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Overall multiobjective optimization of construction projects scheduling using particle swarm

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Abstract

Purpose – Developing an optimized project schedule that considers all decision criteria represents a challenge for project managers. The purpose of this paper is to provide a multi-objectives overall optimization model for project scheduling considering time, cost, resources, and cash flow. This development aims to overcome the limitations of optimizing each objective at once resulting of non-overall optimized schedule.

Design/methodology/approach – In this paper, a multi-objectives overall optimization model for project scheduling is developed using particle swarm optimization with a new evolutionary strategy based on the compromise solution of the Pareto-front. This model optimizes the most important decisions that affect a given project including: time, cost, resources, and cash flow. The study assumes each activity has different execution methods accompanied by different time, cost, cost distribution pattern, and multiple resource utilization schemes.

Findings – Applying the developed model to schedule a real-life case study project proves that the proposed model is valid in modeling real-life construction projects and gives important results for schedulers and project managers. The proposed model is expected to help construction managers and decision makers in successfully completing the project on time and reduced budget by utilizing the available information and resources.

Originality/value – The paper presented a novel model that has four main characteristics: it produces an optimized schedule considering time, cost, resources, and cash flow simultaneously; it incorporates a powerful particle swarm optimization technique to search for the optimum schedule; it applies multi-objectives optimization rather than single-objective and it uses a unique Pareto-compromise solution to drive the fitness calculations of the evolutionary process.

Keywords Optimization techniques, Integration, Construction management, Construction, Financial performance, Critical path analysis

Paper type Research paper

Introduction

Construction projects represent a huge investment. Based on its importance, and due to inherited risks, construction managers and contractors must carefully plan, schedule, and manage projects in the most efficient manner. There are several dimensions that should be monitored to have a realistic schedule; time, cost, resources, and cash flow. Having a schedule that respects the time only may be inappropriate from other views such as the resources used, cost, and/or cash flow, and vice versa.

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Time and cost are two main concerns in construction projects. The more resources assigned to an activity, the less time it will take to complete the activity, but the cost is usually higher (Zhang and Li, 2010). This means that the interrelations between these scheduling components are usually contradictory.

Many relationships between time required to execute an activity, and the corresponding direct cost may be assumed. The most appropriate relationship is the discrete one which assumes that the relationship between activity time and direct cost is just random points (Doerner *et al.*, 2008). Several mathematical-based techniques have been used to solve time-cost trade-off (TCT). Dynamic, integer, and linear programming are used to determine minimum project cost corresponding to optimum project duration as a single-objective. For example, Hegazy and Ayed (1999) developed a simplified spreadsheet-based model for TCT problem using integer programming. Conversely, examples of the heuristic methods for solving the TCT problem include the work of Ammar (1992), Moselhi (1993), and Elbeltagi (2005). Modern researches extended this traditional trade-off to include other components such as quality, resources, and environmental issues. For example, El-Rayes and Kandil (2005) introduced a time-cost-quality trade-off optimization model for highway construction.

Resource scheduling is accomplished through resource leveling and resource allocation techniques. Resource leveling (unconstrained scheduling) is used for smoothing-out resource usage profile to achieve more efficient project executions. Resource allocation (constrained scheduling), on the other hand, is used to develop a project schedule under specific resource constraints. In this context, project duration could be extended (Georgy, 2008).

Zhang *et al.* (2006) introduced a particle swarm optimization (PSO) based approach to solve resource-constrained scheduling problem with the objective of minimizing project duration. Other heuristics applied to resource scheduling problems can be found in Hegazy and Kassab (2003), Fleszar and Hindi (2004), Kandil and El-Rayes (2006), and Belfares *et al.* (2007). However, all these resource-oriented researches aimed at optimizing resources only as a single-objective without considering the mutual relationships with time, cost, and cash flow.

Fathi and Afshar (2008) presented a genetic algorithm (GA) based model for determining best combination of time, cost, and resources. However, the model deals with the multi-objective problem as a single-objective by summing-up the three objective functions into a single weighted equation.

Cash flow optimization is also a challenging task. Minimizing net present value (NPV), minimizing financial charge (FC), and satisfying cash shortage constraints are the common objectives the researchers use when optimizing cash flow. Few researches integrated the cash flow objectives with time, cost, and resources when optimizing overall construction schedules. Najafi and Niaki (2006) used GA to find an optimum schedule considering resources leveling such that the NPV of the project cash flow is minimized. Elazouni and Metwally (2007) expanded the optimization of cash flow to incorporate TCT analysis, resource allocation, and resource leveling using GA. The ultimate goal of the expanded technique is to maximize project saving through minimizing direct costs, overheads' expenses, FC, and resources fluctuations under credit and resource limits, and still producing single optimized schedule. Abbasy *et al.* (2012) introduced a model which aims at developing a multi-objective elitist non-dominated sorting GA for solving finance-based scheduling problem of multi-projects with multi-mode activities. The problem involves minimization of conflicting objectives: projects' duration, financing costs, and maximum negative cumulative balance.

