	86.454
CGA	6288.7445	6293.8432	6308.1497	**7.413**
EOBLDE	6059.7143	6093.8431	6370.7797	83.671

Table 7 Best solutions found for the Speed Reducer.

DV	AIS-GAH	APMbc	APMrc	EOBLDE
x_1	3.500001	3.500000	3.500000	3.500000
x_2	0.700000	0.700000	0.700000	0.700000
x_3	17	17	17	17
x_4	7.300008	7.300000	7.300000	7.300000
x_5	7.800001	7.800000	7.800000	7.713888
x_6	3.350215	3.350215	3.350215	3.350215
x_7	5.286684	5.286683	5.286683	5.285353
$f(X)$	2996.3483	2996.3482	2996.3482	**2.993.6132**

Table 8 Statistical results for the Speed Reducer.

Methods	Best	Mean	Worst	Std
AIS-GAH	2996.3483	2996.3501	2996.3599	**7.45E-3**
APMbc	2996.3482	3033.8807	3459.0948	1.10E+2
APMrc	2996.3482	2997.4728	3051.4556	7.87
EOBLDE	2993.6132	2993.6165	2993.6296	0.33E-2

Table 9 Best solutions found for the Tension/Compression.

DV	CDE	CPSO	CGA	EOBLDE
$x_1(d)$	0.051609	0.051728	0.051480	0.051689
$x_2(D)$	0.354714	0.357644	0.351661	0.356718
$x_3(N)$	11.410831	11.244543	11.632201	11.288947
$g_1(X)$	-0.000039	-0.000845	-0.002080	-2.220E-16
$g_2(X)$	-0.000183	-1.2600E-05	-0.000110	-1.1102E-16
$g_3(X)$	-4.048627	-4.051300	-4.026318	-4.053785
$g_4(X)$	-0.729118	-0.727090	-4.026318	-0.727728
$f(X)$	0.0126702	0.0126747	0.0127048	**0.012665**

Table 10 Statistical results for the Tension/Compression.

Methods	Best	Mean	Worst	Std
CDE	0.012670	0.012703	0.012790	2.70E-5
CPSO	0.012674	0.012730	0.012924	5.19E-5
CGA	0.012704	0.012769	0.012822	3.93E-5
EOBLDE	0.012665	0.012669	0.012713	**9.01E-6**

5. Conclusions

In this research, the two new schemes of applying OBL to improve the performance of self-adaptive control parameters in difference-evaluation algorithms have been proposed to solve complex high-dimension optimization problems. The main idea is that we used the principle of opposition-based learning to generate a better candidate in the process of searching for the optimal solution in DE.

Nineteen benchmark problems and four real constrained mechanical optimizations were used to validate the robustness of the new approaches. The new approaches performed well in all test benchmarks, and both the required function-evaluation calls (FE) and the success rate to the solutions were found. The simulation results show that the new approaches, especially EOBLDE, outperformed in all the objective test functions. The convergence speed of EOBLDE was better and more stable than that of DE and ISADE.

The new method, EOBLDE, is a powerful optimal algorithm. We can use this method as a tool for solving many real-world applications in the optimization design area. By proposing this new approach of the optimization algorithm, it gives more options to researchers and engineers in suitable optimal algorithms in their work.

