

# Research Article **Differential Human Learning Optimization Algorithm**

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Received 5 November 2021; Revised 27 March 2022; Accepted 28 March 2022; Published 30 April 2022

Academic Editor: Zaher Mundher Yaseen

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Human Learning Optimization (HLO) is an efficient metaheuristic algorithm in which three learning operators, i.e., the random learning operator, the individual learning operator, and the social learning operator, are developed to search for optima by mimicking the learning behaviors of humans. In fact, people not only learn from global optimization but also learn from the best solution of other individuals in the real life, and the operators of Differential Evolution are updated based on the optima of other individuals. Inspired by these facts, this paper proposes two novel differential human learning optimization algorithms (DEHLOS), into which the Differential Evolution strategy is introduced to enhance the optimization ability of the algorithm. And the two optimization algorithms, based on improving the HLO from individual and population, are named DEHLO1 and DEHLO2, respectively. The multidimensional knapsack problems are adopted as benchmark problems to validate the performance of DEHLOS, and the results are compared with the standard HLO and Modified Binary Differential Evolution (MBDE) as well as other state-of-the-art metaheuristics. The experimental results demonstrate that the developed DEHLOS significantly outperform other algorithms and the DEHLO2 achieves the best overall performance on various problems.

# 1. Introduction

In the past decades, traditional optimization algorithms are widely used in science, engineering, economics, and industry to solve optimization problems [1]. However, the traditional optimization algorithms need to learn the mathematical characteristics of the optimal solution in advance, which can result in added complexity in the algorithm's designation. In addition, the traditional algorithms cannot escape the local optimal of complex problems effectively. With the development of technology, engineering problems with optimization objectives are becoming more and more complicated and the conventional algorithm to solve the NP problems has become very difficult, which forces researchers to study metaheuristic algorithms [2]. Metaheuristics are general frameworks to build heuristics for combinatorial and global optimization problems [3]. The application of natural or biology-inspired metaheuristic optimizations, such as Genetic Algorithm [4], Particle Swarm Optimization [5], Harmony Search [6], Differential Evolution (DE) [7–10], Artificial Bee Colony [11], Fruit Fly Optimization [12], Distributed Grey Wolf Optimizer (DGWO) [13], Moth Search Algorithm (MSA) [14], Slime Mould Algorithm (SMA) [15], Gaining Sharing Knowledge-Based Optimization [16, 17], Cuckoo Search with Exploratory (ECS) [18], Discrete Jaya with Refraction Learning and Three Mutation (DJRL3M) [19], and Monarch Butterfly Optimization (MBO) [20], Hunger Games Search (HGS) [21], Runge Kutta Method (RUN) [22], and Harris Hawks Optimization (HHO) [23], has been very successful to solve the complex

optimization problems, such as feature selection [24–28], image segmentation [29], controller designation [30], flow-shop scheduling problem [31, 32], and the node placement of wireless sensor networks [33].

Human beings are the smartest creature in the world because of their strongest learning ability; they are smarter than other living beings, such as birds, ants, and fish. To solve complex problems effectively, humans are always repetitively learning to improve their skills for adapting to the external environment better. Many human learning activities are similar to the search process of metaheuristics. For example, when a person learns something new, he or she repeatedly practices to improve new skills and evaluates his or her performance for guiding the following study. The process of human learning just like the metaheuristic algorithms iteratively generates a new solution and calculates the corresponding fitness for adjusting the following search. Therefore, it is reasonable to consider that the metaheuristic algorithm based on the human learning mechanisms may have advantages over other biological systems-based algorithms on complicated problems. Inspired by this thought, Wang et al. [34] proposed the Human Learning Optimization Algorithm (HLO) based on a simplified human learning model, in which three learning operators, i.e., the random learning operator (RLO), the individual learning operator (ILO), and the social learning operator (SLO), are developed to search out the optimal solution, which represents that a person may learn randomly due to the lack of prior knowledge or exploring new strategies, learn from his or her previous experience, and learn from his or her friends and books, respectively.

To strengthen the search efficiency of HLO, a few enhanced variants have been subsequently developed. An adaptive simplified human learning optimization algorithm (ASHLO) [35] is proposed in which the pr and pi, two control parameters determining the rates of performing RLO, ILO, and SLO, are linearly adjusted to achieve the balance between the global search and local search. Encouraged by the success of ASHLO, a sine-cosine adaptive human learning optimization algorithm (SCHLO) [36] is proposed in which the pr and pi are dynamically tuned in a reasonable range by the sine and cosine functions so that SCHLO can efficiently escape from the local optimal. Later, a new improved adaptive human learning optimization algorithm (IAHLO) [37] is presented to accurately tune the control parameter pr so that IAHLO can keep the diversity better at the early stage and perform the local search more efficiently at the later stages of iterations. Besides, inspired by the intelligence quotient (IQ) of humans, a diverse human learning optimization algorithm (DHLO) [38] is presented in which the control parameter pi is initialized by a Gaussian distribution and dynamically adjusted according to the pi value of the best individual. To further extend HLO, a novel hybrid-coded HLO (HcHLO) [39] is proposed to tackle mix-coded problems, in which realcoded parameters are optimized by a new continuous HLO (CHLO) [39] and the binary and discrete variables are handled by the binary learning operators of HLO. Until now, HLO has been successfully applied to engineering design problems [37], knapsack problems [40], optimal power flow calculation [41], extractive text summarization [42], financial

markets forecasting [43], furnace flame recognition [44], scheduling problems [45], and intelligent control [46]. In particular, HLO obtained the best-so-far results on two well-studied sets of multidimensional knapsack problems, i.e., 5.100 and 10.100 [40], as well as the set of mixed-variable optimization problems [39] which implies the promising advantages of HLO.

In HLO, social learning adopts the greedy strategy to generate a new candidate, i.e., simply yet efficient copying the bit value from the SKD, which makes the algorithm easy to fall into local optimal. So, the relearning operator is introduced into HLO [40] to help the algorithm to escape from the local optimal. However, the relearning operator may destroy the existing optimal information, which further reduces the performance of the algorithm. On the other hand, the social learning of the HLO just learns from the global solution, which is inconsistent with the actual society. In real life, people could learn from the best solution of other individuals in the population. The Modified Binary Differential Evolution (MBDE, modified binary DE which is the previous work) [47] reverses the updating strategy of the standard Differential Evolution (DE) [7] so that DE can better keep the robustness of parameter settings and the diversity of the population to search for optimal bit information effectively. Therefore, this paper proposes two novel differential human learning optimization algorithms (DEHLOs), in which the strategy of MBDE is introduced into HLO to further improve the performance of DEHLOs algorithm by using the optimal information of other individuals.

This paper is organized as follows. Section 2 gives a brief review of the HLO and MBDE, respectively. Section 3 presents the concepts, operators, and implementation of the proposed DEHLO1 and DEHLO2 in detail. Section 4 verified that the proposed DEHLOs have significant advantages over the compared algorithms on the multidimensional knapsack problems. Finally, conclusions are drawn in Section 5.

#### 2. Related Works

2.1. Human Learning Optimization. The HLO adopts the binary-coding framework, and consequently an individual in HLO is represented by a binary string as

$$\begin{aligned} x_i &= \begin{bmatrix} x_{i1} & x_{i2} & \dots & x_{ij} & \dots & x_{iM} \end{bmatrix}, \\ x_{ij} &\in \{0, 1\}, \\ 1 &\leq i \leq N, \\ 1 &\leq j \leq M, \end{aligned} \tag{1}$$

where  $x_i$  denotes the *i*-th individual, *N* is the size of the population, and *M* is the dimension of solutions. Each bit of binary string is initialized as "0" or "1" randomly.

Random learning operator: At the beginning of the learning process, people always keep exploring new strategies to solve problems because there is no prior knowledge [48]. Besides, an individual cannot fully replicate their previous experience and social knowledge because of the disturbance of external and forgetting. To emulate these phenomena of human random learning, the HLO executes random learning operator (RLO) with a certain probability as

$$x_{ij} = RE(0,1) = \begin{cases} 0, & r_1 \le 0.5, \\ 1, & \text{else,} \end{cases}$$
(2)

where  $r_1$  is a stochastic number between 0 and 1.

Individual learning operator: Individual learning is defined as the ability to build knowledge through individual reflection about external stimuli and sources [49], which could be regarded as individual behavior in the trial and error process of continuous improvement. To mimic human individual learning, the best individual solutions are reserved in the individual knowledge database (IKD) as

$$IKD_{i} = \begin{bmatrix} ikd_{i1} \\ ikd_{i2} \\ \vdots \\ ikd_{ip} \\ \vdots \\ ikd_{iK} \end{bmatrix} = \begin{bmatrix} ik_{i1,1} & ik_{i1,2} & \cdots & ik_{i1,j} & \cdots & ik_{i1,M} \\ ik_{i2,1} & ik_{i2,2} & \cdots & ik_{i2,j} & \cdots & ik_{i2,M} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ ik_{ip,1} & ik_{ip,2} & \cdots & ik_{ip,j} & \cdots & ik_{ip,M} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ ik_{iK,1} & ik_{iK,2} & \cdots & ik_{iK,j} & \cdots & ik_{iK,M} \end{bmatrix},$$

$$1 \le i \le N,$$

$$1 \le p \le K,$$

$$1 \le j \le M,$$
(3)

where  $IKD_i$  denotes the individual knowledge database of the person *i*, *K* is the predefined number of solutions saved in the IKD, and  $ikd_{ip}$  represents the *p*-th best experiment of the person *i*. When HLO conducts the individual learning operator, (4) is operated to generate a new candidate solution.

$$x_{ij} = ik_{ip,j}.$$

Social learning operator: During social learning, people can acquire knowledge and experience from other individuals to further develop their ability directly or indirectly [50], and the efficiency and effectiveness of learning will be improved from experience share [51]. To simulate the social learning of humans in HLO, the social knowledge database (SKD) is adopted to reserve the best knowledge of the population as

$$SK D = \begin{bmatrix} skd_{1} \\ skd_{2} \\ \vdots \\ skd_{q} \\ \vdots \\ skd_{s} \end{bmatrix} = \begin{bmatrix} sk_{11} & sk_{12} & \cdots & sk_{1j} & \cdots & sk_{1M} \\ sk_{21} & sk_{22} & \cdots & sk_{2j} & \cdots & sk_{2M} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ sk_{q1} & sk_{q2} & \cdots & sk_{qj} & \cdots & sk_{qM} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ sk_{S1} & sk_{S2} & \cdots & sk_{Sj} & \cdots & sk_{SM} \end{bmatrix}, \quad (5)$$

$$1 \le q \le S,$$

$$1 \le i \le M,$$

where S is the size of the SKD and  $skd_q$  is the q-th solution in the SKD. q is a stochastic number; it decides which one of the SKD will be used. HLO performs social learning operator as

(6) to generate the new candidate solution during the search process.

$$x_{ij} = sk_{qj}.$$
 (6)

In summary, the above operators can be integrated and operated as

$$x_{ij} = \begin{cases} RE(0,1), & 0 \le r \le pr \\ ik_{ip,j}, & pr < r \le pi , \\ sk_{qj}, & \text{else}, \end{cases}$$
(7)

where r is a stochastic number between 0 and 1, and pr and pi are the control parameters to determine the rates of HLO performing the three learning operators. Specifically, pr, (pipr), and (1-pi) are the probabilities of random learning, individual learning, and social learning, respectively. Algorithm 1 describes the implementation of HLO, and more details can be found in [35].

2.2. Modified Binary Differential Evolution. The MBDE [47] adopts the binary-coding scheme and reserves the updating formulas of the standard DE, including the mutation operator, the crossover operator, and the selection operator. A probability estimation operator is introduced into MBDE to integrate the mutant operator.

Probability estimation operator: The probability estimation operator is used to build the probability distribution vector  $f(p_i^G)$  of the parent individuals. The new mutant binary individual  $u'_{ij}^G$  is generated from parents' sampling randomly through the probability estimation vector as equations (8) and (9),

$$f(p_{ij}^G) = \frac{1}{1 + e^{-(2b/1 + 2F) \times \left(p_{r_{1,j}}^G + F \times \left(p_{r_{2,j}}^G - p_{r_{3,j}}^G\right) - 0.5\right)}},$$
(8)

$$u_{ij}^{'G} = \begin{cases} 1, & \text{if rand}() \le f\left(p_{ij}^G\right) \\ 0, & \text{otherwise,} \end{cases}$$
(9)

where *F* is the scaling factor and *b* denotes the bandwidth factor which is a positive real constant;  $p_{r1,j}^G$ ,  $p_{r2,j}^G$ , and  $p_{r3,j}^G$  are the j-th bits of three randomly chosen individuals of *G* generation. rand is random number;  $u_{ij}^{'G}$  is the mutation of the current target individual according to the probability estimation vector  $f(p_{ij}^G)$ .

Crossover operator: The crossover operator is used to produce the trailing individual by mixing the target individual and its mutant individual in MBDE. The trail vector  $v_{ii}^{'G+1}$  can be obtained as

$$\nu_{ij}^{'G} = \begin{cases} u_{ij}^{'G}, & \text{if } (\text{rand}() \le CR) \text{ or } (j = \text{rand} i), \\ p_{ij}^{G}, & \text{otherwise,} \end{cases}$$
(10)

where  $v_{ij}$  is the element of the trailing individual  $v_i$  and *CR* is the crossover probability ranged (0,1). The rand is a stochastic number uniformly distributed within (0, 1); rand *i* is a random integer with 1, 2, ..., *N* where *N* is the length of the individual.

