A Genetic Algorithm for Subcontractors Selection and Allocation in Multiple Building Projects

Mohammad Reza Afshar
Amirkabir University of Technology Department of Civil Engineering: Amirkabir University of Technology Department of Civil and Environmental Engineering
Vahid Shahhosseini (shahhosseini@aut.ac.ir)
Amirkabir University of Technology Department of Civil Engineering: Amirkabir University of Technology Department of Civil and Environmental Engineering
Mohammad Hassan Sebt
Amirkabir University of Technology Department of Civil Engineering: Amirkabir University of Technology Department of Civil and Environmental Engineering

---

Research Article

Keywords: Subcontractors selection, Subcontractors assignment, Genetic algorithm, multiple project environment

Posted Date: April 26th, 2021

DOI: https://doi.org/10.21203/rs.3.rs-219258/v1

Version of Record: A version of this preprint was published at Soft Computing on July 19th, 2021. See the published version at https://doi.org/10.1007/s00500-021-06008-5.

A Genetic Algorithm for Subcontractors Selection and Allocation in multiple building projects

Mohammad Reza Afshar[a], Vahid Shahhosseini[b, 1], Mohammad Hassan Sebt[c]

[a]Ph.D, Department of Civil Engineering, Amirkabir University of Technology, Tehran, Iran.

[b]Assistant professor, Department of Civil Engineering, Amirkabir University of Technology, Tehran, Iran.

[c]Full professor, Department of Civil Engineering, Amirkabir University of Technology, Tehran, Iran.

Abstract

In construction industry general contractors (GCs) need to manage and conduct numerous projects simultaneously. To this aim, they usually have subcontractors conduct available tasks and projects. So, subcontractor management is becoming a major challenge. To deal with this challenge, GCs aim to reduce total costs of projects including employment /subcontracting costs, indirect costs, tardiness penalties, and the money which must be paid for movement of workforce from one project to another. The aim of current research study is to propose a model for selecting subcontractors and assigning available tasks in the project to them in order to reduce the costs of the GC. Then, a genetic algorithm (GA) is proposed to solve a real problem. The proposed algorithm is innovative from three points of view: (1) generation of initial population; (2) subcontractor assignment approach and (3) the objective function. The problem was also solved by means of an exact method. Then, the results of proposed algorithm were compared to the outcomes of the exact method. This comparison shows that the proposed algorithm can efficiently help GCs select subcontractors and assign available tasks to each subcontractor when several projects must be carried out simultaneously.

Keywords: Subcontractors selection, Subcontractors assignment, Genetic algorithm, multiple project environment.

[1] Corresponding author: Tel. 0098-9122383411.

E-mail addresses: m.afshar67@aut.ac.ir (Mohammad Reza Afshar), shahhosseini@aut.ac.ir (Vahid Shahhosseini), sebt@aut.ac.ir (Mohammad Hassan Sebt)

Full postal address. Iran, Tehran, Hafezstreet, Amirkabir University of Technology, Postal code: 158754413.

1. Introduction

One of the initial steps in project planning is to identify the right subcontractors and assign the available work packages of a project to them. In this research study the word subcontractor means the contractors who are working as some groups at the lowest level in the hierarchy of contractors in a project. For example, the ones who are involved in concreting or reinforcing operations.

Pells (1993) mentioned that “the selection of subcontractors is a difficult and time-consuming process”. General contractor (GCs) usually have limited information about real cost and duration of a project because these parameters depend on capabilities of the subcontractors who carry out the work packages of the project.

Many researchers have studied subcontractor selection in the literature to introduced quantitative approaches to help GCs in this regard (Monghasemi et al., 2003). Most of these approaches have been based on multi-criteria decision making approaches (Afshar et al., 2020; Afshar et al., 2017; Fachrurrazi and Munirwansyah, 2017; Ulubeyli and Kazaz, 2016; Polat, 2016; Abbasianjahromi et al., 2014, Abbasianjahromi et al., 2013). Recent research studies show that a significant proportion of them did not consider the impact of subcontractor selection on overall features of the project including project duration, cost, and feasibility. While, these features are closely linked to performance of subcontractors. Hence, mathematical models were applied more to consider the effect of subcontractor selection on the overall features of a project (Afshar et al., 2020; Sonmez and Gürel, 2016, Polat et al., 2015; Beşikci et al., 2015; Mungle et al.,2013; Mokhtari and Abadi, 2013; Pollack-Johnson and Liberatore, 2006; Józefowska et al., 2001). However, most of these models have studied subcontractor selection when the GC had to conduct only one project.

Whereas, most of GCs must carry out several projects simultaneously (El-Abbasy et al., 2017). To make the problem more realistic, it is necessary to consider the condition in which the GCs need to conduct numerous projects at the same time. Taking these realistic situations in consideration makes the model and the formulation more complicated. To deal with these realistic problems, Afshar et al. (2020) investigated the problem of subcontractor selection when the GC must conduct numerous projects at the same time. However, their model did not consider the appropriate assumption of the projects in construction industry. Additionally, more actions need to be taken in order to consider some other aspects of the project including the cost of employed skilled workers and subcontractors and the time which employed skilled workers and subcontractors need to move from one project to another one. So, it is necessary to reach a more practical approach.

Another drawback is that Afshar et al. (2020) used CPLEX solver of the general algebraic modelling system (GAMS) for solving the problem. However, application of precise techniques would fail to solve the problem in a reasonable computing time because the problem itself was a Non deterministic Polynomial-time hard (NP-hard) type and real construction projects include multiple work packages and subcontractors (Afshar et al., 2020). Thus, in practice, metaheuristic algorithms are required for large construction projects to generate near optimal solutions in reasonable computational time.

In order to fill the mentioned gaps, the current study tries to propose a real model for subcontractor selection and allocation in multiple building projects that fits the real situation. Also, a metaheuristic algorithm is presented to reach desirable solutions.

The remainder of the paper is organized as follows. Section 2 presents the contributions of current study. The problem description is stated in the third section. In section 4, the proposed procedure for solving the subcontractor selection and allocation problem is discussed. The computational experiments are performed in section 5 in order to prove the effectiveness of the proposed model and metaheuristic algorithm. In the end, some conclusions are presented in Section 6

2. Contributions

The aim of current research study is to propose a model to select subcontractors in order to reduce the expenses of the GC in conventional building projects when the GC wants to carry out numerous projects at the same time. To this aim, first the required assumption will be discussed and then the model will be proposed. In this model, different locations, time and effort which is required for movement of employed skilled workers and subcontractors from one project to another are considered. Then, a GA is developed to solve the problem. Innovation of the proposed algorithm can be discussed in three ways:

This algorithm proposes a heuristic method to generate a part of the initial population. An infeasible tackling procedure is also presented to convert infeasible solutions to feasible ones; and a simple fitness function is proposed to handle feasible and infeasible solutions.