Hegazy and Ersahin (2001) presented an approach for modeling and optimization of an overall construction schedule presented on a spreadsheet using GAs. The model integrates TCT, resource allocation, resource leveling, and cash flow simultaneously. They optimized the time, cost, resource, and cash flow via an aggregated cost objective function. In another work, Senouci and Naji (2003) presented a GA model for resource-constrained scheduling and TCT. They used the quadratic penalty function to transform the constrained resource scheduling problem to an unconstrained one. Also, Liu and Wang (2008) introduced an optimization model which integrates resource constraints and cash flow management issues, and maximizes net cash flow to optimize project profit from the contractors' perspective.

Although previous research work considered several scheduling objectives, they did not consider optimizing all objectives simultaneously. In the current study, each activity is assumed to have different execution methods accompanied by different time, cost, and multiple resource utilization schemes. Table I presents a comparison among different models along with the proposed model. In this paper, multi-objectives PSO model with a new evolutionary strategy using Pareto-compromise solution is developed to deal with project schedules and to enhance the four dimensions of projects scheduling including, time, cost, resources, and cash flow.

Multi-objective PSO

In the case of single-objective optimization, the optimal solution is the one that achieves the best (minimum/maximum) value of the objective function. In case of multi-objective optimization, the functions are incommensurable and often have conflicting objectives, so there is no single optimized solution. Multi-objective optimization with such conflicting objectives gives rise to a set of optimized solutions, instead of one. In solving a problem with multiple objectives, different methods can be employed, such as, considering a new single-objective defined by weighted sum of the multiple objectives or bounding all but one of the objectives and trying to optimize the selected one. One other advantageous approach is to find the Pareto-optimal solution set (Iranmanesh *et al.*, 2008). A solution belongs to the Pareto set (set of non-dominated solutions) if there is no other solutions that can improve at least one of the objectives without degradation of any other objectives.

Model	Aggregation of objectives	Optimization engine	Integrating cash flow, TCT and resources
Hegazy and Ersahin (2001)	Yes	GA	Yes
Senouci and Naji (2003)	Yes	GA	Yes
Fleszar and Hindi (2004)	No	Variable neighborhood search	Constrained resources problem only
Najafi and Niaki (2006)	–	GA	No
Zhang *et al.* (2006)	No	PSO	Constrained resources problem only
Elazouni and Metwally (2007)	Yes	GA	Yes
Liu and Wang (2008)	–	Constraint programming	No
Fathi and Afshar (2008)	Yes	GA	No
Abbasy *et al.* (2012)	No	GA	No
Proposed model	No	PSO with new evolution strategy	Yes

Table I. Comparison among optimization models

PSO is inspired by the social behavior of a flock of migrating birds trying to reach an unknown destination (Kennedy and Eberhart, 1995). Elbeltagi *et al.* (2005) introduced a comparison between five evolutionary-based search methods. They concluded that PSO generally outperformed all other algorithms in solving all test problems in terms of obtaining the minimum objective value while ranked second in the processing time. The evolution process in a single-objective PSO is initialized with a group of random particles (solutions) where each particle i monitors the following: its current position ($x_i(t)$); the best position it reached before ($p_i(t)$); and its flying velocity ($v_i(t)$).

In each cycle, the position (P_g) of the best particle (g) is calculated as the best fitness of all particles. Accordingly, each particle updates its velocity $v_i(t)$ to catch the best particle, g, position (Shi and Eberhart, 1998):

$$v_i(t+1) = \omega \cdot v_i(t) + c_1 \cdot r_1 (p_i(t) – x_i(t)) + c_2 \cdot r_2 \left(P_g(t) – x_i(t)\right) \tag{1}$$

Using the new velocity $v_i(t+1)$, the particle's updated position becomes:

$$x_i(t+1) = x_i + v_i(t+1); \quad V_{max} \geqslant v_i \geqslant -V_{max} \tag{2}$$

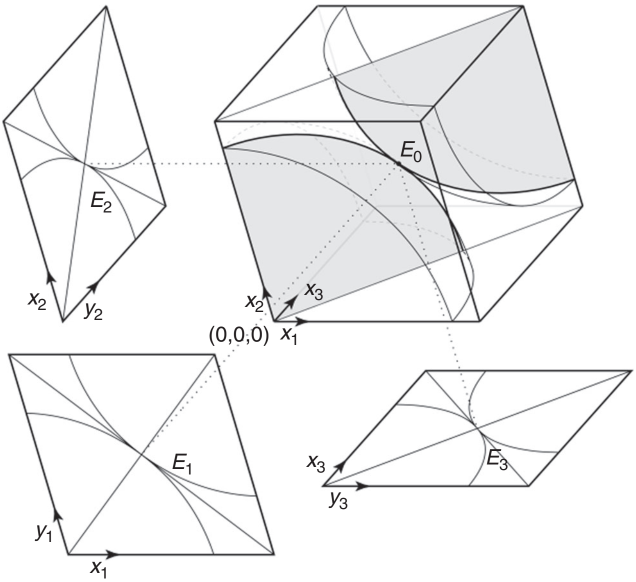
where c_1 and c_2 are learning factors constants (usually $c_1 = c_2 = 2$); r_1 and r_2 are random variables in the range [0, 1], V_{max} is an upper limit on the maximum change of particle velocity, and ω is an inertia weight ranges from 1.5 to 0.5 employed as an improvement proposed by Shi and Eberhart (1998) to control the impact of previous history of velocities on the current particle velocity.