(1) Initialize the population X randomly
(2) Calculate the fitness of the whole population $f(X)$
(3) Initialize the IKDs and SKD
(4) while conditions on the stop criterion do
(5) <b>for</b> $i = 1$ to N do
(6) <b>for</b> $j = 1$ to $M$ do
(7) <b>if</b> $(r \ge 0 \text{ and } r \le pr)$ then
(8) Generate xij as equation (2)
(9) else if $(r > pr and r \le pi)$ then
(10) Generate xij as equation (4)
(11) else if $(r > pi and r < 1)$ then
(12) Generate xij as equation (6)
(13) <b>end if</b>
(14) end for
(15) <b>end for</b>
(16) Calculate the fitness function f(X)
(17) Update the IKDs and SKD
(18) end while

ALGORITHM 1: Pseudocode of HLO.

Selection: The selection operator is defined as the following equation:

$$x_i^{G+1} = \begin{cases} v_i^{G+1}, & \text{if } f(v_i^{G+1}) < f(x_i^G), \\ x_i^G, & \text{otherwise.} \end{cases}$$
(11)

As shown in (11), the MBDE reserved the selection operator of the standard DE. The trail individual  $v_i$  replaces the target individual  $x_i$  if its fitness value is better. Otherwise, the target individual is reserved for the next generation.

## 3. Differential Human Learning Optimization Algorithm

The three operators of HLO represent human learning randomly, learning from their own experience, and collective experience. However, people could learn from other excellent individuals in actual life. The operator of Differential Evolution (DE) is updated based on the optimal information of other individuals in the population. Inspired by this thought, this paper proposes the differential human learning optimization algorithm (DEHLO), in which the learning strategy of the MBDE is introduced into the HLO to develop a novel probability estimation operator for generating the offspring individuals. And this paper modified the HLO from two levels, i.e., individual and population, and named DEHLO1 and DEHLO2, respectively.

3.1. DEHLO1. During the real learning process, different teams always adopt different strategies to search for the optimal solution for the same complex problem. To emulate the phenomena of dividing into groups, the operators of HLO and MBDE are utilized to generate the new solution in DEHLO1, so that the DEHLO1 algorithm could obtain the performance of HLO and MBDE. In

DEHLO1, half of the population is updated by using the operator of HLO as (7) to generate a new solution, and the rest of the population is updated by using the mutation operator of MBDE as equations (8)-(10) to acquire the new individual. The DEHLO1 algorithm could possess both the advantages and shortcomings of the HLO and MBDE, and a dynamic competition strategy is used in DEHLO1 to avoid the disadvantages of the HLO and MBDE. At the beginning of a search, the population is divided into two equal parts which adopt the strategy of HLO and MBDE, respectively. With the progress of the search, the optimal fitness of the HLO and that of MBDE are compared under the specified iterations, and the individual proportion of better fitness value corresponding algorithm will be increased while the individual proportion of the other algorithm will be decreased correspondingly. Therefore, the DEHLO1 algorithm can adaptively compete and use the optimal learning strategy to search for the optimal solution, which effectively enhances the optimization ability of the algorithm. The procedure of DEHLO1 can be illustrated in Figure 1.

3.2. DEHLO2. In real society, the same problem could be solved by using different approaches. But there might be a mainstream method in a certain period, and the mainstream method might be switched to another method due to the needs of the problem. Exactly as the way of human learning: "practice, knowledge, again practice, and again knowledge" [52], this form repeats itself in endless cycles, and with each cycle, the content of practice and knowledge rises to a higher level. This learning process is a vivid metaphor for the spiral. In DEHLO2, the HLO and the MBDE on the whole population are mixed and executed alternately by mimicking these learning behaviors. Firstly, the entire population adopts the HLO algorithm to search for the optimal solution. If it cannot be updated after a specified iteration, the learning process of HLO will be considered to encounter the



FIGURE 1: The flowchart of DEHLO1.

bottleneck; then the strategy of MBDE will be executed, which might make the algorithm escape from the bottleneck and vice versa: if the MBDE algorithm cannot find the optimal solution after certain iterations, the HLO algorithm will be executed to update the individual of the population. The flowchart of DEHLO2 is shown in Figure 2.

The procedure of DEHLO2 can be described as follows: Step 1: Set control parameters, including the population size (popSize), the maximum generation ( $G_{max}$ ), the iterations of the search strategy, and the control parameters of HLO and MBDE; Step 2: Initialize the population randomly, calculate the fitness of each individual, and initialize the IKD and SKD; Step 3: Update the individual of the population as equations (8)–(11) of the MBDE algorithm; when the global optimal of MBDE cannot update after the set iterations, use the HLO algorithm to update the individual of the population as equation (7), and so forth, to generate the new population; Step 4: Calculate the fitness of the new individual and update the IKD and SKD; Step 5: If the terminal conditions are met, terminate the iteration; otherwise go to step 3; Step 6: Output the optimal solution.

3.3. Algorithm Complexity. DEHLO1 and DEHLO2 both have two phases, i.e., the population initialization and the iterative search. The running times of generating the initial population X, individual knowledge database (IKD), and social knowledge database (SKD) are  $N \times M$ ,  $N \times M$ , and  $(M + \log N)$ , respectively, where M and N represent the dimension of solutions and the size of the population, respectively. So, the overall running time of the population initialization is  $((2N + 1) \times M + \log N)$ . During the iterative search of DEHLOS, generating new individuals costs time  $N \times M$ , performing crossover operation costs time  $N \times M$ , and updating the IKD and SKD costs times  $N \times (M + \log K)$  and  $(\log N + \log S + M)$ , respectively, where K is the predefined number of solutions saved in the IKD and S denotes the size of the SKD.



FIGURE 2: The flowchart of DEHLO2.

Therefore, the running time of each iterative step is  $((3N + 1) \times M + \log(N \times S \times K^N))$ . Assume that the maximum generation of DEHLOs algorithms is *G*, so the iterative search phase takes time  $G \times ((3N + 1) \times M + \log(N \times S \times K^N))$ . In general, the maximum generation *G* is much greater than N, K, and S, and therefore the time complexity of DEHLOs is  $O((3N + 1) \times G \times M)$ .

#### 4. Experimental Results and Discussions

To verify the performance of the two algorithms, i.e., DEHLO1 and DEHLO2, the proposed DEHLOS as well as other six binary-coding optimization algorithms, i.e., Improved Adaptive Human Learning Optimization (IAHLO) [37], Simple Human Learning Optimization (SHLO) [34], Modified Binary Differential Evolution (MBDE) [47], Novel Binary Differential Evolution (NBDE) [53], Improved Binary Particle Swarm Optimization (IBPSO) [54], and Novel Binary Gaining Sharing Knowledge-based optimization (NBGSK) [17], were applied to solve multidimensional knapsack problems [55]. The parameters pr, pi, CR, F, and *b* adopt the default

values of HLO and MBDE, and a set of fair parameters, i.e., Cn and K of DEHLO1 and NM and NH of DEHLO2, is chosen for DEHLO1 and DEHLO2 by trial and error in this paper, that is, Cn = 100, K = 5%, NM = 100, and NH = 50. For a fair comparison, the recommended parameters of all compared algorithms were used to tackle the problem, which is listed in Table 1. Since DEHLOs are designed for solving "single-objective" problems, the sizes of IKDs and SKD are both set to 1 [35] to enhance search efficiency and reduce the cost of computation. Besides, the IKD of DEHLOs was reinitialized to further enhance the diversity if it is not updated in the successive 100 generations. The computations were carried out using a PC with Intel Core i5-6402P @ 2.8 GHz CPU and 8 GB RAM while running Java 1.70 on Windows 8.1, 64-bit operating system.

4.1. A Set of Multidimensional Knapsack Problems. Knapsack problems have been studied intensively in the last few decades, and multidimensional knapsack problems (MKPs) [55] are multiconstrained problems instead of only one constraint. It can be formulated as

TABLE 1: The recommended parameter values of all the algorithm.

Algorithm	Parameters settings
DEHLO1	pr = 5/M, $pi = 0.85 + 2/M$ , $CR = 0.2$ , $F = 0.8$ , $b = 20$ , $Cn = 100$ , $K = 5%$
DEHLO2	pr = 5/M, $pi = 0.85 + 2/M$ , $CR = 0.2$ , $F = 0.8$ , $b = 20$ , $NM = 100$ , $NH = 50$
IAHLO [37]	$pr_{\min 1} = 0.02$ , $pr_{\min 2} = 0.05$ , $pr_{\max} = 0.15$ , $pi = 0.85 + 2/M$ , $Sp = 0.2 \times G_{\max}$
SHLO [34]	pr = 5/M, pi = 0.85 + 2/M
MBDE [47]	CR = 0.2, F = 0.8, b = 20
NBDE [53]	$F = 1.0$ , CR = 0.5, filp = 0.2, $U_{\min} = 0.1 \times M$ , $U_{\max} = 0.9 \times M$
IBPSO [54]	$\omega \min = 0.0, \ \omega \max = 2.0, \ c1 = 1.75, \ c2 = 2.00, \ V_{\min} = -6, \ V_{\max} = 6$
NBGSK [17]	NP <sub>min</sub> = 12, Np <sub>max</sub> = 200, $k_f$ = 1.0, $k_r$ = 0.9, $p$ = 0.1, $\delta$ = 100, $\lambda$ = -100

Note. M is the dimension of solutions.

$$Max f (x_1, x_2, ..., x_n) = \sum_{j=1}^n p_j x_j,$$
  
s.t. 
$$\begin{cases} \sum_{j=1}^n w_j x_j \le C \\ x_j \in \{0, 1\}, \ j \in \{1, 2, ..., n\}, \end{cases}$$
 (12)

where the binary decision variables  $x_j$  are used to indicate whether the item j is included in the knapsack or not. Without loss of generality, knapsack problems assume that all profits and weights are positive and all the weights are smaller than the capacity C. Since the maximal volume of the knapsack is limited in knapsack problems and the total volume of the items packed in the knapsack may exceed the constraint, the violation is unacceptable and must be checked. Thus, the penalty function method as (13) is adopted to deal with the infeasible solutions,

$$MaxF(x) = \sum_{j=1}^{n} p_{j}x_{j} - \beta \cdot max\left(0, \sum_{j=1}^{n} w_{j}x_{j} - C\right),$$
s.t. $x_{j} \in \{0, 1\}, j = 1, 2, ..., n,$ 
(13)

where the penalty coefficient  $\beta$  is a big constant which can lead the algorithm to escape from the infeasible area.

For a comprehensive comparison, a total of 30 multidimensional knapsack problems (MKPs), i.e., the instances 5.250.00-29, are adopted to test the performance of DEHLOs as well as the other metaheuristics. The population size and the maximum generation of all the algorithms are set to 100 and 5000. Four indicators, i.e., the best fitness value (Best), the mean best fitness value (Mean), the worst fitness value (Worst), and the standard deviation (Std), are used to evaluate the performance of DEHLOs. Each algorithm ran 100 times on all the problems independently. The numerical results are given in Table 2.

To better compare the performance of DEHLOs with other algorithms, the results of student's *t*-test (*t*-test) and Wilcoxon signed-rank test (W-test) are also listed in Table 2 where "1" indicates that DEHLO2 is significantly better than the compared algorithms at the 95% confidence, "-1" represents that DEHLO2 is significantly worse than the compared algorithms, and "0" denotes that the performance of DEHLO2 is equivalent to other algorithms. Note that the *t*-test, a parameter test, needs to satisfy the normality and

homogeneity of variance, while the W-test, a nonparametric test, does not need. Therefore, the *t*-test is more reliable when the Gaussian distribution assumption is met while the W-test would be more powerful when this assumption is violated [35]. For convenience, the results of the *t*-test and W-test are summarized in Table 3.

Table 2 shows that the proposed DEHLO2 obtains the best numerical results on 26 out of 30 instances. Besides, the summary results of the *t*-test show that DEHLO2 is obviously better than DEHLO1, IAHLO, HLO, MBDE, NBDE, IBPSO, and NBGSK on 21, 30, 30, 24, 30, 30, and 30 out of 30 instances. And W-test results also show that DEHLO2 is significantly superior to DEHLO1, IAHLO, HLO, MBDE, NBDE, IBPSO, and NBGSK on 21, 30, 30, 23, 30, 30, and 30 out of 30 instances. Based on Tables 2 and 3, it is fair to say that DEHLO2 outperforms other algorithms on the multidimensional knapsack problems.

4.2. Another Set of Multidimensional Knapsack Problems. To further verify the performance of the proposed algorithm, another set of multidimensional knapsack problems [53] is adopted as the test benchmark, which is listed in Table 4. The results of all algorithms on the MKPs are given in Table 5 where the best solutions have been highlighted in bold. And the summary results of the *t*-test and W-test are summarized in Table 6. To analyze the superiority of the proposed DEHLOs, the convergence curves of all algorithms on the MKPs are drawn in Figure 3.

It can be seen from Tables 5 and 6 and Figure 3 that DEHLO2 provides the best results and obtained the minimum error among the other algorithms. Specifically, DEHLO2 attains the best numerical results on 13 out of 14 instances and is only inferior to DEHLO1 on the instance 5.500.01. The summarized t-test and W-test results indicate that the proposed DEHLO2 significantly surpasses IAHLO, HLO, MBDE, NBDE, IBPSO, and NBGSK on all the instances while it is better than, competitive to, and worse than DEHLO1 on 10, 4, and 0 instances on the t-test and 11, 3, and 0 instances on the W-test, respectively. Furthermore, Figure 3 shows that the proposed DEHLOs algorithm has a faster convergence rate and higher solution accuracy than the compared algorithms. Therefore, with the introduction of the strategy of MBDE, the optimization performance of the DEHLOs algorithm is significantly enhanced.