To validate the efficiency and feasibility of the proposed model and proposed GA, a real case study of building industry is included.

3. Problem statement

The list of notations which are used in this research study is presented in this part.

Sets and Indices

i, h	Set of work packages
j,g	Set of projects
k	Set of SCs
f	Set of discount levels
SC_{ij}	Set of SCs that can perform work package *i* of project *j*
n_j	Number of work packages of project *j*
pw_j	Predecessors set of project *j*
TC	Total cost

Parameters

IC_j	The indirect cost of project *j* per time period
Cy_k	Full time employment of skilled workers that work for subcontractor *k* (the group of skilled workers *k*) per time period
CT_{jg}	Transfer cost of one subcontractor or one group of skilled workers from project j/g to project g/j.
Bp_{ijk}	The bid price for work package *i* of project *j* proposed by SC *k*
B_j	Early completion bonus of project *j* as per earliness period
I	Maximum number of work packages that GC intends to sublet to each SC
Sp_j	The earliest start time of project *j*
d_{ijk}	Duration of work package *i* of project *j*, operating by SC *k*
d'_{ijk}	Duration of work package *i* of project *j*, operating by group of skilled workers *k*
d''_{jg}	Transfer time of one subcontractor or one group of skilled workers from project j/g to project g/j.
L_{hij}	Time lag between work package *h* and work package *i* in project *j*
A_{fk}	Minimum number of work packages that should be sublet to the SC *k* in order to activate the level *f* of his/her discount levels
B_{fk}	Maximum number of work packages that should be sublet to the SC *k* in order to activate the level *f* of his/her discount levels
IF	Incentive fee
DP_{fk}	Discount percentage of level *f* presented by SC *k*
M	A very large number
DD_j	Due date of project *j*

Decision variables

T_j	Completion time of project *j* (integer variable).
To_k	Completion time of collaboration between GC and group of skilled workers *k* (integer variable).
W_k	Time of collaboration between GC and group of skilled workers *k*
N_k	Percent of SC *k*'s bid prices paid to him/her when one of his/her discount levels is activated (positive variable).
nx_{ijk}	Linearization auxiliary variable (positive variable).
SW_{ijk}	Start time of work package *i* of project *j*, operating by SC *k* (integer variable).
SSW_{ijk}	Linearization auxiliary variable (integer variable).
SW'_{ij}	Start time of work package *i* of project *j*, operating by group of skilled workers *k* (integer variable).
SSW'_{ijk}	Linearization auxiliary variable (integer variable).
K_j	The early completion period of project *j* (integer variable).
G_j	Tardy period of project *j* (integer variable).

$$x_{ijk} = \begin{cases} 1 & \text{if work package } i \text{ of project } j \text{ is sublet to SC } k \\ 0 & \text{otherwise} \end{cases}$$

$$y_{ijk} = \begin{cases} 1 & \text{if work package } i \text{ of project } j \text{ is operated by group of skilled workers } k \\ 0 & \text{otherwise} \end{cases}$$

$$U_k = \begin{cases} 1 & \text{if group of skilled workers } k \text{ is employed on a full time basis by GC} \\ 0 & \text{otherwise} \end{cases}$$

$$P_{ijhgk} = \begin{cases} 1 & \text{if subcontractor } k \text{ or group of skilled workers } k \text{ performs work package } i \text{ of project } j \text{ before work package } h \text{ of project } g \\ 0 & \text{otherwise} \end{cases}$$

$$E_{fk} = \begin{cases} 1 & \text{if discount level } f \text{ is activated for SC } k \\ 0 & \text{otherwise} \end{cases}$$

In order to propose a model for subcontractor selection when numerous projects must be done simultaneously, first 12 assumptions of the manuscript will be discussed and then the model will be produced.

Assumption 1. In order to prevent any possible controversy or interference between subcontractors or the groups of skilled workers, each work package is assigned to one subcontractor/one group of skilled workers. This assignment will be done through employing subcontractor *k* or full time employment of the group of skilled workers which work for subcontractor *k* (From this point as far as the end of the manuscript group of skilled workers *k* means a groups of skilled workers which works for subcontractor *k* and which is employed on a full time basis by GC to carry out the related work packages).

Equation 1 which is mentioned below guarantees this issue.

$$\sum_{k=1}^{SC_{ij}} y_{ijk} + \sum_{k=1}^{SC_{ij}} x_{ijk} = 1 \qquad \forall\ j,i \in n_j \qquad (1)$$

Assumption 2. In order to restrict the influence of subcontractors on overall process of the project and to restrict their capability to stop the project, the number of work packages which can be assigned to each subcontractor will be limited. The level of limitations will be determined by the GC. Equation 2 ensures this policy.

$$\sum_{j=1}^{N} \sum_{i=1}^{n_j} x_{ijk} \leq I \times (1 - U_k) \qquad \forall\ k \qquad (2)$$

Assumption 3. When the group of skilled workers k is employed to carry out the projects, the GC has more capability to control them. So, no limitation will be set on the number of the work packages which the group of skilled workers k can conduct. Equation number 3 grantees this situation.

$$\sum_{j=1}^{N}\sum_{i=1}^{n_j} y_{ijk} \leq M \times U_k \qquad \forall\ k \qquad (3)$$

Assumption 4. When more than one work package is assigned to one subcontractor or one group of skilled workers, they might not be able to carry out the work packages simultaneously due their limited capability. Equations number 4 and 5 confirms this approach.

$$P_{ijhgk} + P_{hgijk} \leq 1 \qquad \forall\ i, \mathrm{j}, \mathrm{h}, \mathrm{g}, k \qquad (4)$$

$$\begin{aligned}(SW'_{ijk} + d'_{ijk})y_{ijk} + (SW_{ijk} + d_{ijk})x_{ijk} \\ \leq y_{hgk} * SW'_{hgk} + x_{hgk} * SW_{hgk} + M(1 - P_{ijhgk})\end{aligned} \qquad \begin{aligned} i \neq h \\ j = g \end{aligned} \qquad (5)$$

Assumption 5. Movement of one subcontractor or one group of skilled workers from one work package to another in one project has been considered in assumption 4. However, the time and money which must be spend on these items have not been taken into account. This fact is happened when the movement is occurred among the work packages of different projects. Accordingly, the time which is required for subcontractors or the group of workers to move from one project to another one must be considered. Equations 6 and 7 show this issues. The cost of movement is also expressed in the objective function.

$$P_{ijhgk} + P_{hgijk} \leq 1 \qquad \forall\ i, \mathrm{j}, \mathrm{h}, \mathrm{g}, k \qquad (6)$$

$$j \neq g$$

$$\left(SW'_{ijk} + d'_{ijk}\right)y_{ijk} + \left(SSW_{ijk} + d_{ijk}\right)x_{ijk} + d''_{jg} \leq y_{hgk} * SW'_{hgk} + x_{hgk} * SW_{hgk} + M(1 - P_{ijhgk}) \quad (7)$$