6. Appendix A

f01 Shere function(1st De Jong): $f(\mathbf{x}) = \Sigma_{i=1}^{n} x_i^2$
f02 Rosenbrock function (Rosenbrock valley): $f(\mathbf{x}) = \Sigma_{i=1}^{n}[b(x_{i+1} - x_i^2)^2 + (a - x_i)^2]$
f03 Griewank function: $f(\mathbf{x}) = 1 + \Sigma_{i=1}^{n} \frac{x_i^2}{4000} - \Pi_{i=1}^{n} cos(\frac{x_i}{\sqrt{i}})$
f04 Rastrigin function: $f(\mathbf{x}) = 10n + \Sigma_{i=1}^{n}(x_i^2 - 10cos(2\pi x_i))$
f05 Ackley function: $f(\mathbf{x}) = -a.exp(-b\sqrt{\frac{1}{n}\Sigma_{i=1}^{n} x_i^2}) - exp(\frac{1}{n}\Sigma_{i=1}^{n} cos(cx_i)) + a + exp(1)$
f06 Ridge function (Schwefel Problem 1.2): $f(x_1 \cdots x_n) = \Sigma_{i=1}^{n}(\Sigma_{j=1}^{i} x_j)^2$
f07 Levy function: $f(\mathbf{x}) = \sin^2(4\pi x_1) + \Sigma_{i=1}^{n-1}(x_i - 1.0)^2(1.0 + sin(3\pi x_{i+1})^2) + (x_n - 1)^2(1 + \sin^2(4\pi x_n))$
f08 Schawefel function (Schwefel 2.22 function): $f(\mathbf{x}) = \Sigma_{i=1}^{n}|x_i| + \Pi_{i=1}^{n}|x_i|$
f09 Schaffer function: $f(x, y) = 0.5 + \frac{sin^2(\sqrt{x^2+y^2})-0.5}{[1+0.001\cdot(x^2+y^2)]^2}$
f10 Alpine function: $f(\mathbf{x}) = \Sigma_{i=1}^{n}|x_i sin(x_i) + 0.1x_i|$
f11 Pathological function: $f(\mathbf{x}) = \Sigma_{i=1}^{n-1} 0.5 + \frac{(\sin\sqrt{100x_i^2+x_{i+1}^2})^2-0.5}{1+0.001(x_i^2+x_{i+1}^2-2x_i x_{i+1})^2}$
f12 Axis Parallel Hyper-Ellipsoid: $f(\mathbf{x}) = \Sigma_{i=1}^{n} ix_i^2$
f13 Sum of Different Power: $f(\mathbf{x}) = \Sigma_{i=1}^{n}|x_i|^{i+1}$
f14 Zakharov Function: $f(\mathbf{x}) = \Sigma_{i=1}^{n} x_i^2 + (\Sigma_{i=1}^{n} 0.5ix_i)^2 + (\Sigma_{i=1}^{n} 0.5ix_i)^4$
f15 Exponential Problem: $f(\mathbf{x}) = -exp(-0.5\,\Sigma_{i=1}^{n} x_i^2)$
f16: Salomon Problem: steepness: $f(\mathbf{x}) = 1 - cos(2\pi\sqrt{\Sigma_{i=1}^{D} x_i^2}) + 0.1\sqrt{\Sigma_{i=1}^{D} x_i^2}$
f17 Bent Cigar Function: f18: Schwefel Function: $f(\mathbf{x}) = 418.9829d - \Sigma_{i=1}^{n} x_i sin(\sqrt{|x_i|})$
f19: Schwefel Function: $f(\mathbf{x}) = f(x_1, x_2, ..., x_n) = 418.9829d - \Sigma_{i=1}^{n} x_i sin(\sqrt{|x_i|})$

7. Appendix B

7.1. Welded-beam design problem (E01)

The problem is to design a welded beam for minimal cost, subject to some constraints (Ragsdell and Phillips, 1976). Figure 15 shows the welded-beam structure. The objective is to find the minimal fabrication cost, considering four design variables: $x_1(h)$, $x_2(l)$, $x_3(t)$, $x_4(b)$ and constraints of shear stress τ, bending stress in beam σ, buckling load on bar P_c, and end deflection on beam δ. The optimization model is summarized in the next equation:

Minimize: $f(x) = 1.10471x_1^2x_2 + 0.04811x_3x_4(14.0 + x_2)$

subject to: $g_1(x) = \tau(x) - 13,600 \le 0$; $g_2(x) = \sigma(x) - 30,000 \le 0$; $g_3(x) = x_1 - x_4 \le 0$; $g_4(x) = 0.10471x_1^2 + 0.04811x_3x_4(14.0 + x_2) - 5.0 \le 0$; $g_5(x) = 0.125 - x_1 \le 0$; $g_6(x) = \delta(x) - 0.25 \le 0$; $g_7(x) = 6,000 - Pc(x) \le 0$

