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AN APPLIED GREY WOLF OPTIMIZER FOR SCHEDULING CONSTRUCTION PROJECTS

Trinh Thi Trang[1*], Nguyen Luong Hai[2]

[1]Campus in Ho Chi Minh City, University of Transport and Communications, No 450-451 Le Van Viet Street, Ho Chi Minh, Vietnam.

[2]University of Transport and Communications, No 3 Cau Giay Street, Hanoi, Vietnam

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* *Corresponding author*
Email: trangtt_ph@utc.edu.vn

Abstract. Construction project delay has been reported as a significant cause of the project's failure, which results in cost overrun, thereby decreasing the effectiveness of the project. Therefore, project management has placed much effort in construction works' scheduling to enhance project performance. However, construction schedule has been commonly addressed within traditional methods that rely on project managers' subjective experiences and manually-performed approaches, resulting in time-consuming and inaccurate decision-making. This study is thus aimed to handle these limitations. Using analyses of the Grey Wolf Optimizer (GWO) model, inspired by the leadership hierarchy and hunting mechanism of grey wolves in nature, this study supports reducing the construction time and minimizing the additional construction cost. Furthermore, another computational tool, namely Solver-addins, is also used to verify the reliability of the result. The findings of this study will provide a valuable tool for supporting construction management to deliver projects on time, improving construction project performance

Keywords: project delay, project scheduling, cost overrun, Grey Wolf Optimizer, construction management, project performance.

1. INTRODUCTION

For years, the literature on construction project management has examined critical issues of project failure in terms of project delay and cost overrun [1]. To control the project schedule from the preparation stage, project managers must strive to generate and optimize the project schedule and increase the robustness of this plan based on some methods such as the improved critical chain method, which helps improve the stability of the scheduling plan [2]; a tabu search procedure that generates stable baseline schedules [3]; and Hybrid Grey Wolf Optimizer with Sine Cosine Algorithm that proposes a novel optimization model of construction duration and schedule robustness [4].

However, construction management has also been confronted with shortening the project schedule while ensuring a cost-minimized value, which forces the project managers to dedicate more efforts to optimizing the project schedule and increasing the robustness of the actual project schedule. This situation requires the project managers to both shorten each activity's duration and balance its used resources [5]. To solve this issue, the Solver-addins tool in Excel is known as a computer-aided tool for calculation. However, its limitation is just 200 variables performed [6] and an undefined-solving method (transformation). Another method is using optimization algorithms. As we know, many optimization algorithms have been invented through the extreme development of computer science. These algorithms are based on artificial intelligence that has been opening up potential solutions for optimization problems [7], time-cost optimization in project schedule management in particular. In the last decades, besides classical algorithms such as Particle Swarm Optimization (PSO) [8], Genetic Algorithm (GA) [9], and Simulated Annealing (SA) [10], a series of new evolutionary algorithms have been developed, such as Gravitational Search Algorithm (GSA) [11], Firefly Algorithm (FA) [12], and Bat Algorithm (BA) [13]. These algorithms are capable of obtaining highly competitive optimal solutions compared to traditional algorithms. The Grey Wolf Optimizer (GWO) [14] is also recommended as a potential algorithm for designing optimal systems. Compared to other potential algorithms, GWO can determine global optimization, allows relocating a solution around another in an n-dimensional search space, and requires less memory. Additionally, GWO model is not only flexible and scalable, but it also has a remarkable capability to strike the right balance between exploration and exploitation during the search which leads to favourable convergence and can be applied in different problem-solving situations [15]. This study employs GWO to address the current limitations in optimizing the construction schedule, which also helps introduce advanced methods in construction schedule management in Vietnam.

The study is structured into four sections. First, the study presents an overview of construction project delays in Vietnam. Second, the methodology of GWO model is introduced. Third, the research results describe the case study using both the manually – performed approach and GWO model for reducing the construction works' duration. In the fourth and final section, conclusions are drawn.