TABLE 2: The results	s of all algorithms	on the multidimensional	knapsack problems.
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Problem         Algorithm         Best         Mean         Worst         Std <i>t</i> -test         W-test           DFIIL01         59206         50071.3         58964         45.81         —         —         —           LAHLO         35916         5901.37         58964         46.51         —         —           5.250.0         MBDE         5897.05         5884.5         66.47         1         1           NBDF         5876.5         5820.45         5744.2         182.27         1         1           NBDF         5874.6         58579.44         55336         411.20         1         1           NBCSK         57486         56579.44         55336         411.20         1         1           NBCSK         57486         562.5         156.6         306.06         1         1         1           S250.1         <				U		1 1		
DFH102         59208         5907.35         58968         45.81             1AHL0         5916.0         5005.47         58941         130.21         1         1           5.250.0         SHL0         5917.0         58990.0         5876.30         5771.2         1         1           MBDF         58940.0         5876.30         5771.2         1         1           MBDF         58940.0         5877.5         5874.4         533.4         411.20         1         1           MBDF         5874.5         5829.4         533.4         411.2         1         1           NBDF         5874.5         5579.4         583.6         411.2         1         1           MBDF         61139         61096.4         6108.6         50.4         -         -         -           MBDF         61139         60096.3         60067.3         214.59         1         1         1           MBDF         61139         60075.2         6187.5         43.05         1         1           MBDF         6117.6         6199.7         6188.5         40.4         1         1           MBDF         6149.7	Problem	Algorithm	Best	Mean	Worst	Std	<i>t</i> -test	W-test
DEHLO1         9996         99054.47         58941         46.52         1         1           5.250.0         SHLO         95170         58990.19         58845         65.47         1         1           5.250.0         SHLO         5890.19         58845         65.47         1         1           NBDE         5897.45         5820.43         57715         229.58         1         1           NBDE         5897.45         5782.44         5533.6         411.20         1         1           NBDE         61446         61381.94         61268         50.44         -         -           SEEL         0117.08         99065         158.23         1         1           NBDE         61073         60127.42         9108         630.60         1         1           SEEL         61073         60127.8         99065         158.23         1         1           NBDE         61078         6029.94         99065         306.02         1         1           NBDE         6107         6029.95         61867         4592         -         -           NBDE         6107         602057         61897.21         61876 <td></td> <td>DEHLO2</td> <td>59208</td> <td>59071.35</td> <td>58968</td> <td>45.81</td> <td>_</td> <td>_</td>		DEHLO2	59208	59071.35	58968	45.81	_	_
IAHLO         5841         5841.5.2         57831         130.21         1         1           SHLO         59170         58940.9         58643         67.7         1         1           NBDE         58940.9         5892.14.5         57942         188.27         1         1           NBDE         5875.5         5875.44         5535.44         5736.4         1         1           NBCS         57466         5657.94.4         533.5         141.20         1         1           NBCS         57466         5657.94.4         533.6         141.20         1         1           DEHLO2         61446         61381.94         6128         50.44         -         -         -           SHLO         6443         6127.45         6118.8         620.6         1         1         1           NBDE         6107.8         59695         158.28         1         1         1           NBDE         6119         61076.4         6975.9         618.32         1         1           NBDE         61213         6075.9         6187.3         14.5         1         1           NBDE         61213         6075.9 <td< td=""><td></td><td>DEHLO1</td><td>59196</td><td>59054.47</td><td>58941</td><td>46.52</td><td>1</td><td>1</td></td<>		DEHLO1	59196	59054.47	58941	46.52	1	1
5.250.0         SHLO         9970         58990.19         58645         66.47         1         1           NBDE         5870         58209.03         57715         229.58         1         1           IBPSO         58935         58321.45         57714         182.77         1         1           DEHLO         61446         61381.94         61268         50.44         -         -           DEHLO         6137         6130.04         61209         46.25         1         1           5.250.1         SHLO         6133         6074.52         6113         61074.52         6113         1         1           NBDE         6107         60209.84         60969         40.32         1         1         1           NBDE         6107         60209.84         60969         40.32         1         1           NBDE         6107         60209.87         60309         14.53         1         1           NBDE         61013         60599.87         60309         154.33         1         1           DEHLO2         62057         61997.51         60309         154.33         1         1           DEHLO2		IAHLO	58541	58145.82	57831	130.21	1	1
Description         Section	5 250 0	SHLO	59170	58990.19	58845	65.47	1	1
NNDE         S8745         S8200.3         S7715         229.58         1         1           NBGSK         57486         56579.44         55336         411.20         1         1           DEHLO2         6146         61381.94         61268         50.44         -         -           DEHLO1         6137         61380.94         61268         50.44         -         -           5250.1         SHLO         6137         61380.94         60269         40.32         1         1           NBDE         6107         60209.98         5965         58.28         1         1           NBDE         6107         60209.98         5965         60073         214.59         1         1           NBDE         6107         60207         61997.72         61376         45.92         -         -           DEHLO1         62057         6199.97         60309         154.33         1         1           1AHLO         6101         61865.90         61682         54.89         1         1           1AHLO         6101         61665         62025         225.67         1         1           NBDE         61441	5.250.0	MBDE	58900	58765.98	58643	47.17	1	1
IBPSO         89835         58521.45         97942         188.27         1         1           NBGSK         57846         56579.44         5533         41.20         1         1           DEHL02         61446         61381.94         61268         50.44             DEHL01         61377         61308.04         61209         46.25         1         1           State         6117         60017.42         61188         62.09         1         1           State         61078         60269.88         59366         380.60         1         1           NBDE         61078         60269.88         59366         380.60         1         1           NBDE         61078         60269.72         6189.73         6145.92         -         -           DEHL02         6207         6199.73         6185.59         61682         54.89         1         1           LAHL0         6108         6106.5         6205         225.67         1         1           NBDE         6407         6070.85         60265         225.67         1         1           State         5910.06         5289         39		NBDE	58745	58269.03	57715	229.58	1	1
NRCSK         57486         56579.44         55336         411.20         1         1           DEHLO2         61446         61381.94         61268         50.44         —         —           DEHLO1         61377         6130.804         61209         64.25         1         1           SHLO         61355         6127.452         61138         62.09         1         1           MBDE         61139         61096.41         60069         40.32         1         1           NBDS         61123         60795.96         60073         214.59         1         1           NBGSK         59324         58075.21         56888         516.38         1         1           NBGSK         59324         58075.21         61855         43.06         1         1           JAHLO         6003         6196.59         61630         61855         43.05         1         1           JAHLO         60046         6165.56         60255         225.67         1         1           JAHLO         6040         6165.56         60255         225.67         1         1           NBDE         61441         60780.55         60261		IBPSO	58935	58521.45	57942	188.27	1	1
DEFILO2         61446         61381,94         61268         50.44             DEFILO1         61377         61308.04         61209         46.25         1         1           5.250.1         SHLO         601377         61308.04         61209         46.25         1         1           5.250.1         SHLO         61435         61274.52         61138         62.09         1         1           NBDE         61078         60269.88         59566         380.60         1         1           NBDE         61078         60275.21         56888         516.38         1         1           NBOSK         59324         58075.21         56888         516.38         1         1           DEHLO1         62028         61946.21         61855         43.06         1         1           JHHO         61013         6059.87         60305         1.1         1         1           JBPSO         61640         61682         54.89         1         1         1           JBPSO         61640         6166.56         60485         240.18         1         1           JBPSO         61640         51823.		NBGSK	57486	56579.44	55336	411.20	1	1
DEFILOI         61440         0136.134         01261         30.44         -         -           5.250.1         DEFILOI         61377         61308.04         61209         46.25         1         1           SHLO         61435         6177.452         61138         62.09         1         1           MBDE         61078         6029.88         59566         30.60         1         1           NBOS         59324         50075.21         56888         516.38         1         1           NBOS         51230.2         61876         645.92         -         -         -         -           DEFILO2         62057         61999.72         61876         43.06         1         1           S120.2         SHLO         62008         6194.621         61857         43.06         1         1           NBDE         61417         60790.85         60265         225.67         1         1         1           NBDE         61417         60780.85         60265         225.67         1         1         1           NBDE         63040         61685.5         9191.33         392.1         -         -         -		DEULO2	61446	(1201.04	(12(9	50.44	-	
DERIOL         0137/         0130.04         0120         48.23         1         1           5.250.1         1AHLO         6053         6017.68         59695         158.23         1         1           S1201         MBDE         61139         6109.641         60069         40.32         1         1           NBDE         61078         60269.88         59566         380.60         1         1           NBDE         61072         61975.21         56888         516.38         1         1           NBDE         62027         6199.72         61876         45.92         -         -           DEHLO1         62028         61946.21         61875         43.06         1         1           S14D         62008         6186.590         6162         54.89         1         1           MBDE         62057         61937.51         6180         41.77         1         1           MBDE         6140         6166.56         60485         240.18         1         1           MBDE         5913         5923.84         59123         41.67         0         0           DEHLO2         59315         5923.84		DEFILO2	61277	61361.94	61208	50.44	1	1
LARLD         60050         60017,68         5999         15.28         1         1           MBDE         61139         61096,41         60069         40.32         1         1           NBDE         61139         61096,41         60069         40.32         1         1           NBDS         61213         60795,96         60073         214,59         1         1           NBCS         59324         58075,21         56888         516,38         1         1           DEHLO1         62028         61946,21         61855         43.06         1         1           JAHLD         61013         60599,87         60309         154,33         1         1           JAHLD         61016         61665,00         61682         54,89         1         1           NBDE         61417         60780,85         60205         225,67         1         1           NBDE         61417         60780,85         60205         240.08         1         1           NBDE         59334         5923,84         59123         41,67         0         0           SHLO         5934         59238,46         59123         44,69 <td></td> <td>DEHLOI</td> <td>613/7</td> <td>61308.04</td> <td>61209</td> <td>46.25</td> <td>1</td> <td>1</td>		DEHLOI	613/7	61308.04	61209	46.25	1	1
5.250.1         SHO         61435         61.2/4.32         61.18         6.0.09         1         1           NBDE         61178         600269.88         59566         380.00         1         1           NBDE         61078         600279.506         60073         214.59         1         1           NBCSK         59324         58075.21         56888         516.38         1         1           DEHLO2         62027         61936.72         61876         45.92         -         -           DEHLO1         62028         61946.21         61855         43.06         1         1           DEHLO2         62057         61937.51         61880         41.77         1         1           NBDE         62057         61937.51         61880         41.77         1         1           NBDSK         60205         59110.06         58294         392.21         -         -         -           NBDE         61440         61166.56         60485         240.18         1         1           NBGSK         60205         5910.06         58294         392.21         -         -         -           LAHLO         5865<		IAHLO	60550	60117.68	59695	158.28	1	1
MBDE         61139         61090-41         60090         40.32         1         1           IBPSO         61213         60795.96         60073         214.59         1         1           NBGSK         59324         58075.21         56888         316.38         1         1           DEHL01         62057         61959.72         61876         45.92         -         -         -           DEHL01         62028         61946.21         61855         43.06         1         1           JAHLO         60136         6059.87         60309         154.33         1         1           JAHLO         60166         56         60482         54.89         1         1           MBDE         61417         60780.85         60265         225.67         1         1           NBCK         60205         59110.06         58286         240.18         1         1           NBDE         56141         60166.56         60485         240.18         1         1           NBCK         60205         59110.06         58294.18         58042         117.85         1         1           S141LO         58615         58294.18<	5.250.1	SHLO	61435	612/4.52	61138	62.09	1	1
NBDE         610/8         60/289.88         59:506         380.00         1         1           NBCSK         59324         58075.21         56888         516.38         1         1           DEHLO1         62028         6199.972         61876         45.92         -         -           DEHLO1         62028         61946.21         61875         43.06         1         1           1AHLO         61013         60599.87         60309         154.33         1         1           SHLO         620057         61937.51         61850         41.77         1         1           NBDE         64107         60780.85         60265         225.67         1         1           NBGSK         60205         59110.06         58296         395.35         1         1           NBGSK         60205         59110.06         58296         395.35         1         1           NBGSK         60205         59123.44         59123         41.67         0         0           IAHLO         59343         59235.19         59143         39.21         -         -         -           DEHLO1         59343         59238.44 <t< td=""><td></td><td>MBDE</td><td>61139</td><td>61096.41</td><td>60969</td><td>40.32</td><td>1</td><td>1</td></t<>		MBDE	61139	61096.41	60969	40.32	1	1
IBPSO         61213         60795.96         60073         214.39         1         1           NBCGK         59324         58075.21         56888         516.38         1         1           DEHLO1         62027         61959.72         61876         45.92         -         -           5.250.2         DEHLO1         62028         61946.21         61855         43.06         1         1           5.250.2         MBDE         6207         61937.51         61850         41.77         1         1           NBDE         61407         60780.85         60265         240.68         1         1           NBDE         61407         60780.85         60265         245.67         1         1           NBGSK         60205         59110.06         58296         395.35         1         1           DEHLO1         5915         59233.44         59123         41.67         0         0           MBDE         5934         59234         59234         3924         17.7         1         1           JEHLO1         5934         59233.44         59123         41.67         0         0           MBDE         5934 <td></td> <td>NBDE</td> <td>61078</td> <td>60269.88</td> <td>59566</td> <td>380.60</td> <td>1</td> <td>1</td>		NBDE	61078	60269.88	59566	380.60	1	1
NBGSK         59324         58075.11         56888         516.38         1         1           DEHLO1         62027         61997.2         61876         45.92         -         -           DEHLO1         62028         61997.2         61875         43.06         1         1           1         1         60399.87         60309         154.33         1         1           5.250.2         SHLO         62008         61865.90         61682         54.89         1         1           NBDE         6417         60780.85         60265         225.67         1         1           NBDC         6140         61166.56         60485         240.18         1         1           NBCSK         60205         59110.06         58296         395.33         1         1           NBCSK         60205         59138         59043         39.21         -         -           SHLO         59343         59238.46         59188         61.14         1         1           NBDE         59760         58382.66         57986         14.45         1         1           NBGK         57855         5704.16         56243		IBPSO	61213	60795.96	60073	214.59	1	1
DEHLO2         62057         61959.72         61876         45.92         —         —           DEHLO1         62028         61946.21         61855         43.06         1         1           5.250.2         MBDE         62008         61865.90         61682         54.89         1         1           MBDE         6147         60780.85         60265         225.67         1         1           NBDE         61417         60780.85         60265         240.18         1         1           NBDE         6140         61166.56         60485         240.18         1         1           NBDE         6140         59235.19         59143         39.21         —         —         —           DEHLO2         59343         59235.19         59143         39.21         —         —         —           JHHO         5804         591916         58988         61.14         1         1         1           MBDE         59134         59238.46         59188         40.94         0         0           SHLO         58076         58752.44         58466         13.98         1         1           MBDE         58		NBGSK	59324	58075.21	56888	516.38	1	1
belliol         62028         61946.21         61855         43.06         1         1           iAHLO         6103         66999.87         6030         15.43.3         1         1           sHLO         62008         61865.90         61682         54.89         1         1           NBDE         62057         61937.51         61850         41.77         1         1           NBDS         61640         61166.56         60485         240.18         1         1           NBGSK         60205         59110.06         58296         395.35         1         1           NBGSK         60205         59110.06         58296         395.35         1         1           DEHLO1         59315         59233.14         59123         41.67         0         0           IAHLO2         59345         58294.18         59042         117.85         1         1           SHLO         59334         59128         58088         61.14         1         1           NBDE         5816         58752.84         5806         184.56         1         1           SL250.4         MBDE         58913         58791.13         586		DEHLO2	62057	61959.72	61876	45.92	_	
5.250.2         IAHLO         61013         6039987         60309         15.4.33         1         1           5.250.2         MBDE         62057         61855.90         61682         44.89         1         1           NBDE         61417         60780.85         60265         225.67         1         1           JBPSO         61640         6166.56         60485         240.18         1         1           NBGSK         60205         59110.06         58296         395.35         1         1           DEHLO2         59343         59235.19         59143         39.21         -         -         -           DEHLO1         59315         59233.84         59123         41.67         0         0           IAHLO         58615         59238.46         59183         40.94         0         0           S.250.3         MBDE         59334         59238.46         59183         44.56         1         1           NBDE         58750         5704.16         56243         340.69         1         1           NBGSK         57855         5704.15         57145         143.82         1         1           NBG		DEHLO1	62028	61946.21	61855	43.06	1	1
5.250.2         SHLO         62008         61685.90         61682         54.89         1         1           NBDE         61077         61937.51         61850         41.77         1         1           NBDE         6140         60780.85         60265         225.567         1         1           NBGSK         60205         59110.06         58296         225.57         1         1           NBGSK         60205         59110.06         58296         393.35         1         1           DEHLO1         59343         59235.19         59143         39.21         -         -           IAHLO         58015         58294.18         5802         117.85         1         1           MBDE         59334         5912.8         58988         61.14         1         1           IAHLO         58050         58760         58388.26         57986         184.56         1         1           NBDE         58760         58785.1         5741.4         5440.69         1         1           NBGSK         57855         5704.14.6         56243         340.69         1         1           1BPSO         58875         58		IAHLO	61013	60599.87	60309	154.33	1	1
5.2.50.2         MBDE         62057         61937,51         61850         41.77         1         1           NBDE         61417         60780.85         60265         225.67         1         1           BPSO         61640         61166.56         60485         240.18         1         1           NBCS         60205         59110.06         58296         395.35         1         1           DEHLO2         59343         59235.19         59143         39.21         -         -           DEHLO1         59315         59233.84         59123         41.67         0         0           SHLO         59304         59238.46         59188         601.4         1         1           MBDE         59334         59238.46         59158         40.94         0         0           NBDE         58750         57014.16         56243         340.69         1         1           NBDE         58755         57014.16         56243         340.69         1         1           SL20.4         MBDE         58878         5879.13         58666         47.27         0         0           SL20.4         MBDE         58875	5 250 2	SHLO	62008	61865.90	61682	54.89	1	1
NBDE         61417         60780.85         60265         225.67         1         1           NBCSK         60205         59110.6         6485         240.18         1         1           NBCSK         60205         59113.6         6445         240.18         1         1           Second         59110.6         59235.19         59143         39.21             DEHL01         59343         59235.19         59143         39.21             Second         5815         59234.8         59123         41.67         0         0           IAHL0         58615         58294.18         5902         17.75         1         1           MBDE         59334         59163         59158         60.14         1         1           MBDE         58760         58388.6         59158         40.49         0         0           NBDS         58765         570116         56243         340.69         1         1           10410         58935         58791.13         58665         44.29         -         -           5.250.4         SHL0         58878         5873.24         5864 <td>5.250.2</td> <td>MBDE</td> <td>62057</td> <td>61937.51</td> <td>61850</td> <td>41.77</td> <td>1</td> <td>1</td>	5.250.2	MBDE	62057	61937.51	61850	41.77	1	1
IBPSO         61640         61166.56         60485         240.18         1         1           NBGSK         60205         5910.06         58296         395.35         1         1           DEHLO2         59343         59235.19         59143         39.21             DEHLO1         59315         5923.84         59123         41.67         0         0           5.250.3         SHLO         59304         5923.84         59123         41.67         0         0           SHLO         59304         5923.84         59123         40.94         0         0           SHDS         59304         5923.84         59188         40.94         0         0           NBDE         58750         57014.16         56243         340.69         1         1           NBGSK         57855         57014.16         56243         340.69         1         1           SHLO         58935         5879.33         58666         44.29         -         -           S1250.4         MBDE         58877         58754.6         5861         44.55         1         1           S141LO         57866         5740.15		NBDE	61417	60780.85	60265	225.67	1	1
NBGSK         60205         59110.06         58296         395.35         1         1           DEHLO2         59343         59235.19         59143         39.21             DEHLO1         59315         59233.44         59123         41.67         0         0           IAHLO         58615         58294.18         58042         117.85         1         1           5.250.3         MBDE         59334         59162.28         58988         61.14         1         1           MBDE         59334         59162.28         58988         61.44.0         0         0           NBGSK         57855         57141.66         14.1         1         1           NBGSK         57855         57141.5         57145         1.1         1           NBGSK         57853         58791.13         58664         47.27         0         0           IAHLO         57865         5740.15         57145         1.48.2         1         1           IAHLO         58765         58760.5         58631         44.55         1         1           SL250.4         MBDE         58176         57660.5         57670		IBPSO	61640	61166.56	60485	240.18	1	1
DEHLO2         59343         59233.19         59143         39.21         -         -         -           DEHLO1         59343         59233.84         59123         41.67         0         0           IAHLO         58615         58294.18         58042         117.85         1         1           SHLO         59304         59223.84         59123         40.94         0         0           NBDE         59334         59238.46         59158         40.94         0         0           NBDE         58360         58385.26         57986         184.56         1         1           IBPSO         59168         58752.84         58406         163.98         1         1           NBGSK         57855         57014.16         56243         340.69         1         1           DEHLO2         58913         58799.33         58665         44.29         -         -         -           JEHLO2         58913         58791.13         58696         47.27         0         0           IAHLO         57865         5710.15         57145         143.82         1         1           St250.4         MBDE         58877 <td></td> <td>NBGSK</td> <td>60205</td> <td>59110.06</td> <td>58296</td> <td>395.35</td> <td>1</td> <td>1</td>		NBGSK	60205	59110.06	58296	395.35	1	1
DEHLO2         59343         5923.19         59143         52.4         —         …		DELLO	E0242	50225 10	501/2	20.21		
IAHLO         5933         5923.84         59123         41,07         0         0         0           5.250.3         IAHLO         58615         58294,18         58042         117,85         1         1           5.250.3         SHLO         59304         59162,28         58888         61.14         1         1           MBDE         59334         59238,46         59158         40.04         0         0           NBDE         58760         58388,26         577986         184,56         1         1           NBGSK         57855         57014.16         56243         30.09         1         1           DEHLO2         58913         58793.3         58665         44.29         -         -           DEHLO1         58935         58791.13         58696         47.27         0         0           IAHLO         57865         5740.15         57145         143.82         1         1           1AHLO         58877         58758.46         58631         44.55         1         1           1AHLO         58876         57670         190.88         1         1         1           1BPSO         58608		DEHLO2	59545	59255.19	59145	39.21 41.67		
IARLO         38015         35294.16         3802         11.85         1         1           5.250.3         MBDE         59304         59162.28         58988         61.14         1         1           NBDE         59334         59238.46         59158         40.94         0         0           NBDE         58760         58388.26         57986         184.56         1         1           IBPSO         59168         58752.84         58406         163.98         1         1           NBGSK         57855         57014.16         56243         340.69         1         1           DEHLO2         58913         58799.33         58665         44.29         -         -           DEHLO1         57855         57014.15         57143         143.82         1         1           MBDE         58878         58703.24         58564         60.21         1         1           MBDE         58876         5784.6         58631         44.55         1         1           NBDE         58176         578640         57670         190.88         1         1           NBCSK         56972         55886.53         5107<			59515	59255.04	59125	41.07	0	0
5.250.3         SHLO         5904         59162.28         5898         61.14         1         1           NBDE         59334         59238.46         59158         40.94         0         0           NBDE         59374         59238.46         59158         40.94         0         0           NBDE         59374         58238.46         59186         184.56         1         1           NBCS         57855         57014.16         56243         340.69         1         1           DEHLO2         58913         58799.13         58666         44.29         -         -           DEHLO1         58935         58791.13         58696         47.27         0         0           1AHLO         57865         57540.15         57145         143.82         1         1           SHLO         58878         58758.46         58631         44.55         1         1           NBDE         58176         57660.00         57090         239.22         1         1           NBDE         58176         55107         17.30         1         1           NBGSK         56972         58984.27         59755         149.44 </td <td></td> <td>IATLO</td> <td>58015</td> <td>58294.18</td> <td>58042</td> <td>117.85</td> <td>1</td> <td>1</td>		IATLO	58015	58294.18	58042	117.85	1	1
MBDE         5934         59238.40         59188         40.94         0         0           NBDE         58760         58388.26         57986         14.56         1         1           IBPSO         59168         58752.84         58406         163.98         1         1           NBGSK         57855         57014.16         56243         340.69         1         1           DEHLO2         58913         58799.33         58695         44.29         -         -           DEHLO1         58935         58791.13         58696         47.27         0         0           IAHLO         57865         57540.15         57145         143.82         1         1           MBDE         58877         58758.46         58631         44.55         1         1           NBDE         58176         57660.00         57090         239.22         1         1           NBDE         58176         57660.00         57090         239.22         1         1           NBGSK         56972         55896.45         5107         417.30         1         1           Stardow         59842.73         59786         43.45	5.250.3	SHLU	59304	59162.28	58988	61.14	1	1
NBDE         38/60         58388.20         5986         184.30         1         1           IBPSO         58168         58752.84         58406         163.98         1         1           NBGSK         57855         57014.16         56243         340.69         1         1           DEHLO2         58913         58799.33         58665         44.29         -         -           DEHLO1         58935         58791.13         58696         47.27         0         0           IAHLO         57865         57540.15         57145         143.82         1         1           MBDE         58877         58758.46         58631         44.55         1         1           NBDE         58176         57666.00         57090         239.22         1         1           NBDE         58176         57666         57090         239.22         1         1           NBGSK         56972         55896.45         5107         417.30         1         1           NBGSK         56972         55896.45         5107         417.30         1         1           S250.5         SHLO         59980         59845.2         5975		MBDE	59334	59238.46	59158	40.94	0	0
IBPSO         59168         58752.84         58406         163.98         1         1           NBGSK         57855         57014.16         56243         340.69         1         1           DEHLO2         58913         58799.33         58665         44.29         -         -         -           DEHLO1         58935         58791.13         58666         47.27         0         0         0           IAHLO         57865         57540.15         57145         143.82         1         1           5.250.4         SHLO         58878         58703.24         58564         60.21         1         1           MBDE         58877         58758.66         58631         44.55         1         1           MBDE         58876         57660.00         57090         239.22         1         1           IBPSO         58608         58171.05         57670         190.88         1         1           MBGSK         56972         55896.45         55107         417.30         1         1           JBPSO         59842.43         599786         43.45         -         -         -           5.250.5         SHLO <td></td> <td>NBDE</td> <td>58760</td> <td>58388.26</td> <td>57986</td> <td>184.56</td> <td>1</td> <td>1</td>		NBDE	58760	58388.26	57986	184.56	1	1
NBCSK         57855         57014.16         56243         340.69         1         1           DEHLO2         58913         58799.33         58665         44.29         —         —           DEHLO1         58935         58791.13         58696         47.27         0         0           IAHLO         57865         57540.15         57145         143.82         1         1           MBDE         58878         58703.24         58564         60.21         1         1           MBDE         58176         57660.0         57090         239.22         1         1           IBPSO         58608         58171.05         57670         190.88         1         1           NBGSK         56972         55896.45         55107         417.30         1         1           NBGSK         56972         55896.45         55107         417.30         1         1           SHLO         59805.34         59752         52.38         1         1         1           MBDE         59200         58724.95         58246         209.78         1         1           SHLO         59969         59784.46         59665         47.8		IBPSO	59168	58/52.84	58406	163.98	1	1
DEHLO2         58913         58799.33         58665         44.29             DEHLO1         58935         58791.13         58696         47.27         0         0           IAHLO         57865         57540.15         57145         143.82         1         1           SHLO         58878         58703.24         58564         60.21         1         1           MBDE         58877         58758.46         58631         44.55         1         1           NBDE         58877         58766.00         57090         239.22         1         1           IBPSO         58608         58171.05         57670         190.88         1         1           NBGSK         56972         55896.45         55107         417.30         1         1           JEHLO2         60005         5984.27         59786         43.45             DEHLO1         59980         59845.34         59752         52.38         1         1           JAHLO         58760         58457.12         57975         149.44         1         1           SHLO         59969         59842.43         59666		NBGSK	57855	57014.16	56243	340.69	1	1
DEHLO1         58935         58791.13         58696         47.27         0         0           IAHLO         57865         57540.15         57145         143.82         1         1           5.250.4         MBDE         58878         58703.24         58564         60.21         1         1           5.250.4         MBDE         58877         58758.46         58631         44.55         1         1           NBDE         58176         57666.00         57090         239.22         1         1           IBPSO         58608         58171.05         57670         190.88         1         1           NBGSK         56972         55896.45         55107         417.30         1         1           DEHLO2         60005         59884.27         59786         43.45         -         -           DEHLO1         59860         58457.12         57975         149.44         1         1           SHLO         59969         59842.43         59696         47.81         1         1           NBDE         59920         58724.95         58246         209.78         1         1           NBGSK         58032 <t< td=""><td></td><td>DEHLO2</td><td>58913</td><td>58799.33</td><td>58665</td><td>44.29</td><td>—</td><td>—</td></t<>		DEHLO2	58913	58799.33	58665	44.29	—	—
5.250.4         IAHLO         57865         57540.15         57145         143.82         1         1           5.250.4         SHLO         58878         58703.24         58564         60.21         1         1           MBDE         58877         58758.46         58631         44.55         1         1           NBDE         58877         58768.60         57670         190.88         1         1           IBPSO         58608         58171.05         57670         190.88         1         1           NBGSK         56972         55896.45         55107         417.30         1         1           DEHLO2         60005         59884.27         59786         43.45             DEHLO1         59980         59865.34         59752         52.38         1         1           IAHLO         58760         5884.27         59745         58245         5585         1         1           SLO         59969         59744.45         59645         5558         1         1           NBDE         59945         59842.43         59696         47.81         1         1           NBDE         5992		DEHLO1	58935	58791.13	58696	47.27	0	0
5.250.4         SHLO         58878         58703.24         58564         60.21         1         1           MBDE         58877         58758.46         58631         44.55         1         1           NBDE         58176         57666.00         57090         239.22         1         1           IBPSO         58068         58171.05         57670         190.88         1         1           NBGSK         56972         5589.645         55107         417.30         1         1           DEHLO2         60005         59884.27         59786         43.45         -         -           DEHLO1         59980         59865.34         59752         52.38         1         1           IAHLO         58760         58457.12         57975         149.44         1         1           SHLO         59969         59784.46         59645         65.58         1         1           MBDE         59205         5874.95         58246         209.78         1         1           NBGSK         58032         56999.98         56025         441.22         1         1           5.250.6         NBGSK         58376		IAHLO	57865	57540.15	57145	143.82	1	1
5.250.4         MBDE         58877         58758.46         58631         44.55         1         1           NBDE         58176         57666.00         57090         239.22         1         1           IBPSO         58608         58171.05         57670         190.88         1         1           NBGSK         56972         55896.45         55107         417.30         1         1           DEHLO2         60005         59884.27         5976         43.45         -         -           DEHLO1         59980         59865.34         59752         52.38         1         1           IAHLO         58760         58457.12         57975         149.44         1         1           SHLO         59969         59784.46         59645         65.58         1         1           MBDE         59920         58724.95         58246         209.78         1         1           NBGSK         58032         56999.98         56025         441.22         -         -           DEHLO2         60363         6030.41         60222         29.38         -         -           5.250.6         SHLO         60353	5 250 4	SHLO	58878	58703.24	58564	60.21	1	1
NBDE         58176         57666.00         57090         239.22         1         1           IBPSO         58608         58171.05         57670         190.88         1         1           NBCSK         56972         55896.45         55107         417.30         1         1           DEHLO2         60005         59884.27         59786         43.45             DEHLO1         59980         59865.34         59752         52.38         1         1           IAHLO         58760         58457.12         57975         149.44         1         1           5.250.5         SHLO         59969         59784.46         59645         65.58         1         1           MBDE         59220         58724.95         58246         209.78         1         1           NBGSK         58032         56999.98         56025         441.22         -         -           DEHLO1         60363         6030.41         60222         29.38         -         -           JBPSO         59778         58953.02         58536         163.95         1         1           S141LO         59378         58953.02	5.250.3 5.250.4 5.250.5	MBDE	58877	58758.46	58631	44.55	1	1
IBPSO         58608         58171.05         57670         190.88         1         1           NBGSK         56972         55896.45         55107         417.30         1         1           DEHLO2         60005         59884.27         59786         43.45             DEHLO1         59980         59865.34         59752         52.38         1         1           IAHLO         58760         58457.12         57975         149.44         1         1           SHLO         59969         59784.46         59645         65.58         1         1           MBDE         59945         59842.43         59696         47.81         1         1           NBDE         59220         58724.95         58246         209.78         1         1           NBDE         59220         58724.95         58246         209.78         1         1           NBGSK         58032         56999.98         56025         441.22         -         -           DEHLO1         60353         6021.02         60199         32.38         1         1           5.250.6         SHLO         60353         60221.83		NBDE	58176	57666.00	57090	239.22	1	1
NBGSK         56972         55896.45         55107         417.30         1         1           DEHLO2         60005         59884.27         59786         43.45         —         —           DEHLO1         59980         59865.34         59752         52.38         1         1           IAHLO         58760         58457.12         57975         149.44         1         1           SHLO         59969         59784.46         59645         65.58         1         1           MBDE         59945         59842.43         59696         47.81         1         1           NBDE         59220         58724.95         58246         209.78         1         1           NBDS         59714         59151.86         58576         258.90         1         1           NBGSK         58032         56999.98         56025         441.22         -         -           DEHLO1         60358         60281.02         60199         32.38         1         1           IAHLO         59378         58953.02         58536         163.95         1         1           5.250.6         MBDE         60341         60295.3 <t< td=""><td></td><td>IBPSO</td><td>58608</td><td>58171.05</td><td>57670</td><td>190.88</td><td>1</td><td>1</td></t<>		IBPSO	58608	58171.05	57670	190.88	1	1
DEHLO2         60005         59884.27         59786         43.45             DEHLO1         59980         59865.34         59752         52.38         1         1           IAHLO         58760         58457.12         57975         149.44         1         1           5.250.5         MBDE         59969         59784.46         59645         65.58         1         1           NBDE         59945         59842.43         59696         47.81         1         1           NBDE         59220         58724.95         58246         209.78         1         1           IBPSO         59714         59151.86         58576         258.90         1         1           NBGSK         58032         56999.98         56025         441.22         -         -           DEHLO2         60363         60300.41         60222         29.38         -         -         -           5.250.6         MBDE         59378         58953.02         58536         163.95         1         1           5.250.6         SHLO         60353         60221.83         59964         58.84         1         1 <td< td=""><td></td><td>NBGSK</td><td>56972</td><td>55896.45</td><td>55107</td><td>417.30</td><td>1</td><td>1</td></td<>		NBGSK	56972	55896.45	55107	417.30	1	1
DEHLO1         59980         59865.34         59752         52.38         1         1           IAHLO         58760         58457.12         57975         149.44         1         1           SHLO         59969         59784.46         59645         65.58         1         1           MBDE         59945         59842.43         59696         47.81         1         1           NBDE         59220         58724.95         58246         209.78         1         1           IBPSO         59714         59151.86         58576         258.90         1         1           NBGSK         58032         56999.98         56025         441.22         -         -           DEHLO1         60358         60281.02         60199         32.38         1         1           IAHLO         59378         58953.02         58536         163.95         1         1           5.250.6         SHLO         60353         60221.83         59964         58.84         1         1           IAHLO         59378         58953.02         58535         334.58         1         1           5.250.6         SHLO         60341 <td< td=""><td></td><td>DFHI O2</td><td>60005</td><td>59884 27</td><td>59786</td><td>43 45</td><td>_</td><td></td></td<>		DFHI O2	60005	59884 27	59786	43 45	_	
IAHLO         57300         57300         5732         52300         1         1         1           IAHLO         58760         58457.12         57975         149.44         1         1           5.250.5         SHLO         59969         59784.46         59645         65.58         1         1           MBDE         59945         59842.43         59696         47.81         1         1           NBDE         59220         58724.95         58246         209.78         1         1           IBPSO         59714         59151.86         58576         258.90         1         1           NBGSK         58032         56999.98         56025         441.22             DEHLO2         60363         60300.41         60222         29.38             DEHLO1         60353         6021.02         60199         32.38         1         1           S.250.6         SHLO         60353         60221.83         59964         58.84         1         1           S.250.6         MBDE         60341         60295.39         60216         31.27         0         0           NBDE		DEHLO1	59980	59865 34	59752	52.38	1	1
5.250.5         SHLO         500 00         500 00         500 00         500 00         100 00 </td <td></td> <td>IAHLO</td> <td>58760</td> <td>58457 12</td> <td>57975</td> <td>149 44</td> <td>1</td> <td>1</td>		IAHLO	58760	58457 12	57975	149 44	1	1
5.250.5       MBDE       59945       59842.43       59696       47.81       1       1         NBDE       59220       58724.95       58246       209.78       1       1         IBPSO       59714       59151.86       58576       258.90       1       1         NBGSK       58032       56999.98       56025       441.22           DEHLO2       60363       60300.41       60222       29.38           DEHLO1       60358       60281.02       60199       32.38       1       1         SHLO       59378       58953.02       58536       163.95       1       1         SL250.6       SHLO       60353       60221.83       59964       58.84       1       1         SL250.6       SHLO       60341       60295.39       60216       31.27       0       0         NBDE       59968       59306.75       58585       334.58       1       1       1         IBPSO       60128       59697.42       58954       210.21       1       1         NBGSK       58256       57192.39       55838       529.42       1       1		SHLO	50960	59784.46	59645	65.58	1	1
NBDE         59943         53642.45         5905         47.81         1         1           NBDE         59220         58724.95         58246         209.78         1         1           IBPSO         59714         59151.86         58576         258.90         1         1           NBGSK         58032         56999.98         56025         441.22         -         -           DEHLO2         60363         60300.41         60222         29.38         -         -           DEHLO1         60358         60281.02         60199         32.38         1         1           5.250.6         SHLO         60353         60221.83         59964         58.84         1         1           5.250.6         MBDE         60341         60295.39         60216         31.27         0         0           NBDE         59968         59306.75         58585         334.58         1         1           IBPSO         60128         59697.42         58954         210.21         1         1           NBGSK         58256         57192.39         55838         529.42         1         1	5.250.5	MEDE	50045	50842 43	50606	47.81	1	1
INBDE         39220         36724,93         38240         209,78         1         1           IBPSO         59714         59151.86         58576         258.90         1         1           NBGSK         58032         56999.98         56025         441.22		NEDE	59945	59042.45	59090	47.01	1	1
InFSO         39714         39131.86         38376         238.90         1         1           NBGSK         58032         56999.98         56025         441.22		INDEL	59220	50724.95	58240	209.78	1	1
NBGSK         38032         3699,98         36023         441,22           DEHLO2         60363         60300,41         60222         29,38         —         …		NPCSV	59/14	59151.60	56570	236.90	1	1
DEHLO2         60363         60300.41         60222         29.38         —         … <td></td> <td>NDG5K</td> <td>56052</td> <td>30999.98</td> <td>30023</td> <td>441.22</td> <td></td> <td></td>		NDG5K	56052	30999.98	30023	441.22		
DEHLO1         60358         60281.02         60199         32.38         1         1           IAHLO         59378         58953.02         58536         163.95         1         1           5.250.6         SHLO         60353         60221.83         59964         58.84         1         1           MBDE         60341         60295.39         60216         31.27         0         0           NBDE         59968         59306.75         58585         334.58         1         1           IBPSO         60128         59697.42         58954         210.21         1         1           NBGSK         58256         57192.39         55838         529.42         1         1		DEHLO2	60363	60300.41	60222	29.38		—
IAHLO         59378         58953.02         58536         163.95         1         1           5.250.6         SHLO         60353         60221.83         59964         58.84         1         1           5.250.6         MBDE         60341         60295.39         60216         31.27         0         0           NBDE         59968         59306.75         58585         334.58         1         1           IBPSO         60128         59697.42         58954         210.21         1         1           NBGSK         58256         57192.39         55838         529.42         1         1		DEHLO1	60358	60281.02	60199	32.38	1	1
5.250.6         SHLO         60353         60221.83         59964         58.84         1         1           5.250.6         MBDE         60341         60295.39         60216         31.27         0         0           NBDE         59968         59306.75         58585         334.58         1         1           IBPSO         60128         59697.42         58954         210.21         1         1           NBGSK         58256         57192.39         55838         529.42         1         1		IAHLO	59378	58953.02	58536	163.95	1	1
MBDE         60341         60295.39         60216         31.27         0         0           NBDE         59968         59306.75         58585         334.58         1         1           IBPSO         60128         59697.42         58954         210.21         1         1           NBGSK         58256         57192.39         55838         529.42         1         1	5 250 6	SHLO	60353	60221.83	59964	58.84	1	1
NBDE5996859306.7558585334.5811IBPSO6012859697.4258954210.2111NBGSK5825657192.3955838529.4211	5.250.0	MBDE	60341	60295.39	60216	31.27	0	0
IBPSO6012859697.4258954210.2111NBGSK5825657192.3955838529.4211		NBDE	59968	59306.75	58585	334.58	1	1
NBGSK 58256 57192.39 55838 529.42 1 1		IBPSO	60128	59697.42	58954	210.21	1	1
		NBGSK	58256	57192.39	55838	529.42	1	1