With

$$\tau(x) = \sqrt{(\tau')^2 + (2\tau'\tau'')\frac{x_2}{2R} + (\tau'')^2} \;;\quad \tau' = \frac{6,000}{\sqrt{2}x_1x_2} \;;\quad \tau'' = \frac{MR}{J}$$

$$M = 6,000\left(14.0 + \frac{x_2}{2}\right) \;;\quad R = \sqrt{\frac{x_2^2}{4} + \left(\frac{x_1+x_3}{2}\right)^2} \;;\quad J = 2\left\{x1x2\sqrt{2}\left[\frac{x_2^2}{4.0} + \left(\frac{x_1+x_3}{2}\right)^2\right]\right\}$$

$$\sigma(x) = \frac{504,000}{x_4x_3^2} \;;\quad \delta(x) = \frac{65,856,000}{(30\times10^6)x_4x_3^3}\quad Pc(x) = \frac{4.013(30\times10^6)\sqrt{\frac{x_3^2x_4^6}{36.0}}}{196.0}\left(1 - \frac{x_3\sqrt{\frac{30\times10^6}{4(12\times10^6)}}}{28.0}\right)$$

With $0.1 \le x_1, x_4 \le 2.0$, and $0.1 \le x_2, x_3 \le 10.0$.

7.2. Pressure-vessel design problem (E02)

Designing an air-storage tank that works under high-compression pressure of 3000 psi (Sandgren,1990). The initialization design is a cylindrical vessel with both ends by hemispherical heads Fig. 16. The objective is to get the lowest total cost. Design variables are end thickness $x_1(Ts)$, head thickness $x_2(Th)$, inner radius $x_3(R)$, and length of cylindrical length $x_4(L)$. This design is constrained to single-objective optimization as below:

Minimize: $f(x) = 0.6224x_1x_3x_4 + 1.7781x_2x_3^2 + 3.1661x_1^2x_4 + 19.84x_1^2x_3$

subject to: $g_1(x) = -x_1 + 0.0193x_3 \le 0$; $g_2(x) = -x_2 + 0.00954x_3 \le 0$;

$g_3(x) = -\pi x_3^2x_4 - \frac{4}{3}\pi x_3^3 + 1,296,000 \le 0$; $g_4(x) = x_4 - 240 \le 0$

$1 \times 0.0625 \le x_1, x_2 \le 99 \times 0.0625$, and $10 \le x_3, x_4 \le 200$.

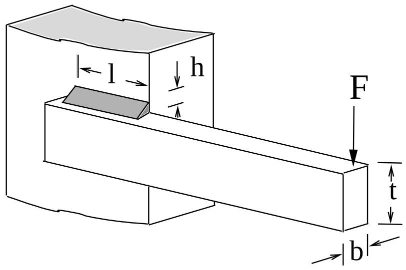

Fig. 15 Welded-beam design-optimization problem

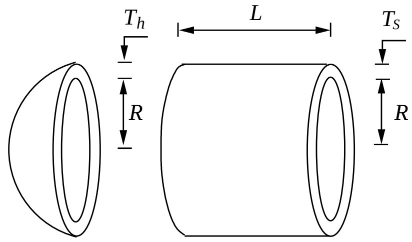

Fig. 16 Pressure-vessel design-optimization problem.