2. CONSTRUCTION PROJECT DELAYS IN VIETNAM

In the construction industry, project delays can be defined as the extra time required in the completion of construction activities from its stipulated time in the contract or can be defined as late completion of construction activities to the baseline schedule, directly affecting specified costs. [5]. It also can understand that schedule delays as an activity that extends the time required to deliver the project through additional days of work [16]. Because of the technical-economical features of both construction products and the construction production process, many of these projects have been facing schedule delays, and this problem has been becoming a chronic issue worldwide [17]. Similarly, Vietnamese construction projects have faced up delays and cost overruns regularly [17]. According to a report of the Ministry of Transport to the Congress in May 2020, 6 out of 6 ongoing key projects overrun time and budget. Particularly, Ho Chi Minh City urban railway construction project line 1 (Ben Thanh – Suoi Tien), one of eight government-approved urban railway lines, was kicked off in 2012, and it was expected to be completed by 2016. The project had to be rescheduled for a new operational day at the end of 2020 because of delays, but it has been constructed up till now. Long Le Hoai et al. identified the principal factors that led to this problem consisted of slowness and lack of constraint, incompetence, design, market and estimate, financial capability, government, and worker by studying on time delay and cost overrun of 87 construction projects [18]. Many other studies showed that poor quality of time and schedule management significantly affected the project schedule [19]. Time delays and cost overruns caused some consequences such as project failure, reduction of profit margin, loss of belief of citizens in government-funded projects, etc. [20].

Many difficulties can occur during the execution of a project, so in practice, the initial schedule is likely to be adjusted. Therefore, it is necessary to have better schedule management from early construction project delivery [19]. In Vietnam, drafting the project schedule is still mainly based on traditional methods and the experience of managers [21]. One of the common methods for project scheduling is the critical path method (CPM) using Microsoft Project or WinQSB [22]. When a deviation occurs in the project implementation, adjustments are made based on the ground rules, such as shortening only the activities on the critical path and accelerating activity with a lower cost of acceleration per unit of time [23]. Although this method has initially solved the optimization problem, there are many limitations. For example, many new critical paths can be created during the optimization process, or time-consuming as well as depending on the capacity and experience of the managers. This is an obstacle in the organization and implementation of the project [22]. Recently, several studies have applied optimization algorithms to solve time-cost optimization problems such as Differential Evolution [21] or genetic algorithms binding with penalty functions [22]. The results of these studies showed that the efficiency of their approach was better than that of the traditional method in terms of time and the optimal solution. However, according to the superior performance of GWO as mentioned above, GWO is able to be a potential candidate for solving the time-cost optimizing problem of construction projects associated with actual conditions in Vietnam. Thus, this study proposes an effective method using the global searchability of GWO for optimizing issues in construction project management as an innovative alternative to the traditional approach.

3. GWO METHODOLOGY

GWO model is a new metaheuristic algorithm developed by Seyedali Mirjalili et al. [14] This algorithm is inspired by the social dominance hierarchy and the hunting mechanism of grey wolves in nature. The alpha (α), beta (β), delta (δ), and omega (ω) represent the leadership hierarchy in the wolf pack from top to bottom. Three main phases of the hunting process consisting of tracking, chasing, and approaching the prey in the first phrase; pursuing, encircling, and harassing the prey until it stops moving in the second phrase and attacking towards the prey in the last phrase are used to develop this algorithm [24].

3.1. Social hierarchy

Grey wolves usually live in a pack of about 5-12 individuals and have a very strict social dominance hierarchy. As mentioned above, this hierarchy is applied to algorithm development. In the algorithm, the best solution will default to wolf α. Then, the two next best solutions can be termed wolf β and wolf δ, respectively. The other possible solution is considered as wolf ω. Simultaneously, the hunt is led by wolves α, β and δ except for wolf ω, which follows the control of these above wolves [14].