Problem	Algorithm	Best	Mean	Worst	Std	t_test	W_test
Tioblem	DEHLO2	61443	61364.97	61258	38.10	1 1051	<i>w</i> cor
	DEHLO1	61443	61354.31	61227	45.12	0	0
	IAHLO	60401	60031 70	59625	147 33	1	1
	SHLO	61443	61276.94	61141	61.80	1	1
5.250.7	MBDF	61443	61329.16	61185	45.60	1	1
	NBDE	60741	60127 33	59586	285.43	1	1
	IRPSO	61195	60793.69	60209	183 45	1	1
5.250.7 5.250.8 5.250.9 5.250.10	NBGSK	59397	58110.16	57055	496.41	1	1
	DEHLO2	61885	61783.26	61698	37.56	-	1
	DEHLO1	61873	61776.09	61688	38.60	0	0
	IAHLO	60832	60330.40	59847	192.49	1	1
	SHLO	61849	61711.02	61579	53.10	1	1
5.250.8	MBDF	61831	61750.80	61627	36.37	1	1
5.250.8	NBDE	61332	60640.49	59841	293.99	1	1
	IRPSO	61626	61116.24	60530	208.09	1	1
	NBGSK	59896	58378.40	57110	608.34	1	1
	DEHLO2	58906	58825.17	58768	26.75	t-test           0           1           1           1           1           1           1           1           1           1           1           1           1           1           1           0           1           1           0           1           1           0           1 <td></td>	
	DEHLO2	58915	58818 13	58755	20.75	0	0
	IAHLO	58085	57822.15	57505	127.82	1	1
	SHLO	58865	58759 37	58618	51.08	1	1
5.250.9	MBDF	58918	58831 57	58695	43 94	0	0
	NBDE	58651	58235.22	57531	240.98	1	1
	IBPSO	58803	58407 19	57940	165.90	1	1
	NBGSK	57454	56359.20	55279	444.44	1	1
	DEHLO2	100031	108045 41	108878	35.61	-	-
	DEHLO1	109051	108945.41	108850	37.12	0	
	IAHLO	109051	107737 36	103850	157.60	1	1
	SHLO	100104	108879.42	107401	49.85	1	1
5.250.10	MBDF	109047	108930.03	108875	29.74	1	1
	NBDE	108652	108235.63	107873	188.02	1	1
	IBPSO	108820	108358.03	107786	183.12	1	1
	NBGSK	107078	105016.71	102248	830.71	1	1
	DFHI O2	109788	109724 02	109671	30.13		
	DEHLO2	109821	109715.09	109620	34.97	0	0
	IAHLO	108832	108389.65	109020	157 90	1	1
	SHLO	109778	109643 79	109526	55.61	1	1
5.250.11	MBDE	109821	109731.71	109666	33.94	0	0
5.250.10	NBDE	109407	109035.96	108574	182.36	1	1
	IBPSO	109498	109134.90	108575	203.18	1	1
	NBGSK	107415	105664.99	102848	960.86	1	1
	DEHLO2	108480	108421.36	108341	31.26	_	
	DEHLO1	108481	108391.59	108271	44.11	1	1
	IAHLO	107602	107248.20	106838	147.38	1	1
	SHLO	108472	108308.74	108154	63.91	1	1
5.250.12	MBDE	108504	108402.61	108317	36.50	1	1
	NBDE	108108	107752.60	107255	177.67	1	1
	IBPSO	108202	107802.48	107355	188.54	1	1
	NBGSK	106129	104260.07	101348	956.81	1	1
	DEHLO2	109352	109291.79	109229	28.48	_	_
	DEHLO1	109356	109279.64	109210	31.72	1	1
	IAHLO	108392	108113.52	107871	117.43	- 1	1
5 050 10	SHLO	109325	109220.67	109081	45.88	1	1
5.250.7 5.250.8 5.250.9 5.250.10 5.250.11 5.250.12 5.250.12	MBDE	109351	109276.32	109208	31.63	1	1
	NBDE	109124	108621.42	108222	192.78	1	1
	IBPSO	109113	108650.60	107755	230.00	1	1
	NBGSK	107356	105919.36	104001	825.83	1	1



