TIME-COST-QUALITY TRADE-OFF MODEL FOR SUBCONTRACTOR SELECTION USING DISCRETE PARTICLE SWARM OPTIMIZATION ALGORITHM

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In general, construction projects consist of several work packages. The general contractors usually tend to sublet these work packages to various subcontractors. In such cases, general contractors are responsible for the quality of the work packages performed by the selected subcontractors. In this context, the success of a construction project and thereby the general contractor depends on the performances of the subcontractors. Therefore, one of the main problems that a general contractor faces is the selection of the right subcontractors for the right work packages. In most cases, general contractors make this decision at the beginning of the project and they have to evaluate potential subcontractors' performances in terms of time, cost and quality during the subcontractor selection process. After this evaluation process, they select an optimal combination of subcontractors that will carry out the work packages in the project. It is not an easy task for a general contractor to select the most appropriate combination, which balances the trade-off between time, cost and quality. The main objective of this study is to generate a discrete particle swarm optimization algorithm (DPSO), which will assist general contractors to select the most appropriate subcontractors that will carry out different work packages in a construction project considering the trade-off between time, cost and quality. In order to illustrate how this algorithm can be used in the subcontractor selection problem, the data obtained from a trade centre project is used. Findings of the research revealed that the proposed algorithm is satisfactory.

Keywords: subcontractor selection, time-cost-quality trade-off, discrete particle swarm optimization.

INTRODUCTION

Nowadays, general contractors usually prefer to act as construction management agencies. They generally win the contract, subdivide the tasks that need to be completed in the project into main work packages, and contract these work packages out to different subcontractors. The actual production work is carried out by subcontractors, whereas the general contractors are responsible for organizing, controlling and coordinating the works of the selected subcontractors. Since the general contractors are directly responsible for the quality of the works performed by the subcontractors to the owner/client, the subcontractors play critical role in the overall performance of the project and thereby the success of the general contractor.

Subletting large portions of construction activities to subcontractors promise several benefits to general contractors, such as; 1) reduced liability for labour retention as well as reduced overheads, especially during periods of low construction activity; 2) risk

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sharing arrangements with subcontractors for their specific work packages; 3) higher quality and productivity from a core of people engaged in specialist work packages; and 4) better cost control through fixed-price subcontracting (CIDB, 2013). In spite of these benefits, subcontracting is also very risky practice as it requires the coordination of subcontractors, control of the quality and progress of subcontractors' works (Karim *et al*., 2006; Ng *et al*., 2009; Cooke and Williams, 2013).

In practice, general contractors usually tend to select their subcontractors after they sign the contract with the owner at the very beginning of the project or when the specific tasks to be done by the subcontractor get closer. Therefore, general contractors usually do not have adequate time to evaluate and select subcontractors in a realistic way. General contractors select their subcontractors based on two traditional approaches, which are: selecting the subcontractor, who offers the lowest bid price (Tserng and Lin, 2002; Mbachu, 2008; Hartmann *et al*., 2009) or selecting the subcontractor whom they know from previous projects (Tserng and Lin, 2002; Ulubeyli, *et al*., 2010; Choudhry *et al*., 2012). Selecting the subcontractors based on only the lowest the bid price criterion may bring about severe problems such as; employing unskilled, inexperienced, and financially inadequate subcontractors. On the other hand, working with the known subcontractors may result in problems in cost control; usage of new technologic innovations; and negotiation processes (Tserng and Lin, 2002). Therefore, general contractors should consider several criteria when they select their subcontractors.

In the construction management literature, there are a great number of valuable studies that deal with subcontractor selection problem. The common point of these studies is that they all focus on selecting the most appropriate subcontractor for one work package in the project. However, in real life, general contractors usually divide construction projects into major work packages and sublet most/all of these work packages to the subcontractors, who are selected through bidding or negotiation. Since the overall performance of the project is directly affected by the performances of the subcontractors, who undertake different work packages in the construction project, the interactions between all subcontractors should be considered during the subcontractor selection process. The main contribution of this study is that it considers the subcontractor selection process as a time-cost-quality trade-off problem and takes into account the interactions between the subcontractors, who are in charge of carrying out different work packages in the project, during the subcontractor selection process. This study proposes a multi objective optimization model, which aims to assist general contractors in selecting the most appropriate subcontractors. The selection model aims to optimize the time, cost and quality performances of the subcontractors. In the proposed model, discrete particle swarm optimization algorithm (DPSO) is employed.