In the case of a multi-objective optimization problems governed by $i = 1, 2, 3, \ldots, n$ objective functions, there are many optimal solutions that collectively define the Pareto-front in the n-dimensional objectives space for the problem. The main difference between single-objective and multi-objectives PSO is on the determination of both the individual best (p_i) and global best (P_g). In multi-objective PSO both the P_i and R_h, Equation (3), are used instead of p_i and P_g, respectively. Consequently, these two parameters need to be determined repetitively during PSO (Zhang and Li, 2010). Accordingly, the particles' velocities will be updated as follows (Baltar and Fontane, 2006):

$$v_i(t+1) = \omega \cdot v_i(t) + c_1 \cdot r_1 (P_i(t) - x_i(t)) + c_2 \cdot r_2 (R_h(t) - x_i(t)) \tag{3}$$

where R_h represents a solution selected from the external repository in each iteration t, and P_i represents the best position vector of particle i. Then, the particles' updated positions are carried out using Equation (2).

In such multi-objectives complex space, there is a unique solution represents a mutually agreeable trade-off between all competing objectives for the problem. This unique solution is called the "compromise solution" (Grierson, 2008). Figure 1 shows the Pareto-compromise solution for a three-objectives space. In this paper, the compromise solution is determined to help project managers and decision makers in presenting the solution that satisfies all objectives fairly. This unique Pareto-compromise solution is, also, used to drive the fitness calculations of the multi-objectives PSO evolutionary process (El-Ghandour and Elbeltagi, 2014).



Source: Adapted from Grierson (2008)

Figure 1. Unique Pareto trade-off point

For a set of Pareto-optimal solutions, N, located in the Pareto-front, the Pareto-compromise solution is identified using the procedure described in Grierson (2008). The Euclidean distance ($d_{k,\,pc}$) between the Pareto-compromise solution (pc) and other solutions (k) located in the Pareto-front with n objectives is computed as follows (El-Ghandour and Elbeltagi, 2014):

$$d_{k,pc} = \sqrt{\sum\nolimits_{i=1}^{n} \left(f_{ki} - f_{pci}\right)^2} \quad k = 1, 2, 3, \ \ldots, \ N \tag{4}$$

where f_{ki}, f_{pci} are the values of the objective function i for the solution k and the pc, respectively. Accordingly, the fitness of each solution in the Pareto-front is proportional to its distance from the (pc) and is calculated as follows:

$$\text{Fitness}_k = d_{k,pc} \quad k = 1, 2, 3, \ \ldots, \ N \tag{5}$$

Model formulation

The proposed model considers time, cost, resources, and cash flow to obtain a set of Pareto-optimal solutions (schedules). In order to optimize construction resources, resource leveling should be performed to smooth-out the unconstrained resource utilization along project duration.

The objective of resource leveling is to reduce fluctuations between period-to-period usages. Harris (1978) proposed the minimum moment algorithm for resource leveling to lower daily resource usage using X-moment (X) is the time axis). According to Hegazy (1999), and Fathi and Afshar (2008), X-moment (M_x^j) for resource j can be expressed by the following equation:

$$M_x^j = \frac{1}{2}\sum_{i=1}^{T} y_d^2 \tag{6}$$

where T is the total working time units of the project, y is the daily resource usage, and d is the day number.

Another moment about Y-axis is considered to minimize the gaps between resource clusters over the project duration. Y-moment can be calculated for a resource j using the following equation:

$$M_y^j = \sum_{i=1}^{T} y_d(d-0.5) \tag{7}$$

In order to tackle all resources simultaneously, it is assumed that moments of each resource are summed up as expressed by Equation (8). This simple summation is approximate way to treat multiple resources:

$$M_{tot} = \sum_{j=1}^{R} M_t^j \tag{8}$$

where M_{tot} is the total moment for all resources, M_t^j is the total moment of resource j ($M_t^j = M_x^j + M_y^j$), and R is the total number of resources.

Regarding time-cost interaction, project's total cost is comprised of direct and indirect costs as expressed by the following equation:

$$\text{Project's total cost} = (\text{IC} * T) + \sum_{i=1}^{S} \text{DC}_{ij} \tag{9}$$

where S is the total number of activities in the project, DC_{ij} is the direct cost of activity i using construction method j, and IC is the indirect cost per unit of time.

FC, fluctuation between consecutive and individual overdrafts are the main parameters that should be modeled properly for cash flow optimization. Elazouni and Metwally (2005) introduced an algorithm to determine FC considering the compound interest effect of monthly overdrafts using Equation (10). Figure 2 shows part of typical construction project cash flow profile:

$$\hat{F}_n = \left(O_n + \sum_{i=1}^{n-1} \hat{F}_i \right) r \tag{10}$$

$$FC = \sum_{n=1}^{N} \hat{F}_n \tag{11}$$

where FC is the financial charge affected by compound interest, $\hat{F}_n$ is the interested FC

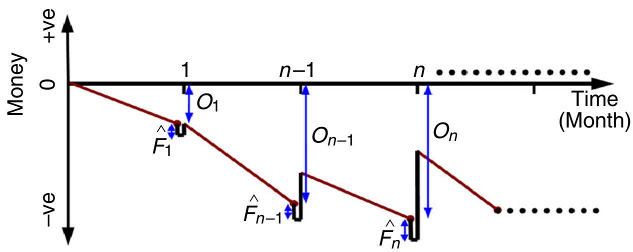


Figure 2.
Cash flow profile

at period no. n ($n=1$-N) and N is the total number of periods (usually in months), O_n is the overdraft at period no. n, and r is the interest rate in the period.

