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RESEARCH ARTICLE

# A multi-objective improved teaching learning based optimization algorithm for time-cost trade-off problems

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#### Abstract

In this paper, a multi-objective optimization model based on modified adaptive weight approach and improved teaching-learning based optimization (MAWA-ITLBO) algorithm is proposed for the solution of time-cost trade-off problems. The MAWA-ITLBO algorithm is the improved version of basic MAWA-TLBO algorithm by adding the concept of number of teachers as well as adaptive teaching factor. The effects of these parameters in TLBO are investigated in order to demonstrate the variation of the Pareto front solution. Thereby, the performance of the MAWA-ITLBO is compared to the existing methods using a well-known 18-activity benchmark problem. A 63-activity problem is also included in computational experiments to validate the efficiency of the proposed MAWA-ITLBO. The results obtained by using the MAWA-ITLBO are compared with those obtained by using the basic MAWA-TLBO, genetic algorithm (GA), and ant colony optimization (ACO) algorithms. The obtained results demonstrate that the utilized MAWA-ITLBO is able to provide a superior set of Pareto-front solutions than that of previously proposed models.

#### Keywords

Modified Adaptive Weight Approach (MAWA); Teaching-Learning-Based Optimization (TLBO); Adaptive Teaching Factor (ATF); Pareto Front (PF); Number of Teacher (NT)

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#### 1. Introduction

Considering the competitive environment in all industries, construction management is getting to be noticeably essential for the parties. And both the client and contractor look for the best economical scheduling subjected to different parameters such as time, cost and other operational resources. Project scheduling calculations are based on CPM (Critical Path Method). Each activity has a normal duration and a forced duration. Completing an activity in its forced duration needs more direct cost and resources. On the other hand, it leads to decrease project's total duration and indirect costs. The balancing between time and cost of a project is

known as time cost trade-off problems (TCTP) in the literature. Reviewing the literature it is found out that, the solution to TCTP problems has been a challenge to researchers for a long time. Despite the considerable variety of techniques developed in optimization research and other to deal with problem. The disciplines this complexities of its solution calls for alternative approaches such as weighted sum method and nondominating sorting approach have been used to solve the TCTP problems. Moreover, weighted sum method is one of the firstly used methods on solving the time-cost trade off problems.

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The weighted sum method (WSM) aggregates a set of objectives into a single objective by premultiplying each objective with a user-supplied weight [1]. Although the idea is simple, the challenge is determining what values of the weights to use. It depends on the importance of each objective in the context of the problem and also a scaling factor.

Gen and Cheng [2] adopted the Adaptive Weight Approach (AWA) in construction TCO (also referred to as the GC approach hereafter). This approach converts the multiobjective problem to a single-objective problem and then utilizing a single-objective optimization approach to find the satisfactory solution which is known as adaptive weighted approach (AWA). The GC approach overcomes the weakness of weights selection in the conventional sum method. Also, under the four conditions, the Modified Adaptive Weighted Approach (MAWA) is proposed by Zheng et al. [3] and the deficiencies associated with the previous approaches are likely to be minimized.

Numerous studies have focused on achieving the Pareto front for the discrete time-cost trade-off problems. Genetic algorithms [3-4]; and ant colony optimization [5-7] are among the metaheuristic solution procedures proposed for the Pareto front optimization of discrete time-cost trade-off problems.

In recent decades, various modern metaheuristic optimization methods including genetic algorithms, simulated annealing, particle swarm optimization, ant colony optimization, and shuffled frog leaping optimization have been applied for solving TCT problems. Thereby, in this study, TLBO algorithm is applied as an alternative for solving TCTP problems.

TLBO that was proposed by Rao et al [8] simulates the influence of a teacher on the output of learners in a class. It has emerged as one of the simple and efficient techniques for solving single-objective benchmark problems and real life application problems in which it has been empirically shown to perform well on many optimization problems. The basic TLBO algorithm has been already modified by Rao and Patel [9] to

improve its efficiency and applied it to the optimization of thermal systems by introducing the number of teachers and adaptive teaching factor. It is observed that the proposed sole MAWA-TLBO algorithm is not able to find out the optimum solutions for the 18-activity and a more complex 63-activity problems [10]. Thereby, in the present study, number of teacher and adaptive teaching factor on obtaining the Pareto-front solution is also adapted to further investigate the exploration

#### 2. Time – Cost Trade-off Problem (TCTP)

capacity of the proposed algorithm.