3.2. Predatory mechanism

According to the above assumptions, the hunting process mainly depends on the 3 leading wolves. After each iteration, the three best solutions (α, β and δ) in the processing optimization will be recognized. These values are used to govern and update the position of the wolf ω. The formula for determining the location of wolves is as follows:

$$\vec{\boldsymbol{D}}_{\alpha/\beta/\delta} = \left|\vec{\boldsymbol{C}}_{1/2/3} \times \vec{\boldsymbol{X}}_{\alpha/\beta/\delta} - \vec{\boldsymbol{X}}\right| \tag{1}$$

$$\vec{\boldsymbol{X}}_{1/2/3} = \vec{\boldsymbol{X}}_{\alpha/\beta/\delta} - \vec{\boldsymbol{A}}_{1/2/3} \times \vec{\boldsymbol{D}}_{\alpha/\beta/\delta} \tag{2}$$

$\vec{\boldsymbol{X}}_p(iter)$, $\vec{\boldsymbol{X}}(iter)$ represent the vector of wolf and prey's positions at the current iteration *iter*. The two coefficient vectors $\vec{\boldsymbol{A}}, \vec{\boldsymbol{C}}$ can be computed based on two random vectors $\vec{\boldsymbol{r}}_1$, $\vec{\boldsymbol{r}}_2$ in an interval [0 1] and the max number of iteration $iter_{max}$. The value $\vec{a}$ is reduced linearly from 2 to 0 throughout the iteration to bring the efficiency in the searching process and the determining target:

$$\vec{\boldsymbol{A}} = 2 \times \vec{\boldsymbol{a}} \times \vec{\boldsymbol{r}}_1 - \vec{\boldsymbol{a}} \tag{3}$$

$$\vec{\boldsymbol{a}} = 2 \times \left(1 - \frac{iter}{iter_{max}}\right) \tag{4}$$

$$\vec{\boldsymbol{C}} = 2 \times \vec{\boldsymbol{r}}_2 \tag{5}$$

A new position of each wolf in the next iteration can be identified as follows:

$$\vec{\boldsymbol{X}}(iter+1) = \frac{\vec{\boldsymbol{X}}_1 + \vec{\boldsymbol{X}}_2 + \vec{\boldsymbol{X}}_3}{3} \tag{6}$$

It can be observed that the three wolves α, β, and δ try to locate the prey's position, and the positions of other wolves can be randomly updated around the prey. Finally, the GWO stops working when the loop termination conditions are satisfied [14].

The GWO model processing includes 8 steps and is described in Figure 1.