PREVIOUS WORKS ON TIME-COST-QUALITY TRADE-OFF PROBLEM

Time, cost and quality are three conflictive objectives. It is even hard to provide compromise solutions between these objectives. In the construction management literature, several researchers (Khang and Myint, 1999; El-Rayes and Kandil, 2005; Pollack-Johnson and Liberatore, 2006; Afshar *et al*., 2007; Tareghian and Taheri, 2006, 2007; Rahimi and Iranmanesh, 2008; Zhang and Li, 2010; Zhang and Xing, 2010; Zhang *et al*., 2013; Mungle *et al*., 2013; Heravi and Faeghi, 2014; Tavana *et al*., 2014) made significant efforts to solve the time-cost-quality trade-off problem in the construction projects. The solution methods employed in these studies can be categorized into three main groups, namely (1) mathematical algorithms, (2) heuristic algorithms, and (3) evolutionary algorithms. Among these groups, evolutionary algorithms are the most favourable one because of the fact that they are capable to deal with more than one objective, easily achieve diverse solutions and better in complex problems compared to the other algorithms. Genetic algorithm (El-Rayes and Kandil, 2005; Mungle *et al*., 2013; Tavana *et al*., 2014), particle swarm optimization (Zhang and Xing, 2010), ant colony algorithm (Afshar *et al*., 2007), and electromagnetic scatter search (Tareghian and Taheri, 2007) are some of evolutionary algorithms used in time-cost-quality trade-off problem.

RESEARCH METHODOLOGY

Particle swarm optimization

Particle swarm optimization (PSO) is a population based stochastic optimization technique, which is commonly used to search an optimal solution in the search space. It was first developed by Eberhart and Kennedy (1995). This optimization technique is a kind of swarm intelligence inspired from the social behaviour and dynamic movement of flocks of birds and schools of the fishes (Tripathi *et al*., 2007). Basically, PSO algorithm integrates self-experiences of the particles with their social experiences to search for globally optimal solutions (Song, 2014). A proper PSO algorithm must have an ability to combine exploration (i.e., ability to check different regions of the space to find optimum) with exploitation (i.e., ability to converge the search promising regions to locate optimum) in order to provide balance in the algorithm and achieve the effective solution in the search space (Parsopoulos and Vrahatis, 2004, 2007; Zhang and Li, 2010). PSO uses particles to move around in the search space searching for the best solution, and these particles also constitute a population, which is called *swarm* (Parsopoulos and Vrahatis, 2008). In this algorithm, each particle has a memory (i.e., ability to remember) to store its flying experience especially for identifying its best position (Parsopoulos and Vrahatis, 2008). The algorithm aims to move particles gradually towards better areas of the solution space for obtaining optimal solutions. The direction of the movement of each particle is adjusted according to the function of algorithm. The position and velocity of the each particle is adjusted according to the best position visited by itself (i.e., pbest) and the best position visited by the entire swarm (i.e., gbest) at each step. The PSO algorithm is initialized randomly. In a D-dimensional space position of i^{th}particle is represented with $x_i(t) = (x_{i1}(t), x_{i2}(t), \cdots, x_{iD}(t))$, and its velocity is presented with $v_i(t) = \left(v_{i1}(t), v_{i2}(t), \cdots, v_{iD}(t)\right)$, and as well as its best position is shown by $pbest_i = (p_{i1}, p_{i2}, \cdots, p_{iD})$.