TCTP is a bi-objective problem and the balanced relationship between time and cost is called TCT Problem. During planning or in case of a delay, the project manager needs to balance the time and cost of a project to improve the overall efficiency. Therefore, TCTP is adapted to identify the set of time – cost alternatives that will provide the optimal schedule. The time of a project T can be calculated according to the following equation.

$$T = \sum_{i}^{k} t_i^{k} x_i^{k} \tag{1}$$

where n is the number of total activities of a project;  $t_i^k$  is the duration of activity  $t_i^k$  when performing the  $t_i^{th}$  option;  $t_i^k$  is index variable of activity  $t_i^k$  when performing the  $t_i^{th}$  option:

The project duration *T* is calculated by using the critical path method depending on the defined activity relationships for that project. The total cost of a project consists of two parts: direct cost and indirect cost. Direct cost is determined by the sum of direct costs of all activities within a project network. On the other hand, indirect cost depends heavily upon the project duration, i.e., the longer the duration, the higher the indirect cost. The total

cost of a project can be calculated by the following equation:

$$C = \sum_{i}^{k} DC_{i}^{k} x i^{k} + t_{i} x i c_{i}^{k}$$
(3)

where C is the total cost of a project;  $DC_i^k$  is the direct cost of activity i when performing the  $k^{th}$  option;  $x_i^k$  is index variable of activity i when performing the  $k^{th}$  option;  $t_i$  is the duration of activity i;  $t_i^k$  is the indirect cost rate of a project.

### 3. Modified Adaptive Weight Approach (MAWA) in Multi-Objective Optimization

Weighted approach is applied to transform a multiple objective optimization problem to the optimization problem having single objective. Modified adaptive weight approach (MAWA) proposed by Zheng *et al.* [11] is used in this study to solve the multiobjective problem. To identify adaptive weight for each objective, MAWA benefits the information from the existing set of solutions. For MAWA, the formulations are expressed through the following four conditions [11]:

1. For 
$$Z_t^{\max} \neq Z_t^{\min}$$
 and  $Z_c^{\max} \neq Z_c^{\min}$ 

$$v_c = Z_c^{\min} / Z_c^{\max} - Z_c^{\min}$$

$$v_t = Z_t^{\min} / Z_t^{\max} - Z_t^{\min}$$

$$v = v_t + v_c$$
(4)

wt = vt / v

wc = vc / v

2. For 
$$Z_t^{\text{max}} = Z_t^{\text{min}}$$
 and  $Z_c^{\text{max}} = Z_c^{\text{min}}$ 

$$w_t = w_c = 0.5 \tag{5}$$

3. For 
$$Z_t^{\text{max}} = Z_t^{\text{min}}$$
 and  $Z_c^{\text{max}} \neq Z_c^{\text{min}}$ 

$$w_t = 0.9$$
 (6)  $w_c = 0.1$ 

4. For 
$$Z_t^{\text{max}} \neq Z_t^{\text{min}}$$
 and  $Z_c^{\text{max}} = Z_c^{\text{min}}$ 

$$w_t = 0.1$$

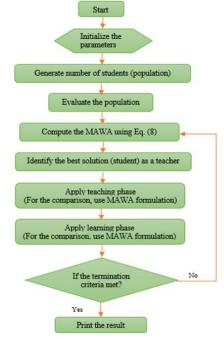
$$w_c = 0.9$$
(7)

where  $Z_t^{\text{max}}$  and  $Z_t^{\text{min}}$  are maximum and minimum values for the objective of project duration,

respectively, in the current iteration. Similarly,  $Z_c^{\max}$  and  $Z_c^{\min}$  are maximum and minimum values for the objective of total direct cost, respectively, in the current iteration.  $v_t$  and  $v_c$  are ratio between the minimum value and difference between maximum and minimum points for the objective project duration and total direct cost, respectively.  $w_c$  is weight for the objective of total direct cost, and  $w_t$  is weight for the objective of time. These weights adjust itself with adaptive manner. It means that their values changes depending on the performance of the current population. According to MAWA, the following equation is evaluated to assign fitness to each solution:

$$f(x) = w_t \frac{Z_t - Z_t^{\min} + r}{Z_t^{\max} - Z_t^{\min} + r} + w_c \frac{Z_c - Z_c^{\min} + r}{Z_c^{\max} - Z_c^{\min} + r}$$
(8)

where x shows any candidate solution in the current generation; f(x) is the fitness of that solution;  $Z_c$  and  $Z_t$  represent the total cost and the time of the xth solution, respectively. r is a small positive random number between 0 and 1;  $w_c$ , and  $w_t$  are the adaptive weights for cost and time. To avoid a case of  $Z_c^{max} = Z_c^{min}$  or  $Z_t^{max} = Z_t^{min}$ , r is added in Eq. (8), [11]. The flowchart of the process can be seen in Fig. 1.



**Fig 1.** Flowchart of the MAWA-TLBO algorithm for TCTP

#### 4. Multi-objective improved TLBO algorithm

In the basic MAWA-TLBO algorithm, the output of the students is enhanced either by a teacher or by interaction among themselves. However, in the MAWA-ITLBO algorithm, this is done by introducing more than one teacher to the students. Furthermore, teaching factor is also improved to adaptive teaching factor.

### 4.1. Number of teachers

In the core TLBO, there is only one teacher, who teaches the students and struggles to raise their knowledge. This portion goes through the enhancement in TLBO by offering number of teachers (NT). In this system of learning, the whole class is isolated into various groups of students as per their levels, and the individual instructor is appointed to each gathering of students. In this way, every teacher attempts to enhance the information of appointed students. The Pseudo code of this modification is given below:

Initialize the population randomly and evaluate the same.

For RN = 1: Number of runs.

Rank the evaluated solutions (In ascending order for the minimization problem and in descending order for the maximization problem)

Select the best solution  $f(X^b)$ . This solution acts as the chief teacher  $(T_I)$  of the class. Mathematically,  $T_I = f(X^b)$  Select the other teachers  $(T_s)$  based on the best solution (i.e.  $f(X^b)$ )

$$T_s = f(X^b) \pm r_i \times f(X^b) \ s = 2, 3, ...,N$$

(Where,  $r_i$  is the random number. If the value of the right side of the above equation is not equal to any of the values of the initially evaluated population then the value closer to that is selected from the initial population). Once, the teachers are identified, distribute the learners to the teachers based on their fitness value (i.e. result) as,

For k = 1 to Population

If 
$$T_1 \le f(X^k) < T_2$$
  
Assign the learner  $f(X^k)$  to teacher  $I$  (i.e  $T_1$ )  
Else If  $T_2 \le f(X^k) < T_3$   
Assign the learner  $f(X^k)$ to teacher  $2$  (i.e  $T_2$ )

Else If  $T_{N-1} \le f(X^k) < T_N$ Assign the learner  $f(X^k)$  to teacher N-I (i.e  $T_{N-I}$ ) Else Assign the learner  $f(X^k)$  to teacher N-I (i.e  $T_{N-I}$ ) Teacher phase Learner phase

End For

#### 4.2. Adaptive teaching factor

In TLBO, the teaching factor value (either one or two) is decided through heuristic step, which means that the learners acquire nothing or all the things taught by the teacher. However, in real practice, learners may learn in any proportion from the teacher. Therefore, teaching factor is improved to adaptive teaching factor (ATF). In the optimization algorithm a lower value of  $T_F$  allows the finer search in small steps but causes slow convergence. A larger value of  $T_F$  accelerates the search but it lowers the exploration capability. Considering this fact the teaching factor is modified as,

$$(T_F)_{s,i} = \left(\frac{f(x^k)}{T_s}\right) \qquad If \ T_s \neq 0 \tag{9}$$

$$(T_F)_1 = 1$$
 If  $T_S = 0$  (10)

where  $f(X^k)$  is the result of any learner k associated with group 's' taking into account all the subjects at iteration i and  $T_s$  is the result of the teacher of the same group at the same iteration i. Therefore, teaching factor in ITLBO algorithm is the ratio of the result of the learner to the result of the teacher during an iteration. The teaching factor varies automatically during the search related to the result of the learner and the teacher. Thus, automatic tuning of  $T_F$  improves the performance of the algorithm.