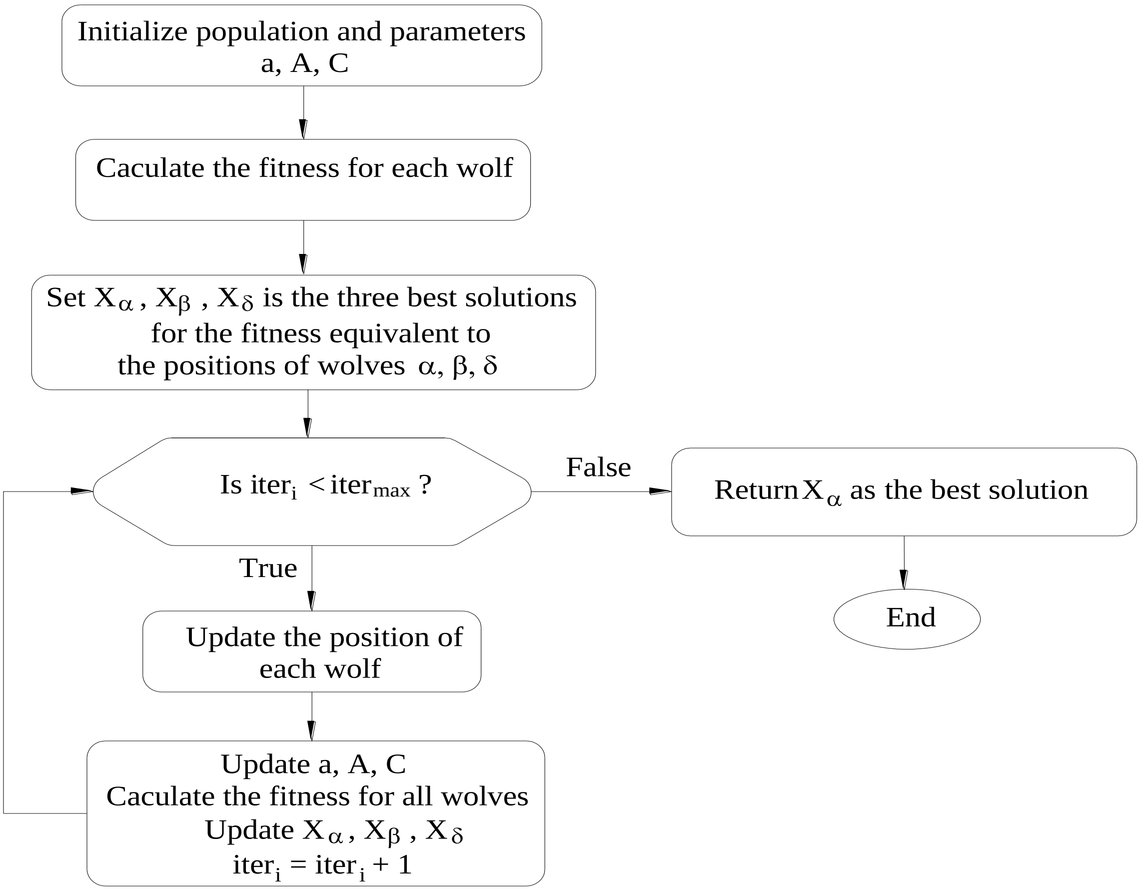


Figure 1. Flowchart of GWO's working procedure.

4. CASE STUDY

Practical project implementations usually need to accelerate a project because of the inaccuracy of anticipated schedules. In this study, a sample of 8 construction activities is analyzed with having considering their technological dependency relationships, normal cost, and initial duration (Table 1). According to the objective requirements during the project implementation, the manager must find out a way to shorten the duration of the project by 25-time units so as not to delay the project. This means the project must be allocated more resources to promote the progress of the activities in the project. As a result, these increasing resources lead to an escalation of the cost. The maximum time reduced and the unit cost to accelerate each work are shown in Table 2. The problem posed to the manager is how to shorten the project's schedule as the requirement with the lowest additional cost.

To solve the above problem, two approaches are considered. The traditional method based on the manually-performed approach and the subjective experience was first analyzed. GWO model was then applied. The results obtained in the two cases will help to have an objective evaluation of the effective application of GWO model in construction project management.

It is noticed that the assumption in which direct costs increase linearly as activity time is reduced from its normal time. This assumption implies that when each activity's duration is reduced, the direct cost will increase by the same ratio [23].

Table 1. Sequence and technical dependency relationships of activities in the project.

No	Activity	Dependency relationship	Initial duration	Normal cost
1	1-2	-	6	80
2	1-3	-	30	400
3	2-3	After 1-2	18	180
4	2-5	After 1-2	24	360
5	3-4	After 1-3, 2-3	24	360
6	4-5	After 3-4	0	0
7	4-6	After 3-4	18	270
8	5-7	After 2-5, 4-5	36	240
9	6-7	After 4-6	24	150

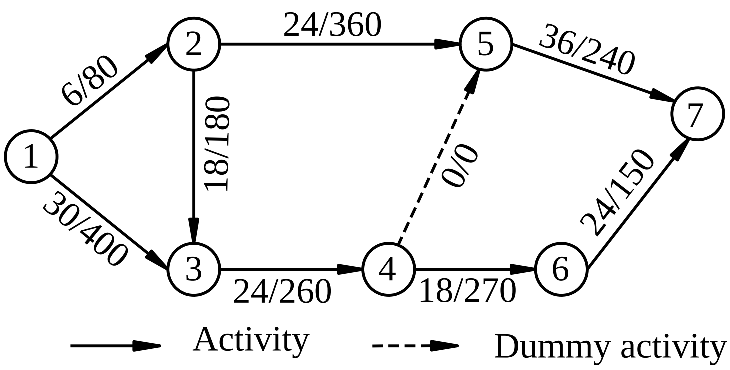


Figure 2. Initial CPM (Critical Path Method) network of the project**.**

Table 2. Maximum time reduced and unit cost for accelerating each activity in the project.