			TABLE 2: Cont	inuea.			
Problem	Algorithm	Best	Mean	Worst	Std	<i>t</i> -test	W-test
	DEHLO2	110654	110559.06	110476	37.70	_	_
	DEHLO1	110639	110537.86	110459	35.69	1	1
	IAHLO	109510	109124.47	108774	150.24	1	1
5 250 14	SHLO	110602	110469.79	110342	56.66	1	1
5.250.14	MBDE	110632	110553.12	110462	33.98	0	0
	NBDE	110256	109752.20	109320	231.02	1	1
	IBPSO	110359	109948.59	109246	222.17	1	1
	NBGSK	108155	106374.74	104159	818.68	t-test              1           1           0           1 </td <td>1</td>	1
	DEHLO2	110202	110108.40	110006	36.40		_
	DEHLO1	110191	110092.18	109992	42.80	1	1
	IAHLO	109213	108875.59	108564	125.81	1	1
5.250.15	SHLO	110136	110005.03	109797	58.11	1	1
5.250.15	MBDE	110175	110078.90	110001	40.38	1	1
	NBDE	109892	109405.00	108941	221.35	1	1
	IBPSO	109885	109526.95	108827	227.84	1	1
	NBGSK	107897	106311.66	103800	828.51	1	1
	DEHLO2	108990	108921.89	108852	29.26		—
	DEHLO1	109002	108905.32	108811	33.75	1	1
	IAHLO	107916	107558.11	107196	146.05	1	1
5.250.16	SHLO	108987	108837.38	108712	52.22	1	1
5.250.10	MBDE	109002	108914.46	108837	25.72	1	0
	NBDE	108638	108251.11	107792	185.92	1	1
	IBPSO	108741	108383.70	107829	186.15	1	1
	NBGSK	106606	105029.12	103040	813.45	1	1
	DEHLO2	108978	108880.64	108798	38.02	_	—
5 250 17	DEHLO1	108979	108875.64	108794	40.73	0	0
	IAHLO	107931	107553.41	107164	154.42	1	1
	SHLO	108942	108807.05	108662	58.16	1	1
5.250.17	MBDE	108931	108861.85	108756	33.72	1	1
	NBDE	108555	108011.37	107658	197.88	1	1
	IBPSO	108695	108306.38	107821	190.34	1	1
	NBGSK	106414	104892.29	102497	910.07	1	1
	DEHLO2	109944	109831.24	109759	33.43	_	_
	DEHLO1	109908	109821.03	109746	37.57	0	0
	IAHLO	109171	108759.55	108514	122.98	1	1
5 250 18	SHLO	109858	109722.03	109575	62.95	1	1
5.250.18	MBDE	109956	109814.82	109654	57.86	1	1
	NBDE	109703	109325.19	108829	164.61	1	1
	IBPSO	109647	109241.38	108573	212.85	1	1
	NBGSK	108304	106184.02	103343	1013.96	1	1
	DEHLO2	107023	106945.49	106871	27.69	—	—
	DEHLO1	106999	106927.56	106833	27.89	1	1
	IAHLO	106167	105667.04	105270	154.47	1	1
5 250 10	SHLO	107009	106872.17	106786	49.62	1	1
5.250.19	MBDE	107023	106952.87	106844	27.00	0	0
	NBDE	106694	106226.87	105724	248.58	1	1
	IBPSO	106679	106364.73	105897	181.83	1	1
	NBGSK	104423	102663.29	99947	962.96	1	1
	DEHLO2	149623	149543.31	149484	29.41	_	_
	DEHLO1	149634	149533.39	149468	34.64	1	1
	IAHLO	148681	148320.02	147978	140.74	1	1
5.250.20	SHLO	149573	149470.07	149382	41.14	1	1
5.250.14 5.250.15 5.250.16 5.250.17 5.250.18 5.250.19 5.250.20	MBDE	149539	149342.64	149032	110.93	1	1
	NBDE	148884	148622.34	148307	123.10	1	1
	IBPSO	149306	148955.74	148331	181.61	1	1
	NBGSK	147760	146521.63	143993	672.83	1	1