### 5. Numerical examples

To demonstrate the performance of the utilized MAWA-ITLBO model for obtaining Pareto front solutions of the TCTP, small and medium scale problems taken from the technical literature are investigated. The utilized algorithm was coded in

MATLAB environment implemented on a personal computer having Intel (R) Core (TM) i3 CPU 2.40 GHz and 3GB RAM. Consecutive experimental run number is adopted as 10 for the entire instances.

## 5.1. Empirical example of 18-activity project with five modes

This 18-activity example problem was originally introduced by Feng *et al.* [4]. The network with logical relationship of FS is shown in Fig. 2. The model project includes five construction modes

(options) for some activities, and the activity relationships are presented in Table 1 with corresponding construction time and cost values. The value of \$1500/day is adopted as indirect cost rate for the example.

Comparisons amongst the MAWA-ITLBO with the basic MAWA-TLBO [10], MAWA-GA [3], MAWA-AS [6] and MAWA- SGPU algorithms [7] are presented in Table 2 and Fig. 3 for this model project.

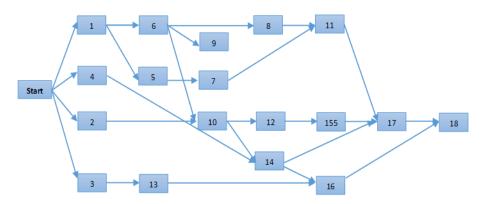


Fig. 2. Network configuration for the model project of 18 activities

**Table 1.** Options for 18- activities project with five modes

		Optio	otion /Mode1 Optio		n/Mode2 Option/Mode3		Option /Mode4		Option /Mode5		
Activity Number	Precedent Activity	Dur. (day)	Direct Cost (\$)	Dur. (day)	Direct Cost (\$)	Dur. (day)	Direct Cost (\$)	Dur. (day)	Direct Cost (\$)	Dur. (day)	Direct Cost (\$)
1	-	14	2400	15	2150	16	2400	21	1500	24	1200
2	-	15	300	18	2400	20	1900	23	1500	25	1000
3	-	15	4500	22	4000	33	1800				
4	-	12	45000	16	35000	20	3200				
5	1	22	20000	24	17500	28	30000	30	10000		
6	1	14	40000	18	32000	24	15000				
7	5	9	30000	15	24000	18	18000				
8	6	14	220	15	21	16	22000	21		24	
9	6	15	300	18	240	20	200	23	208	25	120
10	2,6	15	450	22	400	33	180		150		100
11	7,8	12	450	16	350	20	320				
12	5,9,10	22	2000	24	1750	28	1500	30			
13	3	14	4000	18	3200	24	1800				
14	4,10	9	3000	15	2400	18	2200				
15	12	12	4500	16	3500						
16	13,14	20	3000	22	2000	24	1750	28	1500	30	1000
17	11,14,15	14	4000	18	3200	24	1800				1200
18	16,17	9	3000	15	2400	18	2200				1000

Description	MAWA-GA [3]		MAWA-ACS [7]		MAWA-AS [6]		MAWA-TLBO [10]		MAWA-ITLBO (This study)	
	Time (day)	Cost (\$)	Time (day)	Cost (\$)	Time (day)	Cost (\$)	Time (day)	Cost (\$)	Time (day)	Cost (\$)
Best results	100	287720	100	285400	100	286670	100	283420	100	283320
obtained from the	101	284020	101	282508	101	281300	101	281200	101	279820
models (with indirect cost	104	280020	104	277200	104	277265	104	277170	104	276320
=\$1500)	110	273720	110	273165	110	272265	110	273470	110	271270
Pop. Num	50		10		50		40		40	
Num. of iteration	500		200		400		70		70	
NFE = f-count	25000		2000		20000		5640		5640	

**Table 2.** Comparison between different algorithms of 18-activity project with five modes

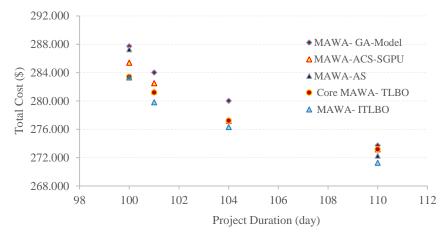


Fig. 3. Comparison of Pareto front between different algorithms for 18-activity TCT problem