It is also important to maintain the difference between consecutive overdrafts to their minimum values. The difference (ΔO) between maximum monthly overdraft (O_{max}) and minimum monthly overdraft (O_{min}) is used to measure the fluctuation between overdrafts. As minimizing the difference between monthly overdrafts ensures minimizing the amounts of individual overdrafts.

Overall multiobjective optimization for project schedules

In PSO, each solution (particle) is represented as a string of elements equals twice the number of activities. Each activity is represented by two variables (Figure 3): activity start index I^s, and construction-method index I^m. Start index I^s represents the start option of the chosen activity, which ranges between (zero) and (activity total float). For example, Activity 1, has $I^s=0$, and $I^m=2$ which means that the activity will start at its original start date, and will be executed using construction method number two. However, solutions of the first iteration will be generated randomly.

Four objective functions are considered to evaluate solutions. The model aims at minimizing project cost, time (project duration), resource moments, and cash flow aspects as stated in Equation (12), while considering constraints of time, resource, and cash flow:

$$\left.\begin{array}{ll}\text{Min. cash flow:} & FC+\Delta O\\ \text{Min. cost:} & (IC*T)+\sum_{i=1}^{S} DC_{ij}\\ \text{Min. resource:} & M_{tot}\\ \text{Min. time:} & T\end{array}\right\} \qquad (12)$$

Subject to:

$$\begin{array}{l}T \leqslant T'\\ \text{For each resource}: y_d \leqslant R_{max},\\ O_{max} \leqslant O_{lim}, \text{ and}\\ \text{Dependency constraints}:\\ \text{In case of } FS\text{-relation}: ST_i \geqslant ST_p + D_p + lag\\ \text{In case of } SS\text{-relation}: ST_i \geqslant ST_p + lag\\ \text{In case of } FF\text{-relation}: ST_i \geqslant ST_p + D_p + lag - D_i\\ \text{In case of } SF\text{-relation}: ST_i \geqslant ST_p + lag - D_i\end{array}$$

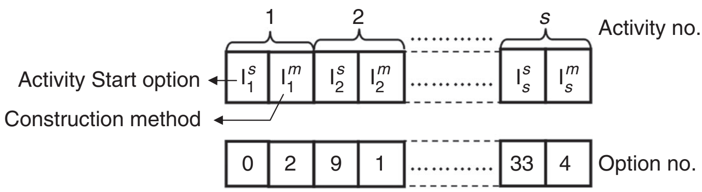


Figure 3. Structure of the solution

where T is the project duration, T′ contract duration, R_{max} daily maximum resource limit, ST_i start time of activity i, ST_p start time of predecessor of activity i, and D is the activity duration.

In order to evaluate solutions based on the four objectives mentioned above, the Pareto-front is first identified. In multi-objective PSO, P_i is initially set equal to the initial position of particle i. In the subsequent iterations, P_i is updated in the following way for each particle i (Baltar and Fontane, 2006):

- if the current P_i dominates the new position, then new P_i is equal to current P_i;
- if the new position dominates the current P_i, then new P_i is equal to new position; and
- if no one dominates the other, then one of them is randomly selected as the new P_i.

In the proposed multi-objective PSO model, there is no global best (P_g) exist as in the single-objective PSO. However, there are several equally good non-dominated solutions (Pareto-front) stored in the external repository. To update the velocity of each particle using Equation (3), R_h should be first determined. In this method, the Pareto-compromise solution is determined from the set of Pareto-optimal solutions located in the Pareto-front. The sparse-degree of any solution equals to the distance between this solution and the Pareto-compromise solution as presented in Equation (4) (El-Ghandour and Elbeltagi, 2014). The sparse-degree for each non-dominated solution should be normalized and the total sum of the normalized sparse-degree equals one. The size of the selection in the roulette-wheel is proportional to the sparse-degree for every non-dominated solution. Consequently, the non-dominated solution with a larger value of the sparse-degree has the priority to be selected as the R_h. The advantage of this technique is to keep convergence and diversity simultaneously (Zhang and Li, 2010).

The method for measuring the convergence of the proposed multi-objective PSO model to the final set of Pareto-optimal solutions is based on tracking the evolving Pareto-compromise solution over the generational search history. For each generation, the Pareto-compromise solution is identified for the current set of existing non-dominated solutions. Termination of the evolutionary process occurs when the Pareto-compromise solution has not changed for a specified number of generations.

Model verification

To verify the developed model and compare the results with other techniques, a sample project presented by Zheng *et al.* (2004) is considered. Each project activity has different construction methods defined by their own duration and cost as presented in Table II. It is required to optimize both the project duration ad cost. The indirect cost is assumed \$500/day. This example was solved by Zheng *et al.* (2004) employing Modified Adaptive Weight Approach and solved later by Abbasnia *et al.* (2008) employing non-dominated sorting GA technique.