TABLE 2: Continued.

Problem	Algorithm	Best	Mean	Worst	Std	<i>t</i> -test	W-test
	DEHLO2	155940	155897.43	155838	23.65	_	_
	DEHLO1	155944	155875.40	155806	30.46	1	1
	IAHLO	155065	154738.49	154326	144.47	1	1
5 250 21	SHLO	155890	155820.99	155677	41.30	1	1
5.250.21	MBDE	155898	155721.54	155461	99.55	1	1
	NBDE	155431	155258.09	154912	91.96	1	1
	IBPSO	155691	155382.19	154855	175.20	1	1
	NBGSK	154255	152302.20	150353	840.25	1	1
	DEHLO2	149301	149239.94	149187	27.44	_	_
	DEHLO1	149301	149218.06	149147	32.76	1	1
	IAHLO	148471	148143.82	147699	146.26	1	1
	SHLO	149301	149172.26	149075	45.63	1	1
5.250.22	MBDE	149229	149013.95	148749	114.15	1	1
	NBDE	148639	148381.64	147994	137.00	1	1
	IBPSO	149091	148772.64	148339	160.97	1	1
	NBGSK	147441	146336.57	144699	605.23	1	1
	DEHLO2	152130	152084.27	152009	20.64	_	
	DEHLO1	152124	152070.18	151999	24.23	1	1
	IAHLO	151098	150707.83	150292	169.01	1	1
	SHLO	152114	152007.41	151871	49.62	1	1
5.250.23	MBDE	152073	151899.50	151719	90.65	1	1
	NBDE	151686	151389.37	150953	159.61	1	1
	IBPSO	151898	151463.97	151054	178.66	1	1
	NBGSK	150151	148785.67	146882	693.66	1	1
	DEHLO2	150353	150297.60	150229	20.04		
	DEHLO2	150353	150297.00	150120	20.04	1	1
	IAHLO	149405	148986 69	148598	153.20	1	1
	SHLO	150310	150235.86	150136	40.98	1	1
5.250.24	MBDF	150353	150096 92	149785	137.68	1	1
	NBDE	149678	149484 92	149221	103 73	1	1
	IBPSO	150095	149672 29	148886	212.06	1	1
	NBGSK	148524	146966 44	145005	709.20	1	1
	DEULO2	150045	140078 52	140970	21.02	-	-
	DEHLO2	150045	149976.32	149070	31.92	1	1
	IAHLO	1/03/08	149934.31	149000	131 50	1	1
	SHLO	149308	140912.90	140032	53.00	1	1
5.250.25	MBDE	149983	149371.30	149720	99.89	1	1
	NRDE	149918	149742.00	149387	83.20	1	1
	IRPSO	149895	149532.97	148973	165 35	1	1
	NBGSK	148482	147229.26	144434	827.86	1	1
	DELILO2	149574	149507.40	149446	24.57	1	1
	DEHLO2	140374	140307.49	140440	24.37	1	1
	LAHLO	146555	140499.03	140423	20.71	1	1
	SHLO	147704	14/410.29	14/0/0	140.90	1	1
5.250.26	MEDE	146542	140445.75	148500	40.51	1	1
	NEDE	140312	140302.40	140147	106.02	1	1
	IBDSO	148199	14/9/2.0/	147518	206.74	1	1
	NBGSK	146709	145373 45	147318	782.85	1	1
	DELLO	140707	140746.07	140714	14.04	1	1
	DEHLO2	149/6/	149/40.9/	149/14	14.04	1	
	DEFILUI	149/82	149/30.//	147030	20.57	1	1
	IATLU	148940	1404004.25	14/929	100./0	1	1
5.250.27	SULO	149/0/	149094.33	1493/9	30.13 102.60	1	1
	NDDE	147/0/	147323.3U	14723/	105.00	1	1
	INDUE	140629	140001.80	140000	100.00	1	1
	IDPSU NRCSV	149028 147575	147230./2	140//3	1/2./3	1	1
	NDG3N	14/3/3	140080.00	144103	//1.83	1	1

TABLE 2: Continued.