No	Activity	Maximum time reduced	Accelerated unit cost
1	1-2	2	20
2	1-3	10	120
3	2-3	6	54
4	3-4	6	90
5	2-5	6	60
6	4-5	0	0
7	4-6	6	48
8	5-7	12	120
9	6-7	9	45

4.1. Using traditional method: The Critical Path Method

It is obvious that the project has several activities that can be enhanced or accelerated. When using the Critical Path Method, it depends on the general rules that decide which activities should be accelerated. These rules include i) Accelerate only critical activities lied on the critical path of the Critical Path Method (CPM) network; ii) First accelerating activity with a lower cost of acceleration per unit of time; and iii) When there are parallel critical paths, each must be accelerated because the acceleration of just one of the paths will not reduce the total duration of the project [25].

According to the theories mentioned above, the critical paths on the CMP network are needed to determine, contributing to the project deadline. Figure 2 presents the CPM network including the critical path of the project. On this network, there are five paths from node 1 (start point) to node 7 (finish point). Among those, path 1-3-4-6-7 shows the longest route (Table 3), the critical path of the initial CPM network.

Table 3. Five paths and their length on the initial CPM network.

No	Path	Length	Note
1	1-2-5-7	66	
2	1-2-3-4-5-7	84	
3	1-2-3-4-6-7	90	
4	1-3-4-5-7	90	
5	**1-3-4-6-7**	**96**	**The critical path**

To reduce the duration of this project by 25-time units from 96 to 71, the activities lying on the critical path are prioritized to accelerate. However, the activities with the lowest cost unit for accelerating are considered first. Therefore, activities 6-7, 4-6, and 3-4 will be shortened by their maximum amount of time, 9, 6, and 6-time units, respectively. Table 4 presents activities with reduced time and the value of accelerating cost.

Table 4. Activities, reduced time, and expenditure spending on accelerating them (the first adjustment).

No	Activity	Accelerated time	Unit cost	Increase in Activity Cost
1	6-7	9 (maximum)	45	405
2	4-6	6 (maximum)	48	288
3	3-4	6 (maximum)	90	540
4	1-3	4	120	480
	Total	**25**		**1713**

After accelerating, the total length of the critical path is decreased by 25-time units as the requirement, which does not mean that the project duration is reduced by the same amount, however. The project duration is thus recalculated in the second round. The results are presented in Table 5 and Figure 3.

Table 5. The new length of five paths on the CPM network (the first adjustment).

No	Path	Length	Note
1	1-2-5-7	66	
2	1-2-3-4-5-7	78	
3	1-2-3-4-6-7	69	
4	**1-3-4-5-7**	**80**	**The critical path**
5	1-3-4-6-7	71	

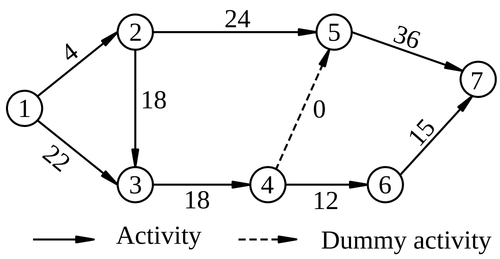


Figure 3. The CPM network, after the first adjustment.

It can be seen that a new critical path created in the new calculation is shown in path 1-3-4-5-7. However, the project duration still stays exceeding its requirement, resulting in a new accelerated process. This new adjustment is presented in Table 6.

Table 6. Activities, reduced time, and expenditure spending on accelerating them (the second adjustment).

No	Activity	Accelerated time	Unit cost	Increase in Activity Cost
1	5-7	9	120	1080
	Total	**9**		**1080**

Based on the adjustment, the duration of each activity will be changed, leading to the changes in the CPM network that can be seen in Table 7 as well as Figure 4.

Table 7. The new length of five paths on the CPM network (the second adjustment).