Steps of basic PSO algorithm are as follows:

1. Initialize swarm (i.e., initialize particles position and velocity randomly);
2. Evaluate each particle position based on the objective (fitness) function;
3. Update particles (pbest) (if the current position is better than its previous position);
4. Determine the best particle (gbest) (choose the particle with best fitness value as the gbest from entire swarm);
5. Update particles velocity (Using Eqn. 1)

$$V_{ij}^{t+1} = wV_{ij}^{t} + c_1 r_1\left(pbest_i - X_{ij}\right) + c_2 r_2\left(gbest_i - X_{ij}\right) \qquad (1)$$

6. Move particles to their new positions (Using Eqn. 2)

$$X_{ij}^{t+1} = X_{ij}^{t} + V_{ij}^{t+1} \tag{2}$$

7. Go to step 2 until stopping criteria is not satisfied;

The definitions of the parameters in Equation (1) are as follows: w is the inertia weight; V_{ij}^{t} is velocity of the particle i, the position of the particle i is denoted as X_{ij}; c_1 and c_2 are two acceleration coefficients, which denote for cognitive and social parameters respectively and are set as 2; $r_1$and r_2 are two uniformly distributed random numbers that are generated within the range of [0, 1]; $pbest_i$ is the best position of the particle; $gbest_i$ is the global best position of the entire swarm; and t is the iteration number. The new position of the particle is updated by using Equation (2); here the new position of the particle is denoted by X_{ij}^{t+1}, X_{ij} is the current position, and V_{ij}^{t+1} is the updated velocity of the particle (Kumar and Minz, 2014).

Problem formulation

Time-cost-quality trade-off problem is a multi-objective optimization problem. In this study, three conflictive objectives are optimized simultaneously. In other words, while time (T) and cost (C) are minimized, quality (Q) is maximized. Equation (3) represents the objective (fitness) function of the multi objective subcontractor selection problem;

$$f \rightarrow Minimization\ (f_T, f_C, \frac{1}{f_Q}) \tag{3}$$

The first objective of the trade-off problem is the minimizing total duration of the project. This objective is expressed with the following equation (4);

$$T = \max \sum_{i=1}^{m} d_{n_i} \tag{4}$$

where T is the total duration of the project, d_{n_i} is the duration of the work package of i on the critical path, m is the total number of work packages in the project, and n_i is the number of subcontractor option for the work package i. Minimizing total cost of the project is the second objective. This objective is calculated by the following equation (5);

$$C = \left\{ \begin{array}{ll} \left(\sum_{i=1}^{m} \sum_{j=1}^{n_i} C_{ij} + IC \times T + \beta [T - D] \right); & if\ T \geq D \\ \left(\sum_{i=1}^{m} \sum_{j=1}^{n_i} C_{ij} + IC \times T - I[D - T] \right); & if\ T \leq D \\ \left(\sum_{i=1}^{m} \sum_{j=1}^{n_i} C_{ij} + IC \times T \right); & if\ T = D \end{array} \right\} \tag{5}$$

where C is the total cost of the project, C_{ij} is the cost of subcontractor option j for activity i, IC is the daily indirect cost, β is the daily penalty cost, T is the total duration of the project, D is due date of the project and I is the daily incentive cost. The third objective is the maximizing overall quality of the project. Equation (6) is used to compute this objective;

$$Q = \sum_{i=1}^{m} w_i \times q_i \tag{6}$$

where Q is the overall quality of the project, w_i is the weight of work package i, and q_i is the quality percentage of the subcontractor option j for activity i.

Development of the Proposed Discrete Particle Swarm Optimization (DPSO) Algorithm

PSO is usually employed to solve continuous problems because of its nature. However, many optimization problems are in discrete type and these problems could only be handled by transforming continuous form of algorithms into discrete form. Time-cost-quality trade-off problem is also a discrete multi-objective optimization problem. Therefore, the PSO algorithm should be developed in a discrete form. The proposed algorithm (DPSO) aims to find most appropriate subcontractors to be worked with for all work packages in a project based on their time-cost-quality performances. In this algorithm, the objective function consists of three objectives, and the algorithm is employed to search for optimal subcontractor sequences, which satisfy the minimum time and cost, and maximum quality objectives. In the DPSO algorithm, the swarm composes of various subcontractor sequences, and a particle corresponds to one of these sequences (see Figure 1).