Problem	Algorithm	Best	Mean	Worst	Std	<i>t</i> -test	W-test
5.250.28	DEHLO2	155075	155012.04	154961	25.70	_	_
	DEHLO1	155075	154993.48	154914	31.91	1	1
	IAHLO	154135	153707.79	153291	165.97	1	1
	SHLO	155029	154927.58	154814	38.04	1	1
5.250.28	MBDE	155032	154900.12	154715	69.24	1	1
	NBDE	154664	154414.09	153963	144.58	1	1
	IBPSO	154806	154514.11	153986	160.66	1	1
	NBGSK	153292	151840.26	149513	704.28	1	1
	DEHLO2	154668	154640.60	154590	17.70	_	_
	DEHLO1	154668	154623.56	154542	21.97	1	1
	IAHLO	153751	153406.13	153011	140.95	1	1
5 250 20	SHLO	154668	154562.83	154434	52.21	1	1
5.250.29	MBDE	154653	154460.96	154239	76.42	1	1
	NBDE	154298	154056.73	153720	108.12	1	1
	IBPSO	154641	154136.17	153595	209.88	1	1
	NBGSK	152952	151403.32	148808	859.73	1	1

TABLE 2: Continued.

TABLE 3: The summary results of the *t*-test and W-test on multidimensional knapsack problems.

Metric	DEHLO2	DEHLO1	IAHLO	SHLO	MBDE	NBDE	IBPSO	NBGSK
	1	21	30	30	24	30	30	30
<i>t</i> -test	0	9	0	0	6	0	0	0
	-1	0	0	0	0	0	0	0
W-test	1	21	30	30	23	30	30	30
	0	9	0	0	7	0	0	0
	-1	0	0	0	0	0	0	0

TABLE 4: The multidimensional knapsack problem benchmarks.

Benchmark NO.	Benchmark name	Best known	п	М
1	mknapcb1-5.100-00	244381	100	5
2	mknapcb1-5.100-01	24274	100	5
3	mknapcb2-5.250-00	59312	250	5
4	mknapcb2-5.250-01	61472	250	5
5	mknapcb3-5.500-00	120130	500	5
6	mknapcb3-5.500-01	117837	500	5
7	mknapcb4-10.100-00	23064	100	10
8	mknapcb4-10.100-01	22801	100	10
9	mknapcb5–10.250–00	59187	250	10
10	mknapcb5-10.250-01	58662	250	10
11	mknapcb6–10.500–00	117726	500	10
12	mknapcb6-10.500-01	119139	500	10
13	mknapcb8-30.250-29	150038	250	30
14	mknapcb9-30.500-29	301021	500	30

TABLE 5: The results of all algorithms on the multidimensic	onal knapsack problems.
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Problem	Algorithm	Best	Mean	Worst	Std	<i>t</i> -test	W-test
	DEHLO2	24381	24373.92	24337	8.95	_	_
	DEHLO1	24381	24364.37	24315	18.76	1	1
	IAHLO	24381	24297.24	24187	41.30	1	1
NO 1	SHLO	24357	24347.09	24292	14.41	1	1
NO.I	MBDE	24332	24327.72	24288	6.59	1	1
	NBDE	24381	24285.06	24185	42.22	1	1
	IBPSO	24381	24177.04	23862	106.18	1	1
	NBGSK	24047	23721.87	23395	140.08	1	1

Problem	Algorithm	Best	Mean	Worst	Std	<i>t</i> -test	W-test
	DEHLO2	24274	24274.00	24274	0.00	_	_
NO.2	DEHLO1	24274	24262.90	24149	35.50	1	1
	IAHLO	24274	24136.40	23911	89.93	1	1
	SHLO	24250	24243.75	24125	27.38	1	1
	MBDE	24225	24222.67	24101	16.43	1	1
	NBDE	24274	24194.46	23878	95.50	1	1
	IBPSO	24274	23964.76	23575	143.60	1	1
	NBGSK	23893	23388.82	22930	174.22	1	1
NO.3	DEHLO2	59208	59071.35	58968	45.81	_	_
	DEHLO1	59196	59054.47	58941	46.52	1	1
	IAHLO	58541	58145.82	57831	130.21	1	1
	SHLO	59170	58990.19	58845	65.47	1	1
	MBDE	58900	58765.98	58643	47.17	1	1
	NBDE	58745	58269.03	57715	229.58	1	1
	IBPSO	58935	58521.45	57942	188.27	1	1
	NBGSK	57486	56579.44	55336	411.20	1	1
	DEHLO2	61446	61381.94	61268	50.44	—	_
	DEHLO1	61377	61308.04	61209	46.25	1	1
	IAHLO	60550	60117.68	59695	158.28	1	1
NO 4	SHLO	61435	61274.52	61138	62.09	1	1
110.1	MBDE	61139	61096.41	60969	40.32	1	1
	NBDE	61078	60269.88	59566	380.60	1	1
	IBPSO	61213	60795.96	60073	214.59	1	1
	NBGSK	59324	58075.21	56888	516.38	1	1
	DEHLO2	119661	119457.17	119243	75.81	—	
	DEHLO1	119588	119409.80	119223	80.53	0	0
	IAHLO	116330	115483.56	114961	249.75	1	1
NO.5	SHLO	119582	119303.70	119008	110.02	1	1
	MBDE	119372	119153.95	118985	93.96	1	1
	NBDE	116080	115220.19	114501	406.61	l	1
	IBPSO	118959	118292.17	117429	361.22	1	1
	NBG5K	115208	112449.12	111021	919.05	1	1
	DEHLO2	117579	117494.62	117356	44.63	_	_
	DEHLOI	11/662	117498.59	117359	54.85	1	1
	IAHLO	11464/	113959.66	113396	248.20	1	1
NO.6	SHLO	11/543	11/345./4	117099	89.98	1	1
	NPDE	11/501	11/320.38	11/141	80.33	1	1
	IRDSO	115477	115941.65	112633	330.61	1	1
	NBGSK	113416	111349 51	109234	887 34	1	1
	DEULOY	22064	22054.01	22026	2 10	1	1
NO.7	DEHLO2 DEHLO1	23064	23034.91	23020	5.19	0	1
	LAHLO	23057	23032.37	22939	36.68	0	1
	SHLO	23041	23040.13	22901	1 17	1	1
	MBDF	23018	23009 34	23009	1.17	1	1
	NBDE	23064	23029 70	22845	51 32	1	1
	IBPSO	23055	22863.90	22574	117.69	1	1
	NBGSK	22876	22593.57	22282	113.85	1	1
NO.8	DEHLO2	22801	22714.70	22541	60.08	_	_
	DEHLO1	22801	22713.56	22547	60.03	0	0
	IAHLO	22739	22517.76	22344	78.27	1	1
	SHLO	22801	22690.79	22502	79.50	- 1	1
	MBDE	22755	22666.18	22539	53.80	1	1
	NBDE	22801	22478.81	22323	77.18	1	1
	IBPSO	22725	22386.50	21994	127.65	1	1
	NBGSK	22422	22067.62	21844	113.60	1	1

TABLE 5: Continued.

Problem	Algorithm	Best	Mean	Worst	Std	t-test	W-test
Tioblem	DEHLO2	59071	58853.87	58670	73.36	i test	W test
NO.9	DEHLO2	59071	58706.65	58614	73.30	1	1
	IAHIO	58300	58031 44	57679	128.03	1	1
	SHLO	59071	58768 02	58551	05 55	1	1
	MBDE	58/38	58254.09	58112	53.55	1	1
	NBDE	58410	57849.68	57416	212.08	1	1
	IRDSO	58756	58337 24	57861	182.21	1	1
	NBGSK	57378	56515.92	55741	420.44	1	1
	DELLO	50627	50515.92	50250	420.44	1	1
	DEHLO2	58637	58519.04	58359	62.07		
	DEHLOI	58567	58449.57	58324	53.74	1	1
	IAHLO	57946	5/355.51	57014	155.67	1	1
NO.10	SHLO	58599	58447.36	58292	70.06	1	1
	MBDE	58596	58457.51	58348	54.78	1	1
	NBDE	57715	57135.82	56790	177.76	1	1
	IBPSO	58277	57812.49	57285	209.48	1	1
	NBGSK	56931	55925.43	55228	289.04	1	1
	DEHLO2	117149	116895.63	116606	103.48	_	_
	DEHLO1	117001	116672.01	116433	112.36	1	1
NO 11	IAHLO	114617	114048.13	113553	230.22	1	1
	SHLO	117194	116847.53	116390	130.52	1	1
NO.11	MBDE	116734	116456.38	116209	118.63	1	1
	NBDE	114440	113394.71	112891	300.95	1	1
	IBPSO	116597	115690.33	114316	391.02	1	1
	NBGSK	112953	111386.10	110305	639.62	1	1
	DEHLO2	118732	118554.12	118281	98.71	_	_
	DEHLO1	118663	118426.25	118216	95.64	1	1
	IAHLO	116171	115720.44	115233	236.82	1	1
2010	SHLO	118768	118446.03	118100	122.62	1	1
NO.12	MBDE	118501	118219.57	118029	103.17	1	1
	NBDE	115669	114706.44	114207	314.98	1	1
	IBPSO	118270	117310.97	116181	383.94	1	1
	NBGSK	115125	112837.49	110855	878.62	1	1
	DEHLO2	149595	149437.59	149346	42.40	_	
	DEHLO1	149593	149432.14	149291	49.73	0	0
	IAHLO	148784	148447 93	148047	151.62	1	1
NO.13	SHLO	149496	149374 31	149222	63 78	1	1
	MBDE	149510	149352.93	149270	60.66	1	1
	NBDE	149204	148977.35	148506	128.08	1	1
	IBPSO	149249	148737.54	147408	321.85	1	1
	NBGSK	148428	146898.01	144999	821.84	1	1
NO.14	DEHLOY	200152	200021.22	200756	60.22	-	
	DEHLO1	300093	299931.22	299730	08.23 87.60	1	1
		205770	299009.33	299704	07.09 267.14	1	1
	SULO	293//9	273030.14	274131	30/.14 117.60	1	1
	SULO	200107	277//0.00	277404	11/.09	1	1
	NDDE	208060	277024./0	277070	/1.82	1	1
	INDUE	298900	270177.47	293981	000.02 726.00	1	1
	IDP3U NRCCV	277270	270333.03	290002	/ JO.77 JJ10 E0	1	1
	NDG2K	2903/3	293231.03	20/009	2210.38	1	1

TABLE 5: Continued.

TABLE 6: The summary results of the *t*-test and W-test on multidimensional knapsack problems.

Metric	DEHLO2	DEHLO1	IAHLO	SHLO	MBDE	NBDE	IBPSO	NBGSK
	1	10	14	14	14	14	14	14
t-test	0	4	0	0	0	0	0	0
	-1	0	0	0	0	0	0	0
W-test	1	11	14	14	14	14	14	14
	0	3	0	0	0	0	0	0
	-1	0	0	0	0	0	0	0



FIGURE 3: Continued.



FIGURE 3: Continued.



FIGURE 3: The convergence curves of the MKP (maximum generation = 5000).

## 5. Conclusions and Future Work

Human learning optimization is a simplified model of human learning; it develops three learning operators, i.e. the random learning operator, the individual learning operator, and the social learning operator, to search for the optimal solution. However, the standard HLO just learns from the global optimal solution; this is inconsistent with reality. In real life, people can learn from the optimal solution of other individuals. And the operators of Differential Evolution (DE) are updated based on the optimal solution of other individuals. Inspired by this fact, this paper introduces the optimization strategy of MBDE into HLO and presents two novel differential human learning optimization algorithms based on individual and population. To comprehensively and fairly evaluate the performance of proposed algorithms, the multidimensional knapsack problems were adopted as the benchmark problems to test DEHLOs, as well as the standard HLO, MBDE, and other metaheuristics. The experimental results demonstrate that the proposed DEHLOs can utilize the

learning ability of the two algorithms to search for the optimal solution more efficiently and have a robust search ability for different problems.

It is well known that humans can adaptively choose and adjust these approaches to solve problems efficiently and effectively. However, the impact of adaptive learning strategy on algorithm parameters is not considered in this paper. Therefore, one of our future works is to develop adaptive switching learning strategies to better release the power of different learning strategies for different problems, which will be very challenging for future work.

#### **Data Availability**

As the data also form part of an ongoing study, the raw/ processed data required to reproduce these findings cannot be shared at this time.

#### **Conflicts of Interest**

The authors declare that they have no conflicts of interest.

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# Acknowledgments

This work was supported by National Natural Science Foundation of China (nos. 61633016, 92067105, and 61833011), Key Project of Science and Technology Commission of Shanghai Municipality (nos. 16010500300, 19510750300, 19500712300, and 21190780300), Natural Science Research Programme of Colleges and Universities of Anhui Province (nos. KJ2020ZD39 and KJ2021A1025), Open Research Fund of AnHui Key Laboratory of Detection Technology and Energy Saving Devices, AnHui Polytechnic University (nos. DTESD2020A02 and JCKJ2021A05), School-Level Scientific Research Project of Chaohu University (no. XLY-202101), 2021 Discipline Construction Quality Improvement Project of Chaohu University (no. kj21gczx02), and 111 Project under Grant no. D18003. The work of P.M. Pardalos was conducted within the framework of the Basic Research Program at the National Research University Higher School of Economics (HSE).