Assumption 6. Since most of the precedence relations among the activities in conventional building projects is based on finish to start criteria with lag (Sonmez and Gürel, 2016), in this project the precedence relations are considered based on the above-mentioned criteria which is expressed in equation number 8.

$$\sum_{k=1}^{SC_{hj}} \left(SW'_{hjk} + d'_{hjk}\right)y_{hjk} + \sum_{k=1}^{SC_{hj}} (SW_{hjk} + d_{hjk})x_{hjk} + L_{hij} \leq \sum_{k=1}^{SC_{ij}} y_{ijk} \times SW'_{ijk} + \sum_{k=1}^{SC_{ij}} x_{ijk} \times SW_{ijk} \qquad \forall\ j,(h,i) \in pw_j,\ h \neq 0 \quad (8)$$

Assumption 7. Starting time of each project must be after official date of that project which is mentioned in the contract. Equation 9 confirms this point.

$$Sp_j \leq \sum_{k=1}^{SC_{ij}} y_{ijk} \times SW'_{ijk} + \sum_{k=1}^{SC_{ij}} x_{ijk} \times SW_{ijk} \qquad \forall\ i,j \quad (9)$$

Assumption 8. When the group of workers k is employed by the GC, the duration of their collaboration with the GC is calculated based on deadline of the projects that they took part in. So, the duration of collaboration is calculated based on Equations 10. Equation 11 calculates the time that the group of skilled workers collaborates with the GC.

$$To_k - y_{ijk} \times SW'_{ijk} - M \times (1 - y_{ijk}) \leq W_k \qquad \forall\ i,j,k \quad (10)$$

$$To_k \geq T_j - M \times (1 - y_{ijk}) \qquad \forall\ i,j,k \quad (11)$$

Assumption 9. If more than one work package is assigned to one subcontractor, the subcontractor would offer a discount because its unemployment costs will reduce under this circumstance. In this research project, the discount is defined by different levels of discount.

Each discount level includes a discount percentage which is applied to subcontractor's bid price. By increasing the number of work packages which are assigned to a subcontractor through subcontracting, the discount percentage will increase. Equations 12 and 13 activate one of the discount levels for subcontractor k. Here, Equation 14 calculates the percentage of subcontractor k bid price which must be paid to this subcontractor (N_k).

$$A_{fk} - M\left(1 - E_{fk}\right) \leq \sum_{j=1}^{N} \sum_{i=1}^{n_j} x_{ijk} \leq B_{fk} + M(1 - E_{fk}) \qquad \forall\, f,k \qquad (12)$$

$$\sum_{f=1}^{F} E_{fk} \leq 1 \qquad \forall\, k \qquad (13)$$

$$1 - \sum_{f=1}^{F} D_{fk} \times E_{fk} = N_k \qquad \forall\, k \qquad (14)$$

Assumption 10. In order to improve the reputation of the GC in front of the main employer, all the projects must be finished within the specified deadline. Equation 15 grantees this point and Equation 16 calculated the duration of the project (j)

$$T_j \leq DD_j \qquad \forall\, j \qquad (15)$$

$$\sum_{k=1}^{SC_{ij}} \left(SW'_{ijk} + d'_{ijk}\right) y_{ijk} + \sum_{k=1}^{SC_{ij}} (SW_{ijk} + d_{ijk})\, x_{ijk} \leq T_j \qquad \forall\, i,j \qquad (16)$$

Assumption 11. If the GC finishes the project sooner than the specified deadline, it will be rewarded. This point is calculated by Equation 17.

$$K_j = DD_j - T_j \qquad \forall j \qquad (17)$$

Assumption 12. Indirect costs are directly linked to the duration of each project and are determined based on the size of the project in objective function (Equation 18). Determination of these costs are not the subject of study in the current research project. In this research project it is assumed that these costs are determined based on the experience of the GC.

Under the mentioned constraints, the GC as an economic organization seeks a way to minimize the total cost. Thus, the objective function (Equation 18) is equal to the total cost of the projects includes the following terms:

a) The cost of employing group of skilled workers (k) ($\sum_{k=1}^{K} Cy_k \times W_k$),

b) payment to the subcontractors ($\sum_{j=1}^{N} \sum_{i=1}^{n_j} \sum_{k=1}^{K} Bp_{ijk} \times N_k \times x_{ijk}$),

c) indirect costs ($\sum_{j=1}^{N} IC_j * T_j$),

d) incentive fee ($\sum_{j=1}^{N} B_j G_j$), and

e) the money which GC should pay to subcontractors or the groups of employed skilled workers for their movement from one project to another one ($\sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{h=1}^{I} \sum_{\substack{g=1 \\ j \neq g}}^{J} \sum_{k=1}^{K} CT_{jg} P_{ijhgk}$).

$$MIN\ TC = \sum_{k=1}^{K} Cy_k \times W_k + \sum_{j=1}^{N} \sum_{i=1}^{n_j} \sum_{k=1}^{K} Bp_{ijk} \times N_k \times x_{ijk} + \sum_{j=1}^{N} IC_j * T_j - \sum_{j=1}^{N} B_j G_j + \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{h=1}^{I} \sum_{\substack{g=1 \\ j \neq g}}^{J} \sum_{k=1}^{K} CT_{jg} P_{ijhgk} \qquad (18)$$

It is clear that the proposed model is a nonlinear model. Solving such a problem will be time-consuming even in small-scale problems. So, this nonlinear model will change to a linear model in the next chapters.

3.1.Linearization of the proposed model.

When some decision variables are multiplied to each other ($x_{ijk} \times SW_{ijk}$, $y_{ijk} \times SW'_{ijk}$, $x_{ijk} \times N_k$), nonlinearity will be produced in the model. In order to avoid nonlinearity, auxiliary variables of SSW_{ijk}/SSW'_{ijk}/nx_{ijk} are replaced by the mentioned multiply operations ($x_{ijk} \times SW_{ijk}$, $y_{ijk} \times SW'_{ijk}$, $x_{ijk} \times N_k$). Plus, the relationship between auxiliary variables and the main variables (equations 19 to 27) are defined in a way that the result becomes equal to the result of the multiply operations which were omitted.

$$SSW'_{ijk} \leq SW'_{ijk} \qquad \forall\ i,j,k \qquad (19)$$
$$SSW'_{ijk} \geq SW'_{ijk} - M \times (1 - y_{ijk}) \qquad \forall\ i,j,k \qquad (20)$$
$$SSW'_{ijk} \leq M \times y_{ijk} \qquad \forall\ i,j,k \qquad (21)$$
$$SSW_{ijk} \leq SW_{ijk} \qquad \forall\ i,j,k \qquad (22)$$
$$SSW_{ijk} \geq SW_{ijk} - M \times (1 - x_{ijk}) \qquad \forall\ i,j,k \qquad (23)$$
$$SSW_{ijk} \leq M \times x_{ijk} \qquad \forall\ i,j,k \qquad (24)$$
$$nx_{ijk} \leq N_k \qquad \forall\ i,j,k \qquad (25)$$
$$nx_{ijk} \geq N_k - M \times (1 - x_{ijk}) \qquad \forall\ i,j,k \qquad (26)$$
$$nx_{ijk} \leq M \times x_{ijk} \qquad \forall\ i,j,k \qquad (27)$$

4. Genetic algorithm (GA) for solving the subcontractor selection and assignment problem

The problem of subcontractor selection and assignment of the available work packages to them can be considered a part of a NP-hard type problem (Afshar et al., 2020). Accordingly, exact methods cannot solve these problems in reasonable amount of time.