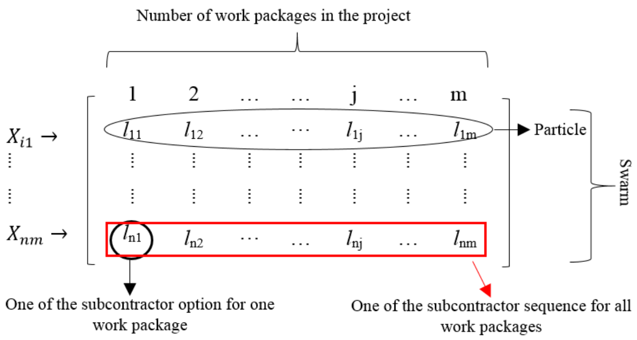

Figure 1: Swarm and particles of representation in the proposed algorithm

The DPSO algorithm was developed as it was explained in the previous sections. In the developed algorithm, the total project duration is determined by using Equation 4. Then, the total cost of the project is calculated using Equation 5. In this equation, the early finish is rewarded with incentive cost; conversely late finish is penalized with penalty cost. The third objective, the overall quality of the project is the computed with Equation 6. Finally, the fitness value of the each particle is evaluated by using Equation 3. Based on the fitness value, the personal best (pbest) for each particle and the global best particle (gbest) in the swarm are identified to guide the swarm in the next iteration. The gbest is determined by using crowded distance (CD) of the each particle that exists in the external archive. The particle with the highest crowded distance is selected as gbest. When archive is full, CD is also used to replace new solutions with existing solutions in the archive. CD is calculated with the following equation:

$$d_{k,k-1} = \sqrt{\left(f_1(X_k) - f_1(X_{k-1})\right)^2 + \left(f_2(X_k) - f_2(X_{k-1})\right)^2 + \left(f_3(X_k) - f_3(X_{k-1})\right)^2} \qquad (7)$$

where $d_{k,k-1}$ is the Euclidean distance from the non-dominated solution of X_k from its one of the adjacent neighbour. $f_1(X_k)$, $f_2(X_k)$ and $f_3(X_k)$ are the time, cost and quality values of the fitness function respectively. The described process repeated until the stopping criterion is satisfied.

Case study

In this study the DPSO was developed using the MATLAB software. After developing the DPSO, the data of the trade centre project is used to run the algorithm. This project was built in Samandira, Istanbul, Turkey in 2014 by one of the largest healthcare groups in Turkey. The estimated construction cost was $7,313,258.07, the total construction area was 2,000 m^2, the anticipated duration for the project was 500 days, and the contract type was turn-key. In the project, the tasks were grouped into 20 main work packages (i.e., A,…,U). General contractor aimed to perform all these 20 work packages by means of subcontracting. The definitions of 20 work packages are as follows; A: Excavation works, B: Insulation works, C: Core construction works, D: Brick laying, E: Facade works, F: Elevator assembly, G: Plaster works, H: Mechanical works, I: Electrical works, J: Screed works, K: Plasterboard works, L: Epoxy coating, M: Marble coating works, N: Indoor insulation works, O: Ceramic tiles works; P: Door assembling, R: Painting works, S: Furniture and sanitary work, T: Carpet works, and U: Landscaping. Based on the predecessor and successor relationships of these work packages, the network diagram of the trade centre project was constructed (see Figure 2).

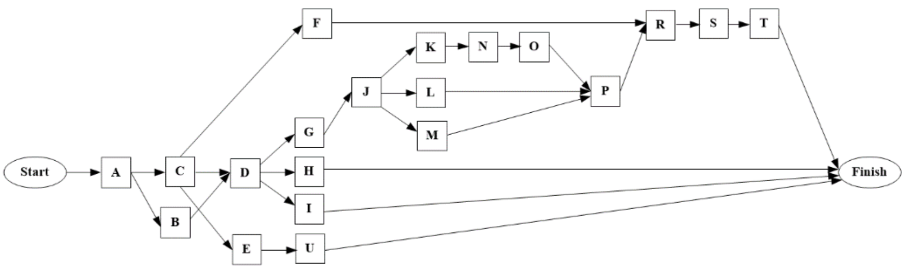

Figure 2: Work packages network diagram

General contractor invited three subcontractor candidates to bid for specified work packages. In other words, three subcontractor options (i.e., Option_1, Option_2 and Option_3) submitted their bids for each work package in the project. In the trade centre project, the duration and bid price values were taken from the bid files of the subcontractors, and the quality of the subcontractors were subjectively evaluated based on the experiences of the general contractors' top managers. Duration, bid price and quality values of the subcontractor options for each work package is presented in Table 1.