#### References

- M. M. R. Elsawy, S. Lanteri, R. Duvigneau, J. A. Fan, and P. Genevet, "Numerical optimization methods for Metasurfaces," *Laser & Photonics Reviews*, vol. 14, no. 10, Article ID 1900445, 2020.
- [2] T. Dokeroglu, E. Sevinc, T. Kucukyilmaz, and A. Cosar, "A survey on new generation metaheuristic algorithms," *Computers & Industrial Engineering*, vol. 137, Article ID 106040, 2019.
- [3] P. Hansen, N. Mladenović, and J. A. Moreno Pérez, "Variable neighbourhood search: methods and applications," *Annals of Operations Research*, vol. 175, no. 1, pp. 367–407, 2010.
- [4] J. H. Holland, "Genetic algorithms," Scientific American, vol. 267, no. 1, pp. 66–72, 1992.
- [5] J. Kennedy and R. Eberhart, "Particle swarm optimization,"vol. 4, pp. 1942–1948, in *Proceedings of the ICNN*'95-international conference on neural networks, vol. 4, pp. 1942–1948, IEEE, Perth, Australia, August 1995.
- [6] Z. W. Geem, J. H. Kim, and G. V. Loganathan, "A new heuristic optimization algorithm: harmony search," *Simulation*, vol. 76, no. 2, pp. 60–68, 2001.
- [7] K. Fleetwood, "An Introduction to Differential evolution," in Proceedings of the Mathematics and Statistics of Complex Systems (MASCOS) One Day Symposium, pp. 785–791, Brisbane, Australia, 26th November 2004.
- [8] W. L. Liu, Y. J. Gong, W. N. Chen, Z. Liu, H. Wang, and J. Zhang, "Coordinated charging scheduling of electric vehicles: a mixed-variable differential evolution approach," *IEEE Transactions on Intelligent Transportation Systems*, vol. 21, no. 12, pp. 5094–5109, 2019.
- [9] S. Zhou, L. Xing, X. Zheng, N. Du, L. Wang, and Q. Zhang, "A self-adaptive differential evolution algorithm for scheduling a single batch-processing machine with arbitrary job sizes and release times," *IEEE Transactions on Cybernetics*, vol. 51, no. 3, pp. 1430–1442, 2019.
- [10] F. Zhao, L. Zhao, L. Wang, and H. Song, "An ensemble discrete differential evolution for the distributed blocking flowshop scheduling with minimizing makespan criterion," *Expert Systems with Applications*, vol. 160, Article ID 113678, 2020.

- [11] D. Karaboga and B. Basturk, "On the performance of artificial bee colony (ABC) algorithm," *Applied Soft Computing*, vol. 8, no. 1, pp. 687–697, 2008.
- [12] W.-T. Pan, "A new fruit fly optimization algorithm: Taking the financial distress model as an example," *Knowledge-Based Systems*, vol. 26, pp. 69–74, 2012.
- [13] B. H. Abed-alguni and M. Barhoush, "Distributed grey wolf optimizer for numerical optimization problems," *Jordanian J. Comput. Inf. Technol.(JJCIT)*, vol. 4, no. 03, p. 21, 2018.
- [14] G.-G. Wang, "Moth search algorithm: a bio-inspired metaheuristic algorithm for global optimization problems," *Memetic Computing*, vol. 10, no. 2, pp. 151–164, 2018.
- [15] S. Li, H. Chen, M. Wang, A. A. Heidari, and S. Mirjalili, "Slime mould algorithm: a new method for stochastic optimization," *Future Generation Computer Systems*, vol. 111, pp. 300–323, 2020.
- [16] A. W. Mohamed, A. A. Hadi, and A. K. Mohamed, "Gainingsharing knowledge based algorithm for solving optimization problems: a novel nature-inspired algorithm," *International Journal of Machine Learning and Cybernetics*, vol. 11, no. 7, pp. 1501–1529, 2020.
- [17] P. Agrawal, T. Ganesh, and A. W. Mohamed, "Solving knapsack problems using a binary gaining sharing knowledge-based optimization algorithm," *Complex & Intelligent Systems*, vol. 2021, pp. 1–21, 2021.
- [18] B. H. Abed-alguni, N. A. Alawad, M. Barhoush, and R. Hammad, "Exploratory cuckoo search for solving singleobjective optimization problems," *Soft Computing*, vol. 25, no. 15, pp. 10167–10180, 2021.
- [19] N. A. Alawad and B. H. Abed-alguni, "Discrete Jaya with refraction learning and three mutation methods for the permutation flow shop scheduling problem," *The Journal of Supercomputing*, pp. 1–22, 2021.
- [20] Y. Feng, S. Deb, G.-G. Wang, and A. H. Alavi, "Monarch butterfly optimization: a comprehensive review," *Expert Systems with Applications*, vol. 168, Article ID 114418, 2021.
- [21] Y. Yang, H. Chen, A. A. Heidari, and A. H. Gandomi, "Hunger games search: Visions, conception, implementation, deep analysis, perspectives, and towards performance shifts," *Expert Systems with Applications*, vol. 177, Article ID 114864, 2021.
- [22] I. Ahmadianfar, A. A. Heidari, A. H. Gandomi, X. Chu, and H. Chen, "RUN beyond the metaphor: an efficient optimization algorithm based on Runge Kutta method," *Expert Systems with Applications*, vol. 181, Article ID 115079, 2021.
- [23] H. Chen, A. A. Heidari, H. Chen, M. Wang, Z. Pan, and A. H. Gandomi, "Multi-population differential evolutionassisted Harris hawks optimization: framework and case studies," *Future Generation Computer Systems*, vol. 111, pp. 175–198, 2020.
- [24] B. H. Nguyen, B. Xue, and M. Zhang, "A survey on swarm intelligence approaches to feature selection in data mining," *Swarm and Evolutionary Computation*, vol. 54, Article ID 100663, 2020.
- [25] P. Agrawal, H. F. Abutarboush, T. Ganesh, and A. W. Mohamed, "Metaheuristic algorithms on feature selection: a survey of one decade of Research (2009-2019)," *IEEE Access*, vol. 9, pp. 26766–26791, 2021.
- [26] P. Agrawal, T. Ganesh, and A. W. Mohamed, "Chaotic gaining sharing knowledge-based optimization algorithm: an improved metaheuristic algorithm for feature selection," *Soft Computing*, vol. 25, no. 14, pp. 9505–9528, 2021.
- [27] P. Agrawal, T. Ganesh, and A. W. Mohamed, "A novel binary gaining-sharing knowledge-based optimization algorithm for

feature selection," Neural Computing & Applications, vol. 33, no. 11, pp. 5989–6008, 2021.

- [28] P. Agrawal, T. Ganesh, D. Oliva, and A. W. Mohamed, "Sshaped and V-shaped gaining-sharing knowledge-based algorithm for feature selection," *Applied Intelligence*, vol. 52, no. 1, pp. 81–112, 2022.
- [29] Y. Li, L. Jiao, R. Shang, and R. Stolkin, "Dynamic-context cooperative quantum-behaved particle swarm optimization based on multilevel thresholding applied to medical image segmentation," *Information Sciences*, vol. 294, pp. 408–422, 2015.
- [30] M. J. Neath, A. K. Swain, U. K. Madawala, and D. J. Thrimawithana, "An optimal PID controller for a bidirectional inductive power transfer system using multiobjective genetic algorithm," *IEEE Transactions on Power Electronics*, vol. 29, no. 3, pp. 1523–1531, 2013.
- [31] F. Zhao, X. He, and L. Wang, "A two-stage cooperative evolutionary algorithm with problem-specific knowledge for energy-efficient scheduling of no-wait flow-shop problem," *IEEE Transactions on Cybernetics*, vol. 51, no. 11, pp. 5291– 5303, 2020.
- [32] F. Zhao, R. Ma, and L. Wang, "A self-learning discrete jaya algorithm for multiobjective energy-efficient distributed noidle flow-shop scheduling problem in heterogeneous factory system," *IEEE Transactions on Cybernetics*, 2021.
- [33] J. M. Lanza-Gutierrez, J. A. Gomez-Pulido, and M. A. Vega-Rodriguez, "A parallel evolutionary approach to solve the relay node placement problem in wireless sensor networks," in *Proceedings of the 15th Annual Conference on Genetic and Evolutionary Computation*, pp. 1157–1164, New York, July 2013.
- [34] L. Wang, H. Ni, R. Yang, M. Fei, and W. Ye, "A Simple human learning optimization algorithm," *Communications in Computer and Information Science*, vol. 2014, pp. 56–65, 2014.
- [35] L. Wang, H. Ni, R. Yang, P. M. Pardalos, X. Du, and M. Fei, "An adaptive simplified human learning optimization algorithm," *Information Sciences*, vol. 320, pp. 126–139, 2015.
- [36] R. Yang, M. Xu, J. He, S. Ranshous, and N. F. Samatova, "An intelligent weighted Fuzzy time Series model based on a sinecosine adaptive human learning optimization algorithm and its application to financial markets forecasting," Advanced Data Mining and Applications, vol. 2017, pp. 595–607, 2017.
- [37] L. Wang, J. Pei, Y. Wen, J. Pi, M. Fei, and P. M. Pardalos, "An improved adaptive human learning algorithm for engineering optimization," *Applied Soft Computing*, vol. 71, pp. 894–904, 2018.
- [38] L. Wang, L. An, J. Pi, M. Fei, and P. M. Pardalos, "A diverse human learning optimization algorithm," *Journal of Global Optimization*, vol. 67, no. 1-2, pp. 283–323, 2017.
- [39] L. Wang, J. Pei, M. I. Menhas, J. Pi, M. Fei, and P. M. Pardalos, "A hybrid-coded human learning optimization for mixedvariable optimization problems," *Knowledge-Based Systems*, vol. 127, pp. 114–125, 2017.
- [40] L. Wang, R. Yang, H. Ni, W. Ye, M. Fei, and P. M. Pardalos, "A human learning optimization algorithm and its application to multi-dimensional knapsack problems," *Applied Soft Computing*, vol. 34, pp. 736–743, 2015.
- [41] J. Cao, Z. Yan, X. Xu, G. He, and S. Huang, "Optimal power flow calculation in AC/DC hybrid power system based on adaptive simplified human learning optimization algorithm," *Journal of Modern Power Systems and Clean Energy*, vol. 4, no. 4, pp. 690–701, 2016.
- [42] R. Alguliyev, R. Aliguliyev, and N. Isazade, "A Sentence Selection Model and HLO Algorithm for Extractive Text

summarization," in Proceedings of the 2016 IEEE 10th International Conference on Application of Information and Communication Technologies (AICT), pp. 1–4, IEEE, Baku, Azerbaijan, October 2016.

- [43] R. Yang, J. He, M. Xu, H. Ni, P. Jones, and N. Samatova, "An intelligent and hybrid weighted fuzzy time series model based on empirical mode decomposition for financial markets forecasting," *Advances in Data Mining. Applications and Theoretical Aspects*, Springer, Cham, pp. 104–118, 2018.
- [44] P. Zhang, M. Fei, L. Wang, C. Peng, and W. Zhou, "Identification method for furnace flame based on adaptive color model (in Chinese)," *Sci Sin Inform*, vol. 48, no. 7, pp. 1–15, 2018.
- [45] W. Fan, J. Pei, X. Liu, P. M. Pardalos, and M. Kong, "Serialbatching group scheduling with release times and the combined effects of deterioration and truncated job-dependent learning," *Journal of Global Optimization*, vol. 71, no. 1, pp. 147–163, 2018.
- [46] Z. Han, H. Qi, L. Wang, M. I. Menhas, and M. Fei, "Water level control of Nuclear power plant Steam generator based on intelligent Virtual Reference Feedback tuning," *Communications in Computer and Information Science*, Springer, Singapore, pp. 14–23, 2018.
- [47] L. Wang, X. Fu, Y. Mao, M. Ilyas Menhas, and M. Fei, "A novel modified binary differential evolution algorithm and its applications," *Neurocomputing*, vol. 98, pp. 55–75, 2012.
- [48] J.-C. Hong, M.-Y. Hwang, K.-H. Tai, Y.-C. Kuo, and P.-C. Lin, "Confusion affects gameplay," *Learning and Individual Differences*, vol. 59, pp. 119–126, 2017.
- [49] T. Stenlund, F. U. Jönsson, and B. Jonsson, "Group discussions and test-enhanced learning: individual learning outcomes and personality characteristics," *Educational Psychology*, vol. 37, no. 2, pp. 145–156, 2017.
- [50] W. Ickes and R. Gonzalez, "Social Cognition and social Cognition," *Small Group Research*, vol. 25, no. 2, pp. 294–315, 1994.
- [51] K. M. Andrews and B. L. Delahaye, "Influences on knowledge processes in organizational learning: the psychosocial filter," *Journal of Management studies*, vol. 37, no. 6, pp. 797–810, 2000.
- [52] R. S Cohen, M. Tse-tung, and J. Struik, "Practice, knowledge, again practice, and again know," For Dirk Struik: Scientific, Historical and Political Essays in Honour of Dirk, vol. 15, p. 37, 1974.
- [53] I. M. Ali, D. Essam, and K. Kasmarik, "Novel binary differential evolution algorithm for knapsack problems," *Information Sciences*, vol. 542, pp. 177–194, 2016.
- [54] B. Ji, X. Lu, G. Sun, W. Zhang, J. Li, and Y. Xiao, "Bio-inspired feature selection: an improved binary particle swarm optimization approach," *IEEE Access*, vol. 8, pp. 85989–86002, 2020.
- [55] K. Deep and J. C. Bansal, "A socio-cognitive particle swarm optimization for multi-dimensional knapsack problem," in *Proceedings of the 2008 First International Conference on Emerging Trends in Engineering and Technology*, vol. 2008, pp. 355–360, Nagpur, India, July 16-18.