An initial schedule of 132 days was obtained considering least-cost options. The corresponding total project cost is \$162,800. For comparison purposes, time and cost only are considered as optimization objectives. As presented in Table III, multiobjective PSO performed better and produced wide distribution of the Pareto-optimal solutions. The time-range covered by the proposed model is 27 days (from 60 to 87), while the cost-range covered is \$30,000 (from 173,000 to 143,000).

Act. no.	Activity description	Preceding Acts	Option	Dur. (day)	Cost ($)
1	Site preparation	–	1	14	23,000
			2	20	18,000
			3	24	12,000
2	Forms and rebars	1	1	15	3,000
			2	18	2,400
			3	20	1,800
			4	30	1,200
			5	60	600
3	Excavation	1	1	15	4,500
			2	22	4,000
			3	33	3,200
4	Pre-cast concrete girders	1	1	12	45,000
			2	16	35,000
			3	20	30,000
5	Pour foundation and piers	2, 3	1	22	20,000
			2	24	17,500
			3	28	15,000
			4	30	10,000
6	Deliver pre-cast girder	4	1	14	40,000
			2	18	32,000
			3	24	18,000
7	Erect girders	5, 6	1	9	30,000
			2	15	24,000
			3	18	22,000

Table II. Time and cost data for the verification example

Sol. no.	Zheng *et al.* (2004) Project dur. (days)	Zheng *et al.* (2004) Project cost ($)	Abbasnia *et al.* (2008) Project dur. (days)	Abbasnia *et al.* (2008) Project cost ($)	Proposed model Project dur. (days)	Proposed model Project cost ($)
1	–	–	60	173,500	60	173,000
2	61	173,000	61	173,000	–	–
3	62	172,000	62	171,000	62	171,000
4	63	162,500	63	162,500	63	162,500
5	66	161,500	66	161,500	66	161,500
6	67	157,000	67	157,000	67	157,000
7	68	152,500	68	152,500	68	152,000
8	74	149,500	74	149,500	74	149,500
9	77	149,000	77	149,000	77	148,500
10	78	146,500	78	146,500	78	146,500
11	84	143,500	84	143,500	84	143,500
12	87	143,000	87	143,000	87	143,000

Table III. Pareto-optimal solutions: comparison with other models

So, distribution of the Pareto-optimal solutions produced by PSO is quite similar to those produced by other models with improvement in the values of some Pareto-optimal solutions. The number of particles experimented with were 40 and the number of generations were 200. Despite the overall similarity of the Pareto-optimal solutions with the previous models, there were some improvements of the solutions as shown in Solutions 7 and 8.

Application project

This section is dedicated to show the ability of the multi-objective PSO model to solve multi-objective project scheduling problems. The steps of applying the developed model are described as follows:

(1) Randomly, generate initial population of particles, and then compute the four objective functions for each particle.

(2) For each particle, compute P_i.

(3) In each cycle, compute P_h for the Pareto-optimal solutions as follows:

- Identify the Pareto-optimal solutions, and assign them a rank of one and determine the Pareto-compromise solution for these Pareto-optimal solutions. The mathematical formulations used to determine the compromise solution among a set of Pareto-optimal solutions, are coded as given by Elbeltagi *et al.* (2010).
- Calculate and normalize the sparse-degree for each Pareto solution.
- Apply roulette-wheel to determine the R_h for each particle.

(4) Having identified the values of P_i and P_h for each particle, the velocity of each particle in the population is calculated, (Equation (3)), and the new position of each particle is determined (Equation (2)).

(5) This process continues until termination criteria are satisfied.

Project description

The application project used in this paper is "Head regulators for Alabbasi Canal." The project is located in Zefta, Egypt. The project comprises the following main items: barrage (eight vents, two concrete abutments, and seven piers), 90 ton capacity concrete bridge with 12 m width, control room, accessories store, electromechanical works, and general road works (Sanad, 2011).

The project has been divided into 24 major activities. Activities descriptions, durations, and logical dependencies among activities are given in Table IV, as it was prepared by the contractor.

In this table, the default relationship type is direct finish-to-start (FS), so any other relationship types are written in the table with the associated overlaps (if any). The project start date was set as October 2, 2004. The initial schedule is generated using MS-Project as shown in Figure 4. The project was planned to finish on August 13, 2006, while the contract duration was set to be 24 months.

Several resources were employed in this project. However, the key resources are only considered. These key resources are concrete mixers (1/2 m^3), excavators, and loaders. The assignment of these resources with their quantities to activities is listed in Table V. The daily availability limits for these resources are five concrete mixers, three excavators, and six loaders. The project indirect cost is assumed as 2,932 Egyptian Pounds (LE)/day.

After studying the available construction methods for activities, the results showed that there are 11 activities having alternative construction methods with different direct costs, durations, and resources as listed in Table VI.