7.3. Speed-reducer design problem (E03)

The design of the speed reducer (Golinski,1973) shown in Fig. 17, is considered with face width $x_1(l)$, module of teeth $x_2(z_1)$, number of teeth on second gear $x_3(z_2)$, length of first shaft between bearings $x_4(l_1)$, length of second shaft between bearings $x_5(l_2)$, diameter of first shaft $x_6(d_1)$, and diameter of second shaft $x_7(d_2)$ (all variables continuous except x_3, that is, integer). The weight of the speed reducer is to be minimized subject to constraints on bending stress of the gear teeth, surface stress, transverse deflections of the shafts, and stresses in the shaft. The mathematical formulation of this problem is:

Minimize: $f(x) = 0.7854x_1x_2^2(3.3333x_3^2+14.9334x_3-43.0934)-1.508x_1(x_6^2+x_7^2)+7.4777(x_6^3+x_7^3)+0.7854(x_4x_6^2+x_5x_7^2)$

subject to: $g_1(x) = \frac{27.0}{x_1x_2^2x_3} - 1 \leq 0$; $g_2(x) = \frac{397.5}{x_1x_2^2x_3^2} - 1 \leq 0$ $g_3(x) = \frac{1.93x_4^3}{x_2x_3x_6^2} - 1 \leq 0$; $g_4(x) = \frac{1.93x_5^3}{x_2x_3x_7^4} - 1 \leq 0$

$g_5(x) = \frac{1}{110.0x_6^3}\sqrt{\left(\frac{745x_4}{x_2x_3}\right)^2 + 16.9\times 10^6} - 1 \leq 0$ $g_6(x) = \frac{1}{85.0x_7^3}\sqrt{\left(\frac{745.0x_5}{x_2x_3}\right)^2 + 157.5\times 10^6} - 1 \leq 0$ $g_7(x) = \frac{x_2x_3}{40.0} - 1 \leq 0$;

$g_8(x) = \frac{5.0x_2}{x_1} - 1 \leq 0$; $g_9(x) = \frac{x_1}{12.0x_2} - 1.0 \leq 0$ $g_{10}(x) = \frac{1.5x_6+1.9}{x_4} - 1 \leq 0$; $g_{11}(x) = \frac{1.1x_7+1.9}{x_5} - 1 \leq 0$

$2.6 \leq x_1 \leq 3.6$; $0.7 \leq x_2 \leq 0.8$; $17 \leq x_3 \leq 28$; $7.3 \leq x_4 \leq 8.3$; $7.8 \leq x_5 \leq 8.3$; $2.9 \leq x_6 \leq 3.9$; and $5.0 \leq x_7 \leq 5.5$.

7.4. Tension/compression-spring design problem (E04)

We designed a tension/compression spring (Belegundu,1982). The objective function was minimal weight, while constraints were minimal deflections, shear stress, surge frequency, and limits on outside diameter and on design variables. The design variables were wire diameter $x_1(d)$, outer diameter $x_2(D)$, and number of turns $x_3(N)$, as seen in Fig. 18. This design was constrained to single-objective optimization as below:

Minimize: $f(x) = (x_3 + 2)x_2x_1^2$

constraints: $g_1(x) = 1-\frac{x_2^3x_3}{7{,}1785x_1^4} \leq 0$; $g_2(x) = \frac{4x_2^2-x_1x_2}{12{,}566(x_2x_1^3-x_1^4)}+\frac{1}{5{,}108x_1^2}-1 \leq 0$; $g_3(x) = 1-\frac{140.45x_1}{x_2^2x_3} \leq 0$; $g_4(x) = \frac{x_1+x_2}{1.5}-1 \leq 0$

$0.05 \leq x_1 \leq 2$, $0.25 \leq x_2 \leq 1.3$, and $2 \leq x_3 \leq 15$.

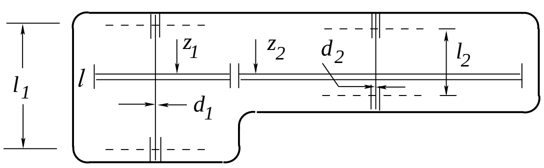

Fig. 17 Speed Reducer.

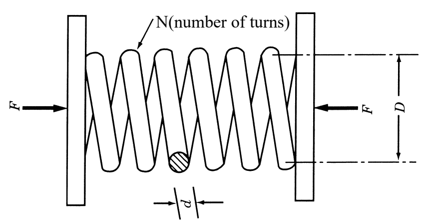

Fig. 18 Tension/Compression Spring.