Therefore, GA, as a meta-heuristic algorithm, is introduced to be used for solving this problem.

4.1.Solution representation

Before a metaheuristic algorithm started to search, a suitable representation scheme must be determined. For this aim, in current study, the random key representation (RKR) is employed to determine the work packages' priorities for scheduling. Also, the subcontractor list representation is used to for assigning the subcontractors to the work packages. The subcontractor list assigns the work package *i* to subcontractor *k* and, it identifies whether the schedule is feasible (considering the equation 2) or not. For the representation of the employment way pertaining to all subcontractors, the binary representation is applied (when a subcontractor is not selected, its employment method is not considered).

Hence, three independent chromosomes (α, β γ) are considered. α and β constitute the first part of each solution, while γ represents the second part of it. The number of genes in chromosomes α and β was set to be the same as the total number of the work packages that the GC must plan to do. Additionally, the number of genes in chromosome γ was set to be the same as the total number of subcontractors who made their bid to execute available work packages.

4.2.Primary population

Using random generation approach for producing initial population may violate the deadline limitation for all of the initial solutions [equation 15]. This violation is not favourable for evolutionary algorithms as they need reliable basis for searching. To avoid this violation, 50% of the initial population was generated by using a heuristic method. The proposed heuristic (Fig. (1)) that is applied on chromosome β tries to distribute the work packages among all subcontractors in order to prevent the delay in conducting work packages.

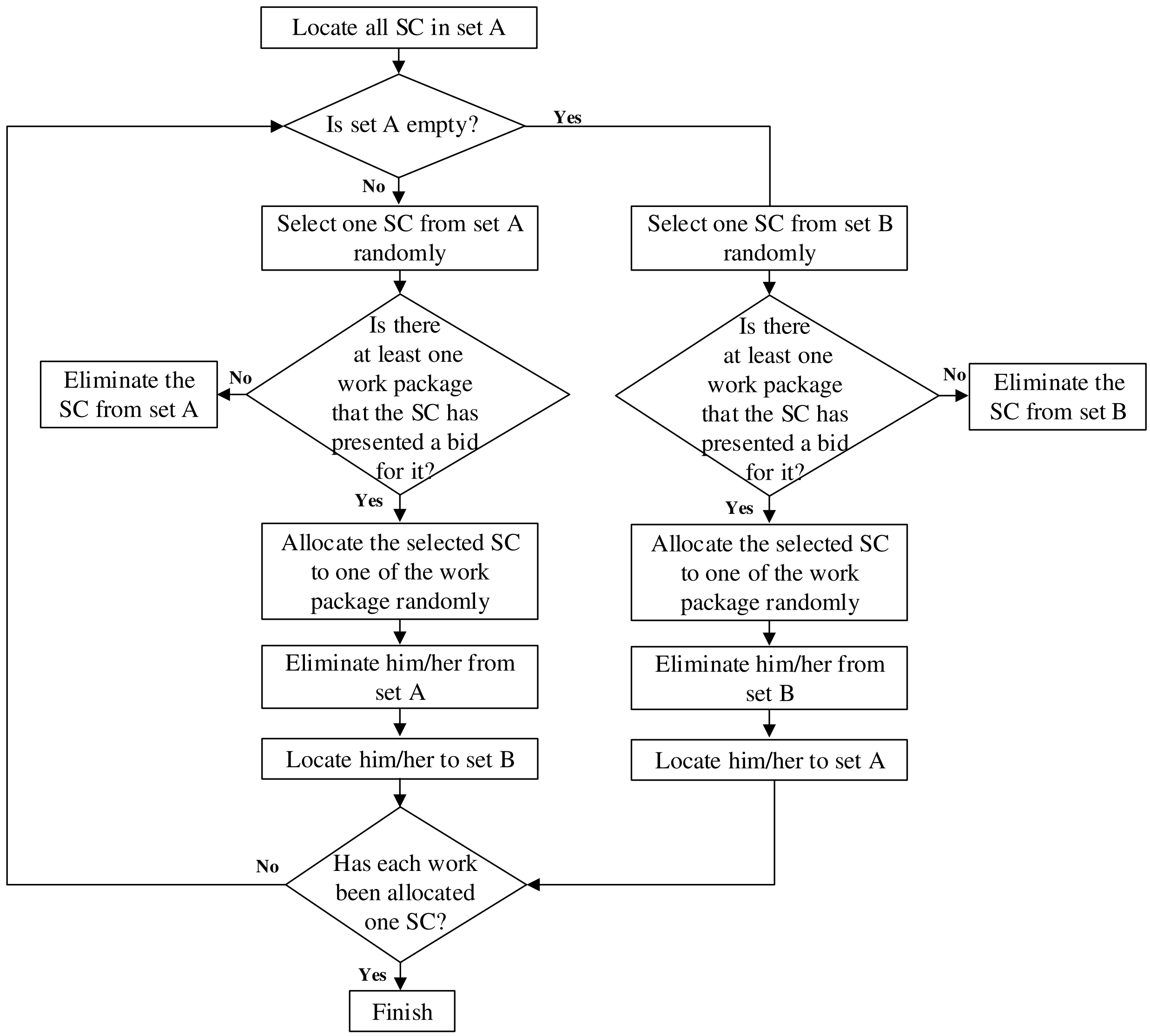


Fig. (1). Generation and development of initial solutions

4.3. Infeasible tackling procedure

Some solutions may violate equation 2. These solutions will change to feasible solutions by use of infeasible tackling procedure. Accordingly, one work package which had been assigned to a subcontractor who violated restriction number 2 is considered and it will be assigned to another subcontractor.

This process will be continued until the violation of equation 2 is removed. Afterwards, the obtained feasible solutions are allowed to be entered into the fitness function assessment.

4.4. Fitness function

To evaluate population, the solutions should be decoded with the help of a schedule generation schemes (SGS). SGS is capable of converting a solution into a schedule. A fitness value is accordingly calculated for each solution. Some solutions may violate equation 15.