Regarding cash flow, the markup is assumed to be 17.7 percent. According to the contract conditions, the retention rate is 5 percent, no advanced payment, and

Act. No.	Activity description	Dur. (days)	Relationship pred (type/overlap)
1	Setup site	180	–
2	Construct diversion channel	180	1
3	Diaphragm and sheet walls	90	2(FS/30)
4	Excavation and dewatering	260	3(FS/30)
5	Plain concrete works	4	4(SS/-50)
6	R.C for foundations	50	5
7	Brickwork and concrete for left abutment	65	6(SS/-10)
8	Brickwork and concrete for pier 1	40	6(SS/-15)
9	Brickwork and concrete for pier 2	40	6(SS/-20)
10	Brickwork and concrete for pier 3	40	6(SS/-25)
11	Brickwork and concrete for pier 4	40	6(SS/-30)
12	Brickwork and concrete for pier 5	40	6(SS/-35)
13	Brickwork and concrete for pier 6	40	6(SS/-40)
14	Brickwork and concrete for pier 7	40	6(SS/-45)
15	Brickwork and concrete for right abutment	52	6(SS/-50)
16	Inlet and outlet approaches	14	15
17	Deck (part 1)	25	7-8-9-10-11
18	Deck (part 2)	22	11-12-13-14-15-17
19	Downstream protective layer	105	15
20	Stone cover	40	19(SS/-20)
21	Electromechanical work	60	18
22	General site works and roads	30	21(SS/-28)
23	Control room and accessories store	50	15(SS/-5)
24	Finalizing project and submission	30	19-20-21-22-23

Table IV. Activities data of the application project

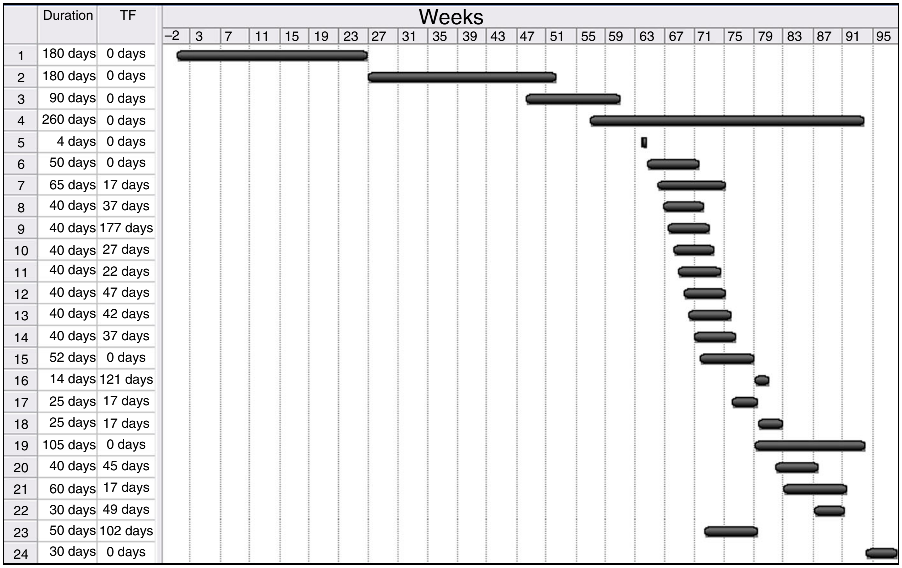


Figure 4. Initial schedule for the application project

Act. no.	Direct cost (LE)	R1[a]	R2[b]	R3[c]
1	–	–	–	–
2	3,653,563	–	2	–
3	3,610,100	–	–	3
4	991,579	–	1	3
5	577,745	2	–	–
6	4,970,679	1	–	–
7	298,851	1	–	–
8	208,357	1	–	–
9	208,357	1	–	–
10	208,357	1	–	–
11	208,357	1	–	–
12	208,357	1	–	–
13	208,357	1	–	–
14	208,357	1	–	–
15	298,851	1	–	–
16	179,818	1	–	–
17	178,985	1	–	–
18	178,985	1	–	–
19	750,978	–	–	–
20	839,166	–	–	–
21	10,000,000	–	–	–
22	2,074,628	–	–	3
23	1,212,787	1	–	–
24	693,290	–	–	3

Notes: [a]No. of concrete mixers $\leqslant 5$; [b]no. of excavators $\leqslant 3$; [c]no. of loaders $\leqslant 6$

Table V.
Activities' resource and cost data for the application

Act. no.	Construction method No.	Dur.	Cost (LE)	R1	R2	R3
2	1	180	3,653,563	–	2	–
	2	140	3,713,563	–	3	–
4	1	260	991,579	–	1	3
	2	241	1,014,196	–	2	3
8-14	1	40	208,357	1	–	–
	2	30	225,400	1	–	–
	3	25	240,400	–	–	–
20	1	40	839,166	–	–	–
	2	25	864,166	–	–	–
24	1	30	693,290	–	–	3
	2	20	737,844	–	–	3

Table VI.
Project application activities with alternative construction methods

no incentive in case of early completion. Also, it is assumed the contractor will pay 18 percent of the incurred cost immediately, and 82 percent by the following month.

Overall multiobjective optimization

The initial schedule is characterized by the following: maximum overdraft of LE4,082,164, project duration of 681 days, total project cost of LE31,682,692, and resources periodic utilization is over constraint limits. The multiobjective optimization is applied using the developed multiobjective PSO model considering time, cost, resources, and cash flow. Using appropriate optimization parameters, i.e. population size = 40 and 100 iterations. The optimization process produced 20 Pareto-optimal solutions (schedules). Table VII lists all Pareto-optimal solutions with their objective function values. All these solutions satisfy the resources constraints.