No	Path	Length	Note
1	1-2-5-7	58	
2	1-2-3-4-5-7	69	

3	1-2-3-4-6-7	69	
4	**1-3-4-5-7**	**71**	**The critical path**
5	**1-3-4-6-7**	**71**	**The critical path**

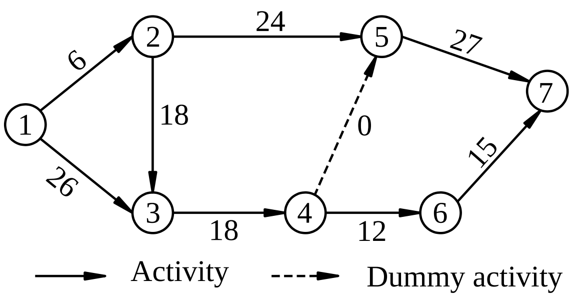


Figure 4. The CPM network, after the second adjustment.

The result of the second accelerating activity shows that all of the new critical paths' lengths are less than 71, which means the total duration of the project is 71-time units, satisfying the initial requirements. The variations of times and costs resulting from changes in the activities after two times of adjustment are presented in Table 8 below:

Table 8. Variations of durations and costs of accelerating activities in the project.

No	Activity	Normal Duration	Time reduced	Accelerated unit cost	Variation in Duration	Increase in Activity Cost
1	1-2	6	0	20	6	0
2	1-3	30	4	120	26	480
3	2-3	18	0	54	18	0
4	3-4	24	6	90	18	540
5	2-5	24	0	60	24	0
6	4-5	0	0	0	0	0
7	4-6	18	6	48	12	288
8	5-7	36	9	120	27	1080
9	6-7	24	9	45	15	405
			Total			**2793**

With the application of the CPM technique in the project, the production time was reduced by 25-time units from 96 to 71, resulting in an increase of 2793-currency units in the total cost.

4.2. Using GWO model

Based on the theory of GWO clarified, this section presents the algorithm's calculation of how much time should be reduced for each activity with the target of minimizing the amount of additional cost. In order to apply the algorithm, the reduced time of each activity is the considered variable, thereby including 8 variables equivalent to 8 activities of the project. The range of variation for each variable is shown in Table 9.

The objective function is to minimize the total cost of reducing the project duration which will be expressed in Eq. (7). The main constraint is that the total length of each path connected between the starting point and the finishing point of the CPM network must be less than 71, ensuring the project duration does not exceed 71-time units (shortening the project duration project by 25-time units). Eq. (8), Eq. (9), Eq. (10), and Eq. (11) will be used to illustrate this constraint.

Table 9. Variables in GWO.

No	Activity	Variable name	Range of variation	Note
1	1-2	x_1	[0,2], $x_1 \in N$	
2	1-3	x_2	[0, 10], $x_2 \in N$	
3	2-3	x_3	[0, 6], $x_3 \in N$	
4	3-4	x_4	[0, 6], $x_4 \in N$	
5	2-5	x_5	[0, 6], $x_5 \in N$	
6	4-5	-	-	Dummy activity
7	4-6	x_6	[0, 6], $x_6 \in N$	
8	5-7	x_7	[0, 12], $x_7 \in N$	
9	6-7	x_8	[0, 9], $x_8 \in N$	

$$f = 20x_1 + 120x_2 + 54x_3 + 90x_4 + 60x_5 + 48x_6 + 120x_7 + 45x_8 \rightarrow \min \quad (7)$$

$$x_1 + x_3 + x_4 + x_6 + x_8 \geq 19 \quad (8)$$

$$x_1 + x_3 + x_4 + x_7 \geq 13 \quad (9)$$

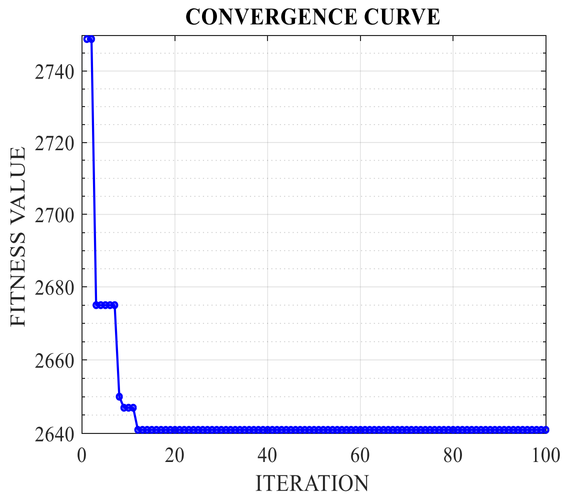
$$x_2 + x_4 + x_6 + x_8 \geq 25 \quad (10)$$