In order to tackle the infeasible solutions, two approaches can be adopted. The first one is to omit the infeasible solutions and the other one is to penalize the available infeasible ones (Lee and El-Sharkawi, 2008). Since there might be a solution among the infeasible solution with low level of impossibility, it is not reasonable to omit them all. So, in this research study the second approach will be adopted and to this aim fitness function (Equation 28) is considered.

$$f(p) = \begin{cases} \text{total cost} , & \text{if } G_j \leq 0 \\ \text{total cost+ very large cost+ very large cost* } G_j, & \text{otherwise} \end{cases} \quad (28)$$

$$G_j = T_j - DD_j \qquad \forall j \quad (29)$$

When it comes to feasibility of the solutions ($G_j \leq 0$), the fitness function will be equal to the project's total cost. In the case of infeasibility of the solution, the fitness function is equal to total project cost in addition to fixed and variable penalty.

In fact, two extra costs have been considered for the infeasible cost. The role of fixed penalty is to reduce the chance of infeasible solutions to produce offspring and control the population. Besides, the variable penalty is designed to separate good and bad infeasible solutions.

4.5. Population updating mechanism

After trial and error between the possible crossover operations, two points crossover has been selected. To this aim, the chances $\frac{2}{3}$ and $\frac{1}{3}$ are assigned for parts 1 and 2, respectively (Fig. 2).

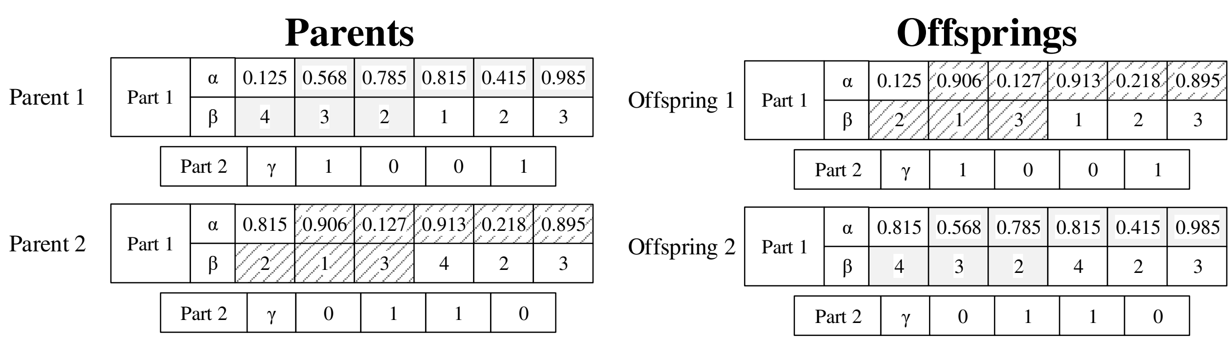


Fig. (2). Proposed crossover operator (part 1 of the solution is chosen for the application of crossover operator).

Then, mutation shall be applied randomly only on one part of each solution (Fig. 3).

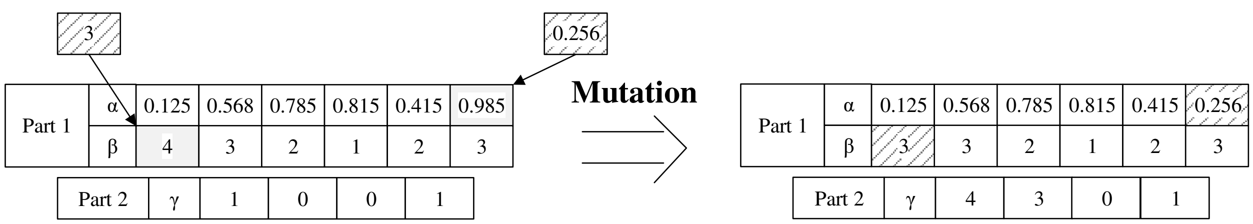


Fig. (3). Proposed mutation operator (part 1 of the solution is selected for the application of mutation operator).

In order to produce evolved population, three populations of previous generation (the population which was produced by crossover operator and the population which was produced by mutation operator) have been mixed up. Then the most appropriate individuals with *POP_size* have been moved to the next generation .

4.6.Stopping criterion

Like the other scheduling problems, a number of 5000 developed schedules are taken into account as stopping criteria.

5. Computational experiments

The performance of the proposed mixed-integer linear programming (MILP) and the GA will be evaluated in this part. To this end, the model and the proposed algorithm will be applied to a real case problem, and the results will be compared to the outcomes of the other methods. MATLAB® software v2016a was used for programming the proposed algorithms. Also a laptop with an Intel® Core i7 6500U 2.5GHz processor was used for testing the proposed algorithm.

5.1.Case study

Case study includes three building projects which are assigned to a GC. Tables 1 to 5 summarize the information of these projects. It must be mentioned that d'_{ijk} and d_{ijk} were considered the same in the case study problem.

Table 1. Lists of bids for work packages which are proposed by potential subcontractor

	Building 1 (2-story building)			***Building 2 (3-story building)***	
ID	***Work package name***	***Predecessor(s)***	***ID***	***Work package name***	***Predecessor(s)***
1	Excavation	-	16	Excavation	
2	Foundation and structure	1	17	Foundation and structure	16
3	Wall post	2FS-10	18	Wall post	17FS-20
4	Wall	3	19	Wall	18
5	Plumbing	4FS-2	20	Plumbing	19FS-2
6	Electrical work	4FS-2	21	Electrical work	19FS-2
7	HVAC	4FS-2	22	HVAC	19FS-2
8	Roofing	5 and 6	23	Roofing	20 and 21
9	lath and plaster	5, 6 and 7	24	lath and plaster	20, 21 and 22
10	Carpentry	9	25	Carpentry	24
11	Doors and windows	10	26	Doors and windows	25
12	Terrazzo	5 and 6	27	Terrazzo	20 and 21
13	Glazing	11	28	Glazing	26
14	Hardware and millwork	10	29	Hardware and millwork	25
15	Painting	9	30	Painting	24
	Building 3 (4-story building)				
ID	***Work package name***	***Predecessor(s)***			

31	Excavation	-
32	Foundation and structure	31
33	Wall post	32FS-25
34	Wall	33
35	Plumbing	34FS-2
36	Electrical work	34FS-2
37	HVAC	34FS-2
38	Roofing	35 and 36
39	lath and plaster	35, 36 and 37
40	Carpentry	39
41	Doors and windows	40
42	Terrazzo	35 and 36
43	Glazing	41
44	Hardware and millwork	40
45	Painting	39

Table 2. Lists of bids for work packages which are proposed by potential subcontractor for subcontracting and full time employment [duration time (days) and cost (1000$)]

	Cy_k	Item	Task ID 1	16	31
Sc1	0.032	d_{ij1}	4	5	6
		Bp_{ij1}	0.16	0.24	0.32
Sc2	0.048	d_{ij2}	3	4	5
		Bp_{ij2}	0.18	0.27	0.35
Sc3	0.08	d_{ij3}	2	3	4
		Bp_{ij3}	0.20	0.29	0.38