References

Alice, S.E., David, C.W., Penalty functions Handbook of Evolutionary Computation, Section C 5.2. Oxford University Press and Institute of Physics Publishing, (1996).

Afonso C.C. Lemongea, Helio J.C. Barbosab, Carlos C.H. Borgesc and Francilene B.S. Silvad., constrained optimization problems in mechanical engineering design using a real-coded steady-state genetic algorithm, Mecanica Computacional Vol.XXIX, pages. 9287-9303 (articulo completo), Argentina, 15-18 November (2010).

[DOI: 10.1299/jamdsm.2019jamdsm0072]

Bernardino H., Barbosa H., and Lemonge A., A hybrid genetic algorithm for constrained optimization problems in mechanical engineering. In Proceedings of the 2007 IEEE Congress on Evolutionary Computation,Singapore:IEEE Press, (2007) pp.646-653.

Bernardino H., Barbosa H., Lemonge A., and Fonseca L., A new hybrid AIS-GA for constrained optimization problems inmechanical engineering. In Proceedings of the 2008 IEEE Congress on Evolutionary Computation, Hong Kong:IEEE Press, (2008) pp.1455-1462.

Belegundu, A., A Study of Mathematical Programming Methods for Structural Optimization, PhD thesis, Department of Civil Environmental Engineering, University of Iowa, Iowa, (1982).

Bui, T. Pham, H. Hasegawa, H., Improve self-adaptive control parameters in differential evolution for solving constrained engineering optimization problems. J Comput Sci Technol Vol.7, No.1 (2013), pp.59-74. DOI:10.1299/jcst.7.59.

Coello, C.A.C., Use of a self-adaptive penalty approach for engineering optimization problems, Computers in Industry 41 (2000), pp.113-127.

David, H. W. and William, G.M., No Free Lunch Theorems for Optimization, IEEE TRANSACTIONS ON EVOLUTIONARY COMPUTATION, APRIL, Vol.1, No.1 (1997), pp.68-82.

Dorigo, M., Optimization, Learning, and Natural Algorithms, PhD thesis, Politecnico di Milano, (1992).

El-Abd, M., Generalized opposition-based artificial bee colony algorithm, in 2012 IEEE Congress on Evolutionary Computation (CEC), (2012), pp.1-4.

Golinski, J., An Adaptive Optimization System Applied to Machine Synthesis, Mech. Mach. Theory, Vol.8, No.4 (1973), pp.419-436.

Holland J.H., Adaptation in Natural and Artificial Systems, University of Michigan Press, Ann Arbor, Michigan; re-issued by MIT Press (1992).

Huang, F. Wang, L. He, Q., An effective co-evolutionary differential evolution for constrained optimization, Applied Mathematics and Computation 186 (2007), pp.340-356.

He, Q. Wang, L., An effective co-evolutionary particle swarm optimization for constrained engineering design problems, Engineering Applications of Artificial Intelligence Vol.19, No.7 (2006), doi:10.1016/j.engappai.2006.03.003.

Karaboga, D. Basturk, B., An artificial bee colony algorithm for numeric function optimization, in Proc. of the IEEE Swarm Intelligence Symposium May (2006), Indiana, USA, pp.12-14.

Kennedy J, Eberhart R., Particle swarm optimization, [J] IEEE International Conference on Neural Networks Conference Proceedings. Perth, Aust, (1995), pp.1942-1948.

Molga, M. Smutnicki, C., Test functions for optimization needs. (online), available from: <http://www.zsd.ict.pwr.wroc.pl/files/docs/functions.pdf>, (accessed, 2005).

Rahnamayan, H. Tizhoosh, R. and Salama, M. A., Opposition-Based Differential Evolution Algorithms, in IEEE Congress on Evolutionary Computation, 2006. CEC 2006, (2006), pp.2010-2017.

Ragsdell, K,. and Phillips, D., Optimal Design of a Class of Welded Structures using Geometric Programming, J. Eng. Ind, Vol.98, No.3 (1976), pp.1021-1025.