Because the optimization problem at hand is of four dimensions, it is difficult to illustrate the results in a four-dimensional chart. Accordingly, the results are illustrated as stacked bars to help the decision maker in visualizing the objectives of each solution. The decision maker may concentrate on the solution(s) of short staked bar(s) such as solutions number 10, 13, and 14.

As shown in Table VII, the produced Pareto-optimal solutions cover wide range of objectives. The project duration varies from 631 to 732 days, project cost varies from LE34,025,392 to LE34,468,224, resource moment varies from LE524,421 to LE1,065,438, and maximum overdraft varies from LE3,739,501 to LE6,036,429.

Solution “9” is characterized by minimum resource moment of 524,421 (most smoothed resource profiles), but the largest amount of project cost and monthly overdraft. Figure 6 illustrates the optimized resources histograms associated with solution “9.” However, solution “13” has a very close value of resources moment (525,834) to that of solution “9.” Moreover, solution no. 13 has additional advantages over solution “9.” Maximum overdraft further minimized than that of solution “9” by having the value of LE4,433,785 instead of LE6,036,429 scored by solution no. “9.” Furthermore, its project cost and duration; both are less than those of solution “9.” Accordingly, solution “13” is better than solution “9.”

As shown in the table, it is clear that solution “3” represents the solution with the least-duration among all solutions, while solution “17” is characterized by minimum monthly overdraft of (LE3,735,162), and solution “8” is characterized by minimum project cost of (LE34,025,392), however, it has large amount of resources moment. On the other

Solution no.	Project dur. (days)	Project cost (LE)	Resource moments	Max. overdraft (LE)	Financial charge (LE)
1	726	34,181,632	976,606	5,192,836	178,265
2	722	34,197,904	659,807	5,186,867	181,342
3	631	34,194,092	990,775	5,559,057	180,272
4	712	34,200,584	624,813	5,617,306	182,435
5	732	34,274,224	961,834	3,806,371	156,677
6	636	34,116,752	1,065,438	5,505,467	182,895
7	729	34,227,428	977,032	4,436,484	159,791
8	656	34,025,392	1,053,351	4,202,792	154,854
9	732	34,468,224	524,421	6,036,429	175,787
10	732	34,287,224	557,874	4,073,222	154,997
11	718	34,231,176	564,060	5,224,766	166,761
12	730	34,153,360	658,552	4,974,665	158,098
13	722	34,289,904	525,834	4,433,785	157,871
14	708	34,273,856	534,407	4,316,647	157,098
15	719	34,264,108	597,792	4,732,714	169,688
16	706	34,227,992	613,801	5,694,012	178,980
17	732	34,301,224	872,636	3,739,501	158,651
18	720	34,218,040	644,339	5,065,604	162,546
19	713	34,260,516	610,229	4,581,023	168,667
20	716	34,154,312	618,179	5,443,356	180,801

Table VII. Pareto-optimal solutions with their objectives values for the project hand, solution "8" introduces the alternative with the least-project cost among all solutions (Figures 5 and 6).

Since each schedule is characterized by one or more advantages than the others, adopting certain schedule is becoming a decision that should be taken by the project manager according to his/her preferences and the project's practical concerns. For example, the project manager may select solution "8" because it has minimum project cost, or he/she may choose solution "3" because it has minimum project duration, or solution "13" because it has small resource moment, or solution "17" because it has minimum value of monthly overdraft , etc.

Selecting a single solution from the presented ones is a difficult task. In order to help the decision maker in selecting a single solution among the set of Pareto-optimal solutions, the procedure introduced by Elbeltagi *et al.* (2010) is applied. The resulted Pareto-compromise solution and its theoretical values are listed in Table VIII. Accordingly, the best-alternative solution among the Pareto-optimal solutions is found to be the solution 12.