	Cy_k	Item	Task ID 2	17	32
Sc4	0.03	d_{ij4}	60	75	90
		Bp_{ij4}	2.25	3	3.75
Sc5	0.036	d_{ij5}	55	70	85
		Bp_{ij5}	2.5	3.33	4.16
Sc6	0.042	d_{ij6}	52	67	82
		Bp_{ij6}	2.75	3.67	4.58

	Cy_k	Item	Task ID 3	18	33
Sc7	0.002	d_{ij1}	5	8	11
		Bp_{ij1}	0.01	0.01	0.01
Sc8	0.002	d_{ij2}	4	7	10
		Bp_{ij2}	0.01	0.01	0.01
Sc9	0.004	d_{ij3}	2	6	9
		Bp_{ij3}	0.01	0.01	0.01

	Cy_k	Item	Task ID 4	19	34
Sc10	0.006	d_{ij10}	28	42	56
		Bp_{ij10}	0.2	0.21	0.22
Sc11	0.007	d_{ij11}	26	40	53
		Bp_{ij11}	0.22	0.23	0.24
Sc12	0.008	d_{ij12}	24	37	50
		Bp_{ij12}	0.24	0.26	0.27

	Cy_k	Item	Task ID 5	20	35
Sc13	0.013	d_{ij13}	30	40	50
		Bp_{ij13}	0.47	0.71	0.94
Sc14	0.014	d_{ij14}	28	36	45
		Bp_{ij14}	0.50	0.75	1
Sc15	0.015	d_{ij15}	27	35	43
		Bp_{ij15}	0.52	0.78	1.04

	Cy_k	Item	Task ID 6	21	36
Sc16	0.027	d_{ij16}	20	25	30
		Bp_{ij16}	0.68	1.02	1.36
Sc17	0.031	d_{ij17}	18	22	25
		Bp_{ij17}	0.70	1.05	1.40
Sc18	0.034	d_{ij18}	17	21	24
		Bp_{ij18}	0.73	1.10	1.46

	Cy_k	Item	Task ID 7	22	37
Sc19	0.019	d_{ij19}	15	17	19
		Bp_{ij19}	0.35	0.36	0.37
Sc20	0.021	d_{ij20}	14	15	17
		Bp_{ij20}	0.36	0.37	0.38
Sc21	0.023	d_{ij21}	13	14	15
		Bp_{ij21}	0.37	0.39	0.40

	Cy_k	Item	Task ID 8	23	38
Sc22	0.009	d_{ij22}	30	45	60
		Bp_{ij22}	0.35	0.52	0.70
Sc23	0.011	d_{ij23}	28	42	55
		Bp_{ij23}	0.38	0.55	0.75
Sc24	0.012	d_{ij24}	27	40	53
		Bp_{ij24}	0.40	0.58	0.78

	Cy_k	Item	Task ID 9	24	39
Sc25	0.008	d_{ij25}	17	26	34
		Bp_{ij25}	0.15	0.22	0.30
Sc26	0.009	d_{ij26}	15	25	32
		Bp_{ij26}	0.17	0.25	0.34
Sc27	0.013	d_{ij27}	12	22	31
		Bp_{ij27}	0.19	0.28	0.38

	Cy_k	Item	Task ID 10	25	40
Sc28	0.003	d_{ij28}	8	12	16
		Bp_{ij28}	0.03	0.04	0.06
Sc29	0.003	d_{ij29}	7	10	14
		Bp_{ij29}	0.03	0.04	0.06
Sc30	0.004	d_{ij30}	6	9	11

	Cy_k	Item	Task ID 11	26	41
Sc31	0.036	d_{ij31}	4	6	8
		Bp_{ij31}	0.18	0.27	0.36
Sc32	0.053	d_{ij32}	3	5	7
		Bp_{ij32}	0.20	0.30	0.40
Sc33	0.056	d_{ij33}	3	4	6

	Cy_k	Item	Task ID 12	27	42
Sc34	0.016	d_{ij34}	10	15	20
		Bp_{ij34}	0.2	0.22	0.23
Sc35	0.020	d_{ij35}	9	14	19
		Bp_{ij35}	0.22	0.23	0.24
Sc36	0.024	d_{ij36}	8	13	18

		Bp_{ij30}	0.03	0.04	0.06			Bp_{ij33}	0.21	0.31	0.42			Bp_{ij36}	0.24	0.26	0.27
	$\boldsymbol{Cy_k}$	**Item**	**Task ID**				$\boldsymbol{Cy_k}$	**Item**	**Task ID**				$\boldsymbol{Cy_k}$	**Item**	**Task ID**		
			13	**28**	**43**				**14**	**29**	**44**				**15**	**30**	**45**
Sc37	0.019	d_{ij37}	3	5	7	Sc40	0.011	d_{ij40}	5	8	12	Sc43	0.002	d_{ij43}	5	8	11
		Bp_{ij37}	0.07	0.10	0.14			Bp_{ij40}	0.07	0.10	0.14			Bp_{ij43}	0.01	0.02	0.03
Sc38	0.032	d_{ij38}	2	4	6	Sc41	0.016	d_{ij41}	4	7	10	Sc44	0.002	d_{ij44}	4	7	10
		Bp_{ij38}	0.08	0.10	0.14			Bp_{ij41}	0.08	0.12	0.15			Bp_{ij44}	0.01	0.02	0.03
Sc39	0.064	d_{ij39}	1	2	3	Sc42	0.024	d_{ij42}	3	6	8	Sc45	0.003	d_{ij45}	3	6	9
		Bp_{ij39}	0.08	0.11	0.15			Bp_{ij42}	0.09	0.13	0.18			Bp_{ij45}	0.01	0.02	0.03

Table 3. Contractual and other data of projects which are related to the case study [duration time (days) and cost (1000$)]

Data type	Item	Project		
		1	2	3
Contractual data	Project start time (day) [Sp_j]	0	0	0
	Due date of project *j* (DD_j)	220	220	220
	Early completion bonus of project *j* (B_j)	0.01	0.02	0.03
Other data	I		3	
	Indirect cost of project j per day (IC_j)	0.001	0.0015	0.002

Table 4. Discount levels and related discount percentage proposed by the subcontractors

	SC1	SC2	SC3	SC4	SC5	SC6	SC7	SC8	SC9	SC10	SC11	SC12	SC13	SC14	SC15
A_{1k}	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
B_{1k}	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
DP_{1k}	10%	5%	10%	5%	10%	5%	5%	5%	10%	5%	5%	10%	5%	10%	5%
A_{2k}	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
B_{2k}	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
DP_{2k}	15%	10%	10%	10%	15%	10%	10%	10%	15%	10%	10%	15%	5%	10%	10%

Table 4. Discount levels and related discount percentage proposed by the subcontractors (continued)