$$x_2 + x_4 + x_7 \geq 19 \quad (11)$$

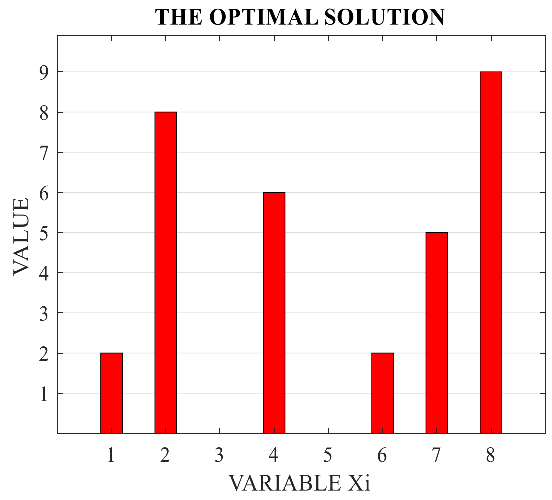
To determine the minimum value of the function f and the optimal solution for this issue, some initial parameters used in the optimization process will be set as follows:

- Creating an initial grey wolf population of 500 wolves
- Selecting the maximum number of loops: $iter_{max}$ = 100 loops
- Number of variables = 8
- Variable scope of variables $[x_{min}, x_{max}]$ as above
- Setting constraints.

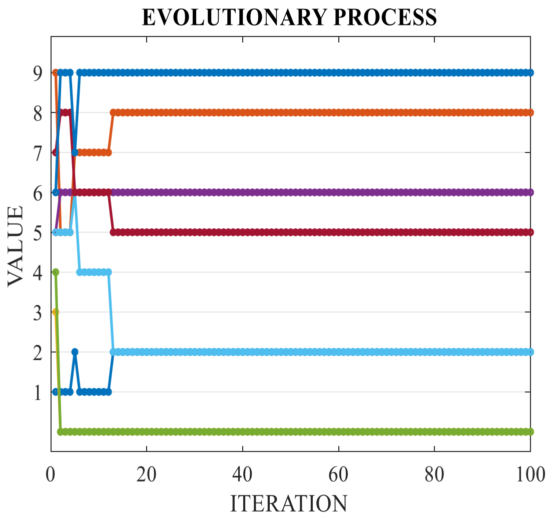
To apply the GWO algorithm, MATLAB software was used to analyze. In each iteration, the 500 particles will participate in the finding process. However, just the three best options are saved (three options make the value of the objective smallest). The search process continues until the last iteration, and the convergence of the search results gives the optimal solution. The result is shown in Figure 5 and Table 10



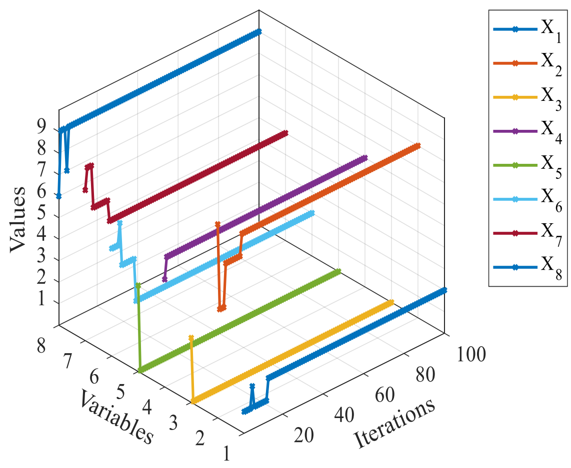
a. The convergence curve of fitness values



b. The optimal solution



c. The evolutionary process of variable x_i



d. The evolutionary process of variable x_i 3D

Figure 5. The result obtained from GWO.

Table 10. The optimal solution obtained from GWO.