It can be seen from Table 2, MAWA-ITLBO based model is executed with less size of population and number of iteration than those of the MAWA-GA and MAWA-AS models. Also, it is noticeable that the MAWA-ITLBO based model offers a more optimal cost value with the same project completion time. For example, for 100 days, the cost of solution obtained by the MAWA-ITLBO is \$283320 while MAWA-GA model cost is to \$287720. This results in a saving of \$4300 which is equivalent to 1.50% of the total cost. Although none of the existing studies achieve the optimal solutions, the proposed MAWA-ITLBO could obtain the optimal solutions for the first time in the literature. Thereby, comparing TLBO with the contemporary methods reveal that proposed TLBO is among the most suitable algorithms for providing optimal Pareto-

front solutions of the more complex small-scale TCTPs.

Pareto front graphical representations of the current examined problem is given in Fig. 4. From the Fig. 4 it is clear that the global optimum solutions are achieved in the 1<sup>th</sup> run analysis.

### 5.2. Empirical example of 63-activities project

To exhibit the performance of improved TLBO integrated with modified adaptive weighting approach on a construction project consisting more than 18 activities, a more comples project with 63 activities taken from the literature [12] is reinvestigated by MAWA-ITLBO. The activity-on-node diagram for the project is presented in Fig. 5, and time—cost optional modes are given in Table 3. The costs in Table 3 are given in US Dollars, and the durations are given in days.

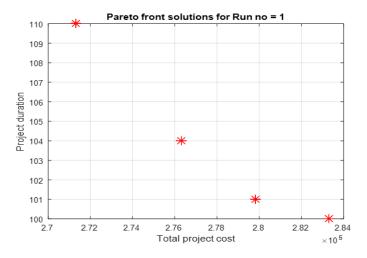


Fig. 4. Pareto optimal solutions of 18 activity problem obtained by MAWA-ITLBO

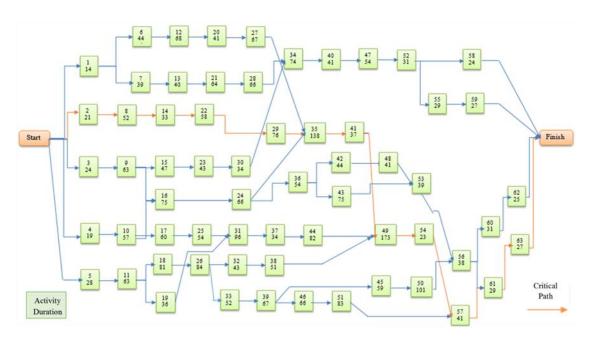


Fig. 5. Network representation of the 63 activity network

Activities of the model project have several different construction modes. For example, two activities consist of three modes, 15 activities have four modes, and 46 activities have five modes. For the project, according to given construction modes for each activity, totally 1.4E+42 time-cost alternatives are possible. The project was investigated in two cases: in the first case (63a), the indirect cost is taken as \$2300/day, while it is

adopted as \$3500/day in the second case (63b). The optimal solutions of 630days, \$5,421,120 for 63a and 621days, \$6,176,170 for 63b had been originally provided by Bettemir [12] using integer programming. Bettemir [12] utilized eight metaheuristic algorithms out of which three core algorithms and five hybrid algorithms incorporating with the non-dominating sorting approach to solve the 63-activity TCTP problem.