Table 1. Subcontractor Options According to the Work packages

Work Packages	Option_1 Duration (days)	Option_1 Bid Price ($)	Option_1 Quality (%)	Option_2 Duration (days)	Option_2 Bid Price ($)	Option_2 Quality (%)	Option_3 Duration (days)	Option_3 Bid Price ($)	Option_3 Quality (%)
A	90	1,244,608.29	74	95	1,235,345.62	70	100	1,193,548.39	68%
B	60	170,368.66	79	68	167,050.69	77	72	163,502.30	75%
C	120	1,506,682.03	71	130	1,470,414.75	69	140	1,405,944.70	65%
D	30	85,437.79	87	33	83,041.47	86	35	80,000.00	83%
E	120	420,368.66	90	125	410,092.17	85	130	404,331.80	80%
F	90	255,483.87	85	95	253,824.88	83	100	253,271.89	80%
G	30	108,940.09	72	33	107,695.85	70	36	106,866.36	69%
H	120	584,562.21	77	130	585,345.62	85	135	603,686.64	95%
I	120	479,032.26	82	125	502,350.23	89	130	507,235.02	93%
J	20	123133.64	70	27	121,152.07	75	32	119,631.34	78%
K	50	182,258.06	88	55	179,907.83	92	60	178,894.01	94%
L	20	80,967.74	74	18	79,354.84	68	15	77,603.69	65%
M	15	56,682.03	77	14	55,668.20	72	13	54654.38	69%
N	15	40,921.66	86	13	42,488.48	91	12	43,778.80	94%
O	20	68,341.01	88	18	70,322.58	91	16	71,428.57	95%
P	15	65,852.53	79	16	63,456.22	75	19	62,811.06	68%
R	45	103,917.05	81	42	105,990.78	77	35	106,958.53	73%
S	20	129,585.25	95	25	128,387.10	90	30	122,488.48	87%
T	20	638,847.93	87	26	617,557.60	82	32	593,732.72	79%
U	60	80,875.58	91	55	83,041.47	85	50	83,870.97	82%

Implementation of the developed multi objective optimization model in the case study

In the studied project, the main objective is to identify the most appropriate combination of subcontractors to be worked with, which offers the minimum project duration and cost, and maximum quality. Since the studied trade centre project consisted of 20 work packages and there are 3 alternative subcontractors for each work package, there are 3.4 billion different subcontractor combinations and each of these combinations will bring about different duration, cost and quality values.

In the first step, the total duration of the trade centre project was calculated by using the critical path method (CPM). For this purpose, the potential paths in the studied project were identified and the durations of these paths were calculated by taking the sum of the durations of the work packages in these paths. Among these paths, the path with the longest duration considered as the total project duration. It should be noted that, the critical path changes in each run due to the change in the combination of subcontractors, so the total project duration was re-calculated in each run.

In the second step, the total cost of the project is calculated based on the due date of the trade centre project. The due date of the trade centre project (D) was given as 500 days and the daily indirect cost was $230.42. Moreover, the early finish (i.e., $T < D$) is rewarded with incentive cost, conversely late finish (i.e., $T > D$) is penalized with penalty cost in the studied project. The incentive payment was $345.62 per day, and the penalty cost was $460.83 per day. The overall quality of the project is evaluated in the third step. In this project, the weight of each work package (w_i) was considered to be equal and set to 1. The optimal control parameters of the DPSO algorithm are taken from the literature review study on multi objective PSO algorithm (Reyes-Sierra and Coello, 2006). The control parameters and boundaries of the objectives are presented in Table 2.

Table 2: Parameters used in the proposed DPSO algorithm

Parameters of the model	Values	Parameters of the model	Values
Swarm size	20	Upper bound of cost	$6,589,170.51
Archive size	100	Upper bound of quality	85%
w_{min} and w_{max}	(0.9, 1.2)	Lower bound of time	458 days
c_1 and c_2	2	Lower bound of cost	$6,318,986.18
r_1 and r_2	[0, 1]	Lower bound of quality	77%
Upper bound of time	564 days	Maximum iteration number	500

RESULTS AND DISCUSSION

After running the DPSO algorithm properly, non-dominated solutions were collected in the external achieve. Since the discussed problem is multi objective optimization problem, it is usual to have more than one optimal solution. This research aims to propose a set of optimal solutions to the decision makers from which they can select the subcontractor combination, which fulfils their targets. Among the obtained solutions, nine different Pareto-optimal solutions are presented in Table 3.