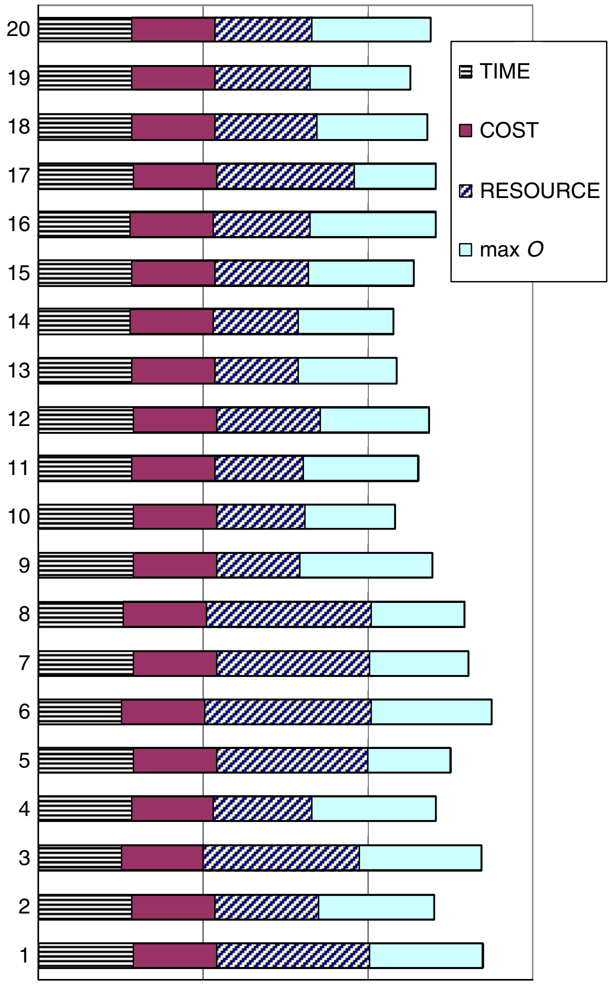


Figure 5.
Results presented as normalized stacked bars

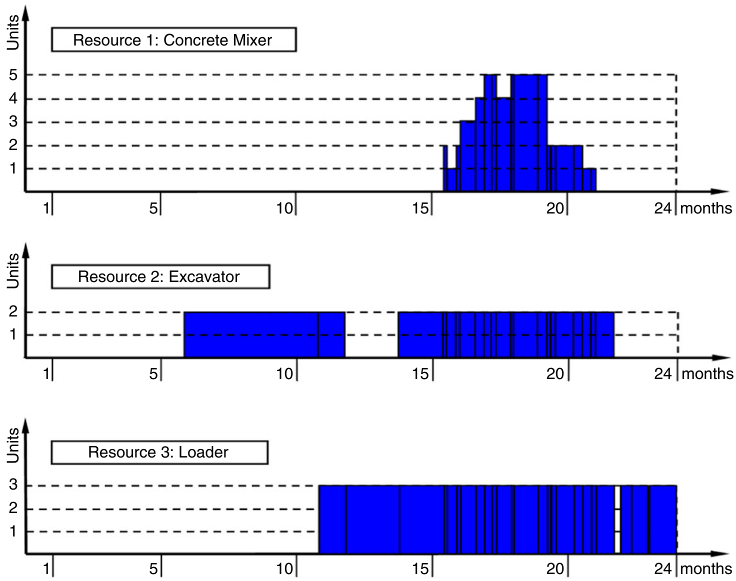


Figure 6. Resources usage for the least-resource moment solution

Table VIII. Pareto-compromise and best-alternative solutions for the example application

Solution no.	Project dur. (days)	Project cost (LE)	Resource moments	Max. overdraft (LE)	Financial charge (LE)
Pareto-compromise solution	708	34,231,560	760,901	4,897,935	168,941
Best-alternative solution	730	34,153,360	658,552	4,974,665	158,098

Comments and future extensions

The model presented in this paper has been demonstrated to work effectively on a comparison example project. With different experimentation, the suitable numbers of particles and generations were set as 40 and 200, respectively. To validate the model, verification example from the literature uses two objectives only were used (no example in the literature using four objectives were found). The results showed that the developed model produces quite similar results to those produced by other model with little improvement. Further experimentation was also conducted on real-life project and the proposed model performed very well. A variety of pareto-optimal solutions that covered a wide solution space (as discussed in the previous section) were presented along with the pareto-optimal compromise solution. The analysis of the application project proves that the proposed model is valid in modeling real-life construction projects and can give important results for schedulers and project managers. The proposed model is expected to help construction managers and decision makers in successfully completing the project on time and reduced budget. The main characteristics of the proposed model that makes it a proper tool for optimizing overall projects schedules stem from: it applies multi-objective optimization using a robust PSO to optimize four objectives simultaneously; it uses a unique solution represents a mutually agreeable trade-off among all competing objectives "compromise solution" to drive solution fitness. In such case, tracking a single point reminiscent of single-objective optimization; and it helps the user by presenting a unique compromise solution especially in complex objective spaces. In addition to creating many Pareto-optimal solutions from which the user can choose based on his/her preferences.

Despite its advantages, the proposed model still has some limitations and there are a number of possible extensions currently being pursued by the authors. These include: introducing some changes to the proposed model formulation to speed up the procedure and enhance the performance, this may include experimenting with other optimization parameters or introducing other optimization technique; and extending the study to consider limited resources problems not just to smooth resources profiles, this is expected to add practicality and improvements to the current model.

Summary and conclusions

The characteristics of successful project management in construction required constructing the project schedule based on the optimum integration of several important information factors. In this paper an overall optimization model for multi-objective project scheduling was developed by integrating the shared information of time, cost, available resources, and cash flow components, and next, by utilizing multi-objective PSO technique that searches for the optimal solution. The mathematical and logic methodology of the utilized optimization technique was also provided. In order to validate the performance of the developed model, a real-life case study of construction example was tested. The project of the "Head regulator of Alabbasi Canal" located in Zefta, Egypt. Multiobjective optimization of PSO is applied using four objective functions of minimized time, cost, resources, and cash flow, with appropriate optimization parameters of population size and iterations. The optimization process of the model generated 20 optimal solutions that satisfy the resources constraints and covers wide range of the objectives. Each characterized by one or more advantages over the others. Based on his/her preferences and the project's practical concerns, Project managers can choose the solution with minimum project cost, or the solution with minimum project duration, or solution with small resource moment, or solution with minimum value of monthly overdraft, etc. Finally, and to overcome the difficulty of selecting single solution among the set of Pareto-optimal solutions, a procedure to obtain the best-alternative solution was applied to get the Pareto-compromise solution.

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