**Table 3.** Data for the 63-activity TCT problem

		Option / Mode 1		Option / Mode 2		Option / Mode 3		Option / Mode 4		Option / Mode 5	
Activity Number	Precedent Activity	Dur	Cost								
		(days)	(\$)								
1	-	14	3700	12	4250	10	5400	9	6250		
2	-	21	11250	18	14800	17	16200	15	19650		
3	-	24	22450	22	24900	19	27950	17	31650		
4	-	19	17800	17	19400	15	21600	-			
5	-	28	31180	26	34200	23	38250	21	41400		
6	1	44	54260	42	58450	38	63225	35	68150		
7	1	39	47600	36	50750	33	54800	30	59750		
8	2	52	62140	47	69700	44	72600	39	81750		
9	3	63	72750	59	79450	55	86250	51	91500	49	99500
10	4	57	66500	53	70250	50	75800	46	80750	41	86450
11	5	63	83100	59	89450	55	97800	50	104250	45	112400
12	6	68	75500	62	82000	58	87500	53	91800	49	96550
13	7	40	34250	37	38500	33	43950	31	48750		
14	8	33	52750	30	58450	27	63400	25	66250		
15	9	47	38140	40	41500	35	47650	32	54100		
16	9,10	75	94600	70	101250	66	112750	61	124500	57	132850
17	10	60	78450	55	84500	49	91250	47	94640		
18	10, 11	81	127150	73	143250	66	154600	47	161900		
19	11	36	82500	34	94800	30	101700	-			
20	12	41	48350	37	53250	34	59450	32	66800		
21	13	64	85250	60	92600	57	99800	53	107500	49	113750
22	14	58	74250	53	79100	50	86700	47	91500	42	97400
23	15	43	66450	41	69800	37	75800	33	81400	30	88450
24	16	66	72500	62	78500	58	83700	53	89350	49	96400
25	17	54	66650	50	70100	47	74800	43	79500	40	86800
26	18	84	93500	79	102500	73	111250	68	119750	62	128500
27	20	67	78500	60	86450	57	89100	56	91500	53	94750
28	21	66	85000	63	89750	60	92500	58	96800	54	100500
29	22	76	92700	71	98500	67	104600	64	109900	60	115600
30	23	34	27500	32	29800	29	31750	27	33800	26	36200
31	19, 25	96	145000	89	154800	83	168650	77	179500	72	189100
32	26	43	43150	40	48300	37	51450	35	54600	33	61450
33	26	52	61250	49	64350	44	68750	41	74500	38	79500
34	28, 30	74	89250	71	93800	66	99750	62	105100	57	114250
35	24, 27, 29	138	183000	126	201500	115	238000	103	283750	98	297500
36	24	54	47500	49	50750	42	56800	38	62750	33	68250
37	31	34	22500	32	24100	29	26750	27	29800	24	31600
38	32	51	61250	47	65800	44	71250	41	76500	38	80400
39	33	67	81150	61	87600	57	92100	52	97450	49	102800
40	34	41	45250	39	48400	36	51200	33	54700	31	58200
41	35	37	17500	31	21200	27	26850	23	32300		
42	36	44	36400	41	39750	38	42800	32	48300	30	50250

Table 3.	Cont'd										
43	36	75	66800	69	71200	63	76400	59	81300	54	86200
44	37	82	102750	76	109500	70	127000	66	136800	63	146000
45	39	59	847500	55	91400	51	101300	47	126500	43	142750
46	39	66	94250	63	99500	59	108250	55	118500	50	136000
47	40	54	73500	51	78500	47	83600	44	88700	41	93400
48	42	41	36750	39	39800	37	43800	34	48500	31	53950
49	38, 41, 44	173	267500	159	289700	147	312000	138	352500	121	397750
50	45	101	47800	74	61300	63	76800	49	91500		
51	46	83	84600	77	93650	72	98500	65	104600	61	113200
52	47	31	23150	28	27600	26	29800	24	32750	21	35200
53	43, 48	39	31500	36	34250	33	37800	29	41250	26	44600
54	49	23	16500	22	17800	21	19750	20	21200	18	24300
55	52, 53	29	23400	27	25250	26	26900	24	29400	22	32500
56	50, 53	38	41250	35	44650	33	47800	31	51400	29	55450
57	51, 54	41	37800	38	41250	35	45600	32	49750	30	53400
58	52	24	12500	22	13600	20	15250	18	16800	16	19450
59	55	27	34600	24	37500	22	41250	19	46750	17	50750
60	56	31	28500	29	30500	27	33250	25	38000	21	43800
61	56, 57	29	22500	27	24750	25	27250	22	29800	20	33500
62	60	25	38750	23	41200	21	44750	19	49800	17	51100
63	61	27	9500	26	9700	25	10100	24	10800	22	12700

The MAWA-ITLBO searched 48120 (= 120 x 200 x 2 + 120) possible different schedules, only searching a negligible portion of the solution space [48120/1.4E+42] could generate the Pareto front solutions where number of population and iteration are 120 and 200, respectively.