Rahnamayan, S. Tizhoosh, H. R. and Salama, M. M. A., Opposition-Based Differential Evolution, U.K. Chakraborty (Ed.): Advances in Differential Evolution, SCI 143, (2008), pp.155-171.

Rahnamayan, S. Tizhoosh, H. R. and Salama, M. M. A., A novel population initialization method for accelerating evolutionary algorithms, Comput. Math. Appl., Vol.53, No.10 (2007), pp.1605-1614.

Rahnamayan, S. Tizhoosh, H. R. and Salama, M. M. A., Opposition versus randomness in soft computing techniques, Appl. Soft Comput., vol.8, No.2 (2008), pp.906-918.

Storn R. , and Price K., Differential Evolution-A Simple and Efficient Heuristic for Global Optimization over Continuous Spaces, Journal Global Optimization, Vol.11 (1997), pp.341-359.

Shaw, B. Mukherjee, V. and Ghoshal, S. P., A novel opposition-based the gravitational search algorithm for combined economic and emission dispatch problems of power systems, Int. J. Electr. Power Energy Syst., Vol.35, No.1 (2012), pp.21-33.

Saha, S. K. Dutta, R. Choudhury, R. Kar, R. Mandal, D. and Ghoshal, S. P., Efficient and Accurate Optimal Linear Phase FIR Filter Design Using Opposition-Based Harmony Search Algorithm, The Scientific World Journal, vol.2013, Article ID 320489, 16 pages (2013). https://doi.org/10.1155/2013/320489.

Shaw, B. Mukherjee, V. and Ghoshal, S.P., A novel opposition-based gravitational search algorithm for combined economic and emission dispatch problems of power systems, Int. J. Electr. Power Energy Syst., Vol.35, No.1 (2012), pp.21-33.

Tizhoosh H. R., Opposition-Based Learning: A New Scheme for Machine Intelligence, in International Conference on Computational Intelligence for Modelling, Control and Automation, 2005 and International Conference on Intelligent Agents, Web Technologies and Internet Commerce, Vol.1 (2005) pp.695-701.

Tizhoosh, H.R., Reinforcement Learning Based on Actions and Opposite Actions, presented at the ICGST International Conference on Artificial Intelligence and Machine Learning (AIML-05), Cairo, Egypt, (2005) pp.94-98.

Tooyama, S. Hasegawa, H., Adaptive plan system with genetic algorithm using the variable neighborhood range control. IEEE Congress on Evolutionary Computation, CEC'09. (2009), pp.846-853, DOI:10.1109/CEC.2009.4983033.

Sandgren, E., Nonlinear Integer and Discrete Pro-gramming in Mechanical Design Optimization, J.Mech. Des.-T. ASME, Vol.112, No.2 (1990), pp.223-229.

Ventresca, M. and Tizhoosh, H. R., Improving the Convergence of Backpropagation by Opposite Transfer Functions, in International Joint Conference on Neural Networks, 2006. IJCNN'06, (2006), pp.4777-4784.

Ventresca, M. and Tizhoosh, H. R., Numerical condition of feedforward networks with opposite transfer functions, in IEEE International Joint Conference on Neural Networks, 2008. IJCNN 2008. (IEEE World Congress on Computational Intelligence),(2008), pp.3233-3240.

Ventresca, M. and Tizhoosh, H.R., Opposite Transfer Functions and Backpropagation Through Time, in IEEE Symposium on Foundations of Computational Intelligence, (2007), pp.570-577.

Wang, H. Wu, Z. Rahnamayan, S. Liu, Y. and Ventresca, M., Enhancing particle swarm optimization using generalized opposition-based learning, Inf. Sci., Vol. 181, No. 20 (2011), pp.4699-4714.

Wang, H. Wu, Z. and Rahnamayan, S., Enhanced opposition-based differential evolution for solving high-dimensional continuous optimization problems, Soft Comput., Vol.15, No.11 (2011), pp.2127-2140.

[DOI: 10.1299/jamdsm.2019jamdsm0072]