	SC16	SC17	SC18	SC19	SC20	SC21	SC22	SC23	SC24	SC25	SC26	SC27	SC28	SC29	SC30
A_{1k}	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
B_{1k}	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
DP_{1k}	10%	5%	5%	5%	10%	5%	5%	10%	5%	10%	5%	10%	5%	10%	5%
A_{2k}	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
B_{2k}	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
DP_{2k}	20%	10%	15%	10%	10%	5%	10%	10%	10%	15%	15%	10%	5%	10%	10%

Table 4. Discount levels and related discount percentage proposed by the subcontractors (continued)

	SC31	SC32	SC33	SC34	SC35	SC36	SC37	SC38	SC39	SC40	SC41	SC42	SC43	SC44	SC45
A_{1k}	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
B_{1k}	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
DP_{1k}	10%	5%	10%	5%	10%	5%	10%	5%	10%	5%	10%	5%	10%	5%	10%
A_{2k}	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
B_{2k}	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
DP_{2k}	15%	15%	10%	5%	15%	10%	10%	10%	15%	10%	10%	15%	10%	10%	15%

Table 5. Transfer time and costs of subcontractors among the projects

	Project 1	Project 2	Project 3
Project 1	0 day/0 $	0 days/0 $	1 days/1 $
Project 2	0 days/0 $	0 day/0 $	1 days/1 $
Project 3	1 days/1 $	1 days/1 $	0 day/0 $

5.2.The performance evaluation of proposed model

The first evaluation is performed in the current study is devoted to the proposed model. Figs. (4) and (5) demonstrates the schedule results of case study using the proposed model. In order to solve the model, the CPLEX solver of GAMS was employed.

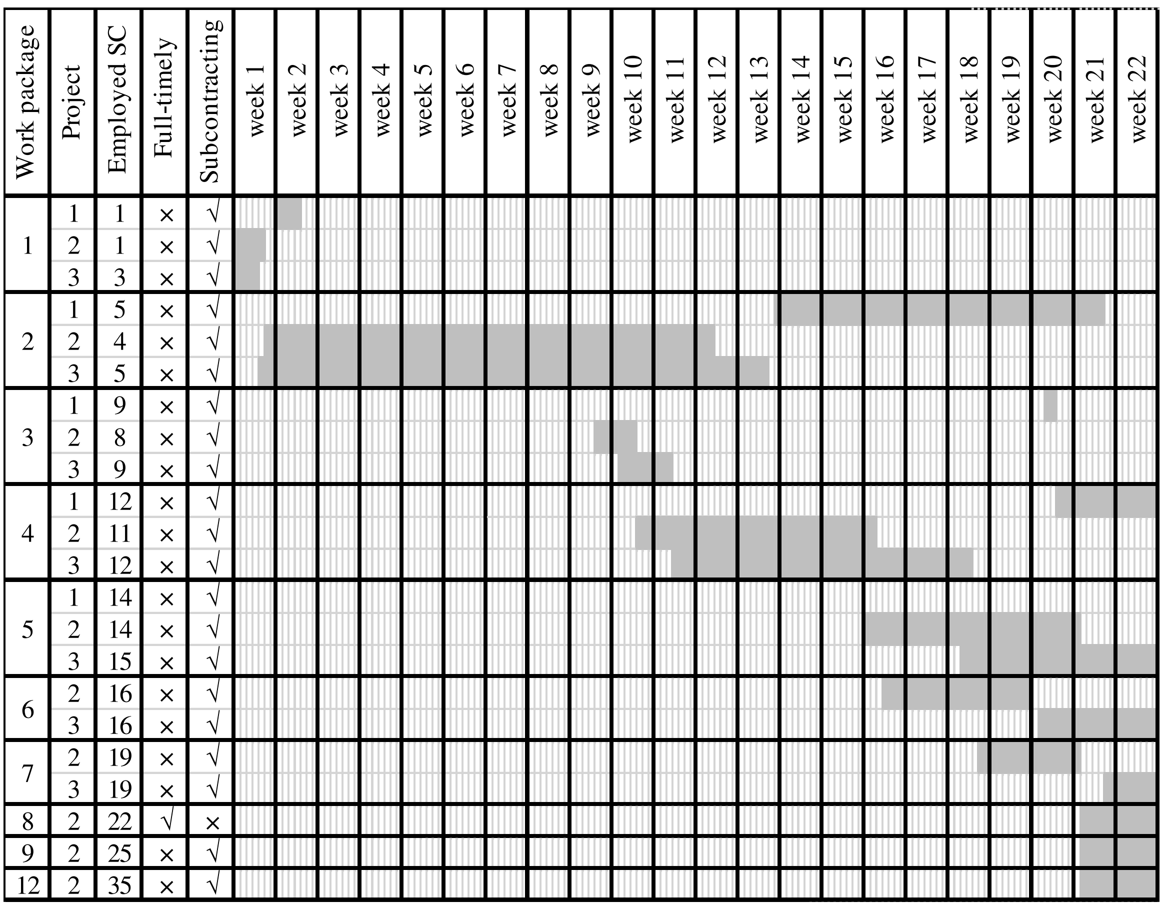


Fig. 5. The optimal schedule of the case study which is computed by CPLEX solver of GAMS,

6.