No	Variable	value
1	x_1	2
2	x_2	8
3	x_3	0
4	x_4	6
5	x_5	0
6	x_6	2
7	x_7	5
8	x_8	9
	f_{min}	**2641**

After adjustment, the CPM network of the project is constructed and shown in Figure 6, whereby the length of all paths is determined in Table 11.

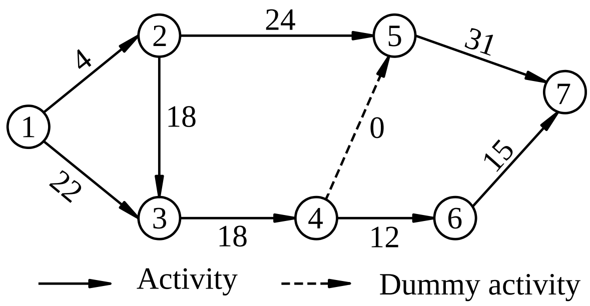


Figure 6. The CPM network constructed from GWO's result.

Table 11: The new length of five paths on the CPM network (based on GWO's result).

No	Path	Length	Note
1	1-2-5-7	59	
2	**1-2-3-4-5-7**	**71**	**The critical path**
3	1-2-3-4-6-7	67	
4	**1-3-4-5-7**	**71**	**The critical path**
5	1-3-4-6-7	67	

Based on the result shown in Figure 5, Figure 6, and

Table **10**, Table 11, the managers can completely make decisions to accelerate activities including 1-2, 1-3, 3-4, 4-6, 5-7, and 6-7. The total minimum shortening cost is 2641-currency units, and the total reduced time is 25-time units to adapt to the requirements.

4.3. Verifying the result obtained from GWO by using Solver-addins

To verify the accuracy of the results obtained from GWO model, the Solver-addins function in Excel software is used to solve the given problem. As can be seen from Figure 7 and Table 12, the result obtained from the application of the GWO and the Solver-addins not only completely coincide but are also better than CPM's result, proving the accuracy of the result obtained from the GWO. Therefore, it shows the high applicability of GWO in solving the problem of construction project management.

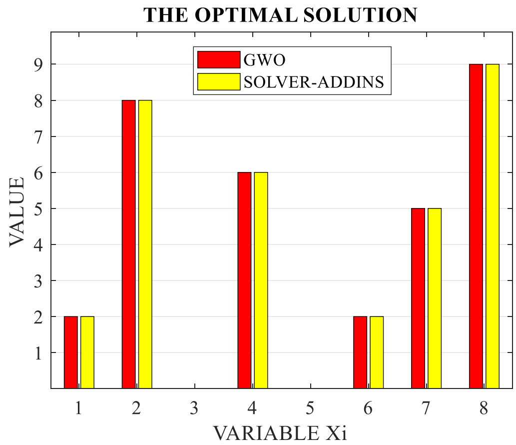


Figure 7. The comparison between predicted value (GWO) and optimal value (Solver-addins).

Table 12. The comparison of the result from CPM, GWO, and Solver-addins.

Methods	Total shortening cost
CPM	2793
GWO	2641
SOLVER-ADDINS	2641

5. CONCLUSIONS

This paper introduces an intelligence-based approach to improve the effectiveness of conventional project management. A stochastic optimization process is utilized to optimize the given objective function by varying the concerned conditions. A typical project consisting of 8 activities was considered in terms of reduction of project duration and cost using the proposed approach and CPM. The findings confirmed that the proposed method has superior performance than that of the CPM in regards to the optimal value of additional cost, with the values of 2461 and 2793-currency units, respectively. A comparative study between the proposed approach and commercial software, namely Solver, was also conducted to verify the reliability of the obtained result. The CPM requires much more time and effort to clarify the optimal solution due to its recalculate process required for every adjustment, while the proposed approach quickly identified the optimal value, with a CPU-time of 1.5264 seconds.

The proposed approach completely solves the single-objective optimization problem as the study considered. However, more complex issues such as a combination of time, cost, and resource distribution should be considered in the practical implementation of projects. In other words, more variables and restricted conditions with a complex objective function are investigated. Therefore, a multi-objective GWO will be used to deal with these issues in further works.

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