Therefore, number of function evaluations is 48120, and the APD values are %1.998 and %0.557 respectively. It can be stated that the proposed MAWA-ITLBO model requires less the size of population and number of iteration than those of the basic MAWA-TLBO and the other models.

Considering the solutions obtained it can be concluded that the proposed MAWA-ITLBO model in this study produces satisfactory results for both 63a and 63b cases. Depending up on this result, and referring on Tables 4-5, it can be stated that MAWA-ITLBO could achieve better solutions than MAWA-TLBO, MAWA-GA [13] and MAWA-PSO [13] for both 63a and 63b cases. MAWA-ITLBO model produces alternatives Pareto front solutions for the first time in the literature.

Table 6 illustrates Pareto front results of ten consecutive experimental runs with corresponding average percent deviations (%APD) from the optima.

#### 6. Conclusion

In this paper, a multiobjective optimization model called as MAWA-ITLBO has been proposed to optimize the total project duration and total cost simultaneously for construction project. The largest model project practiced using metaheuristic algorithms integrated with MAWA approach was the project with 18-activities. None of the previous studies could achieve the global optimal solution with modified adaptive weight approach. However, in the current study, the exploration capacity of the algorithm has improved by means of the multiteacher and adaptive teaching factor strategies and could obtain the global optimal solutions for the first time in the literature. From the results, it is clear that the applied MAWA-ITLBO algorithm is proficient of finding global optimum solutions for the small e.g. 18-activity problems.

**Table 4.** Analysis results of 63a -Activity project for the Case 1 (daily indirect cost of \$2300)

Search no	MAWA-GA [13]		MAWA-PSO [13]		MAWA-TLBO [10]		MAWA-ITLBO (This study)	
	Dur	Cost	Dur	Cost	Dur	Cost	Dur	Cost
1	519	5825480	602	5920580	629	5613820	629	5587780
2	528	5687020	620	5904125	614	5644640	614	5491920
3	522	5725380	594	5701200	630	5600190	612	5499090
4	523	5765800	606	5837980	616	5623260	616	5512835
5	524	5827200	630	5994490	630	5642405	615	5512435
6	516	6052120	617	5925980	637	5637290	611	5515920
7	517	5722600	614	5751470	639	5503940	602	5480820
8	519	5872000	627	5934330	630	5696820	631	5635510
9	519	5818480	610	5924365	627	5588485	626	5529170
10	522	5716980	581	5858295	632	5625310	610	5529120
Populations in an iteration		500		500		180		120
Number of iterations to get the solutions	500			500		450	200	
Number of function evaluation	250000		250000		162180		48120	

Table 5. Analysis results of 63b-Activity project for the Case 2 (daily indirect cost of \$3500)

Search no	MAWA-GA		MAWA-PSO [13]			A-TLBO 10]	MAWA-ITLBO (This study)	
	Dur	Cost	Dur	Cost	Dur	Cost	Dur	Cost
1	521	6350810	615	6951145	630	6291540	630	6278020
2	517	6345370	614	6668150	628	6264970	628	6198070
3	522	6560040	611	6931330	630	6280170	630	6198570
4	513	6435790	620	6572210	637	6262570	637	6232860
5	529	6471800	619	6441665	625	6292850	625	6191230
6	524	6538310	619	6549420	613	6261820	633	6210620
7	525	6322020	628	6621405	624	6289790	627	6188140
8	522	6443780	608	6428310	622	6280170	622	6191940
9	521	6410470	617	6582925	636	6280750	636	6201570
10	519	6397730	622	6783495	634	6263980	634	6215160
Populations in an iteration	500		500		180		120	
Number of iterations to get the solutions	500		500		450		200	
Number of function evaluation	250000		250000		162180		48120	

**Table 6.** Average deviations from the optima for problems 63a and 63b.

Aloosithma	63a	APD (%)	63b	APD (%)	
Algorithms	No of Runs	APD (%)	No of Runs		
MAWA-GA [13]	10	7.013	10	4.071	
MAWA-PSO [13]	10	8.378	10	7.721	
MAWA-TLBO [10]	10	3.528	10	1.630	
MAWA-ITLBO (This paper)	10	1.998	10	0.557	

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