Table 3: Nine Pareto optimal subcontractor sequences for each work packages

Solution	Optimal subcontractor combinations	Project performance		
		Time (day)	Cost ($)	Quality (%)
1	1-1-1-1-1-1-1-1-1-1-1-1-1-1-1-1-3-1-1-1	465	6,524,953.92	81.25
2	3-1-1-1-1-1-1-3-1-1-1-1-1-1-1-1-3-1-1-1	475	6,498,758.06	81.85
3	3-1-1-1-1-1-1-1-1-1-1-1-1-1-1-1-3-1-1-1	475	6,479,654.38	80.95
4	3-1-3-1-1-1-1-3-1-1-1-1-3-3-3-1-3-1-1-1	488	6,409,447.00	81.90
5	3-1-3-1-1-1-1-3-1-1-1-1-3-2-3-1-3-1-1-1	489	6,408,732.72	81.75
6	3-3-3-1-1-1-1-2-1-1-1-1-3-3-3-1-3-1-3-1	500	6,346,036.87	80.80
7	3-3-3-1-3-1-1-2-1-1-1-1-3-2-3-1-3-1-2-1	495	6,349,654.38	80.30
8	3-3-3-1-2-1-1-3-1-1-2-1-3-3-3-1-3-1-1-1	493	6,392,834.10	81.65
9	3-1-3-1-1-1-1-3-1-1-1-1-3-3-3-1-3-1-3-1	500	6,371,244.24	81.50

According the results displayed in Table 3, if the primary target is to minimize the total duration of the project (i.e., Time: 465 days), then the decision maker should select the first solution in Table 4. To achieve the minimum duration, the general contractor should employ the corresponding subcontractor plan (i.e., subcontracting sequence A:1 , B:1, C:1, D:1; E:1; F:1; G:1; H:1; I:1; J:1; K:1; L:1; M:1; N:1; O:1; P:1; R:3; S:1; T:1; U:1) for 20 work packages. Also, this row represents the best compromise solution (i.e., Time: 465, Cost: $6,524,953.92, Quality: 81.25%), which satisfies all objectives simultaneously. If the decision maker attaches more importance to minimize the total cost (i.e., Cost: $6,346,036.87), then the subcontractor combination indicated in the sixth row (i.e., subcontracting sequence A:3 , B:3, C:3, D:1; E:1; F:1; G:1; H:2; I:1; J:1; K:1; L:1; M:3; N:3; O:3; P:1; R:3; S:1; T:3; U:1) should be selected to satisfy this target. If the quality (i.e., 81.85%) is the primary target of the project, decision maker should select the second row (with subcontracting plan A:3 , B:1, C:1, D:1; E:1; F:1; G:1; H:3; I:1; J:1; K:1; L:1; M:1; N:1; O:1; P:1; R:3; S:1; T:1; U:1) to achieve this target. In the same manner, the decision maker can make any selection from the given Pareto optimal solutions to satisfy the project's primary targets. The estimated cost of trade centre was $7,313,258.07 and the anticipated duration was 500 days. Therefore, the trade centre project could be easily executed with lower cost, less duration and high quality by selecting one of the proposed subcontracting plans for employing in the project.

CONCLUSIONS

Selecting the right subcontractor for the right job is a very important decision making problem in the construction industry. This study generated a discrete particle swarm optimization algorithm (DPSO), which aims to assist general contractors to select the most appropriate subcontractors that will carry out different work packages in a construction project considering the trade-off between time, cost and quality. The main contribution of this study is to consider the subcontractor selection problem as a multi objective optimization problem. The real data of a trade centre project was used to run the developed DPSO algorithm. Pareto-optimal solutions indicated that the developed algorithm is quite satisfactory. The developed DPSO is of benefit to general contractors as it allows them to select the most appropriate subcontractor combination among a set of optimal solutions considering their unique project targets.

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