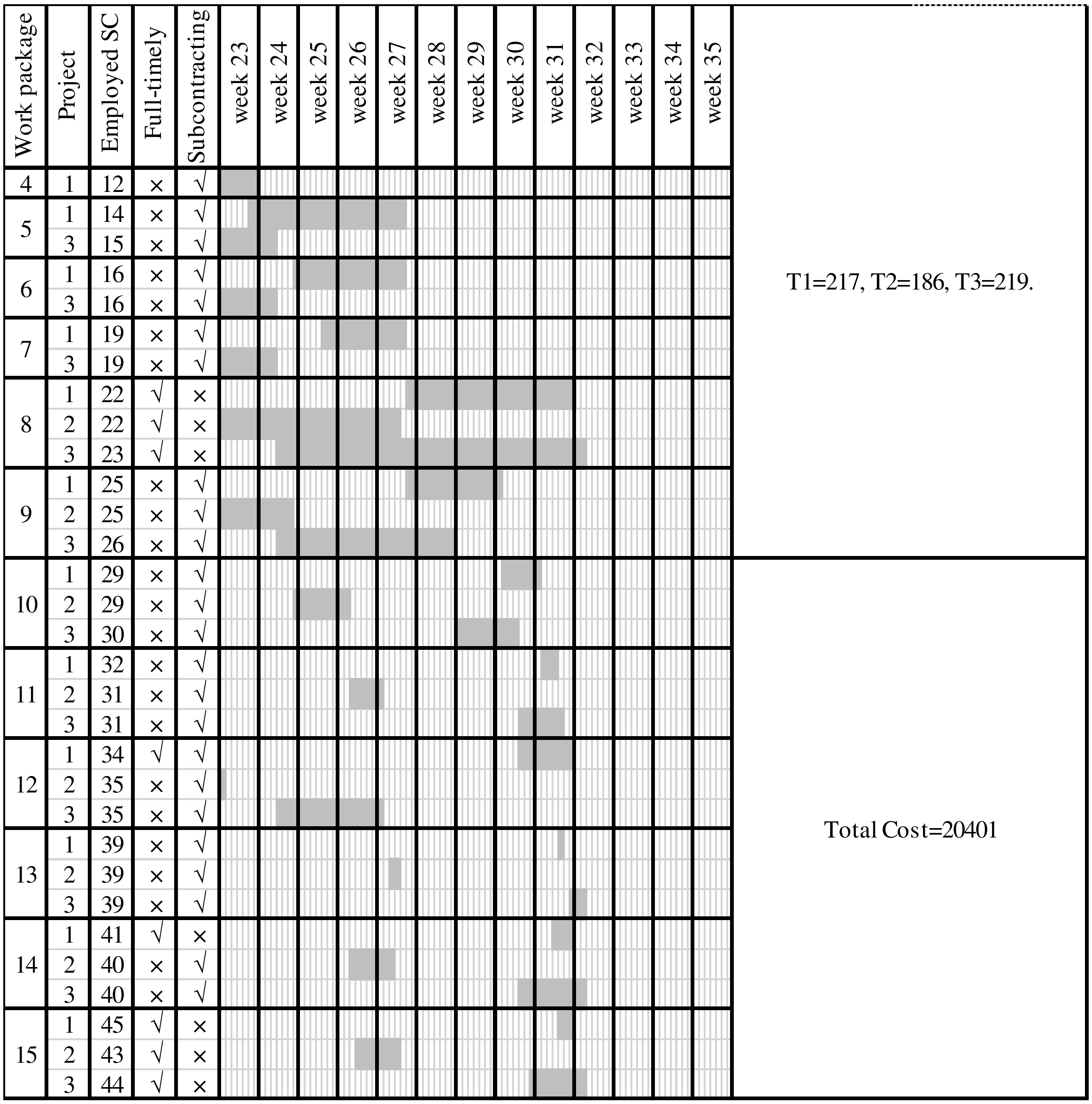


Fig. 5. The optimal schedule of the case study which is computed by CPLEX solver of GAMS (continued).

In order to validate the obtained results, the model of Biruk et al. (2017) (which was proposed when only one project must be done) was also applied on the real case problem and its results were compared to the results of the proposed model. The results are summarized in Table 6. As is observed, the proposed model reduced the expenditure of the GC by around 14 percent.

Therefore, it can be concluded that application of the model of Biruk et al. (2017) cannot result in an optimum solution in multiple project. These outcomes were predictable because Biruk et al did not consider the required assumptions when numerous projects need to be done by the GC simultaneously. As a result, the proposed model suits better when numerous projects need to be done at the same time.

Table 6. Optimal cost using the model of Biruk et al. (2017) and the proposed model

Type of model	Total cost
The model of Biruk et al. (2017)	23552 $
The proposed model	20401 $

5.3.Performance of the proposed GA for subcontractor selection problem

5.3.1. Tuning the parameters

In order to evaluate the proposed GA for solving the subcontractor selection and allocation problem, first, the parameters of the proposed GA must be adjusted. For this aim, the Taguchi experiment design method (Montgomery, 2005) is used. In this regard, three levels for GA parameters (4 factors) are considered (see Table (7)) that should be tested according to values which are illustrated in Table 8.

Table 7. Definition of factor levels for parameters of GA

Factor	Symbol	Number of levels	Level definition
POP_size	A	3	$A1$: 50
			$A2$: 75
			$A3$: 100
ν	B	3	$B1$:1
			$B2$:2
			$B3$:3
P_c	C	3	$C1$: 0.20
			$C2$: 0.50
			$C3$: 0.80
P_m	D	3	$D1$: 0.15
			$D2$: 0.20
			$D3$: 0.25

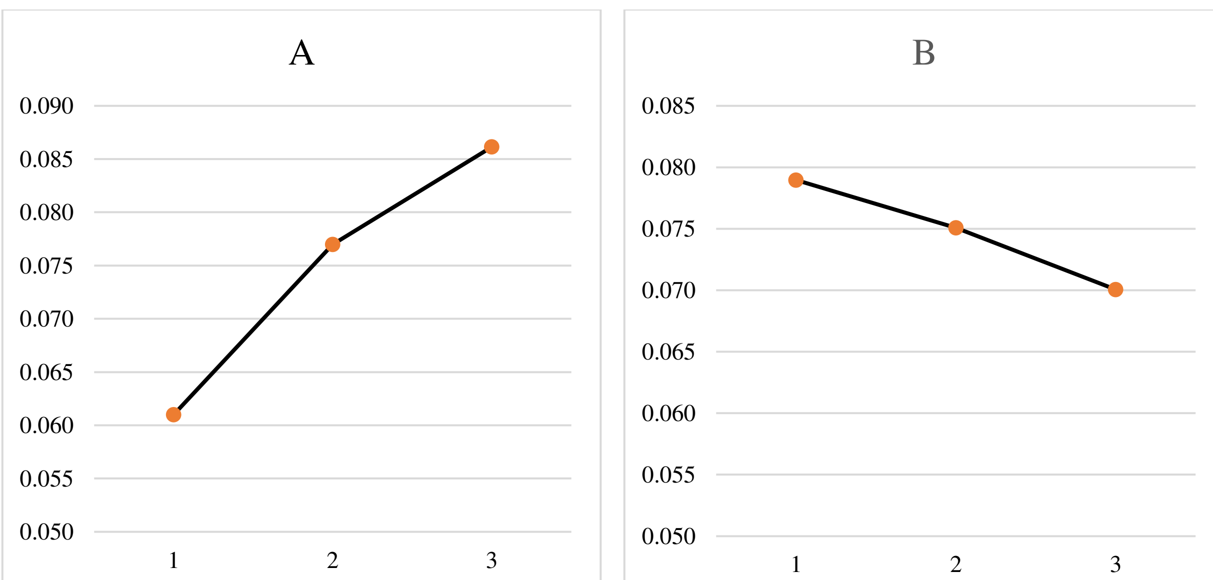
Table 8. The orthogonal arrays L9

Experiment number	A	B	C	D
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

The response variable (RV) value [Eq. (51)] is employed to compare the results of the experiments.

$$RV = \frac{Total\ cost_{GA} - OPT_C}{OPT_C} \quad (51)$$

where $Total\ cost_{GA}$ represents the case study total cost which is obtained through GA, and OPT_C is the optimal total cost of the case study which is calculated through the use of CPLEX solver of GAMS. The average results for each factor level have been reported in Fig. 6. As is observed, the optimum level of the factors A, B, C and D are A(1), B(3), C(1) and D(2).



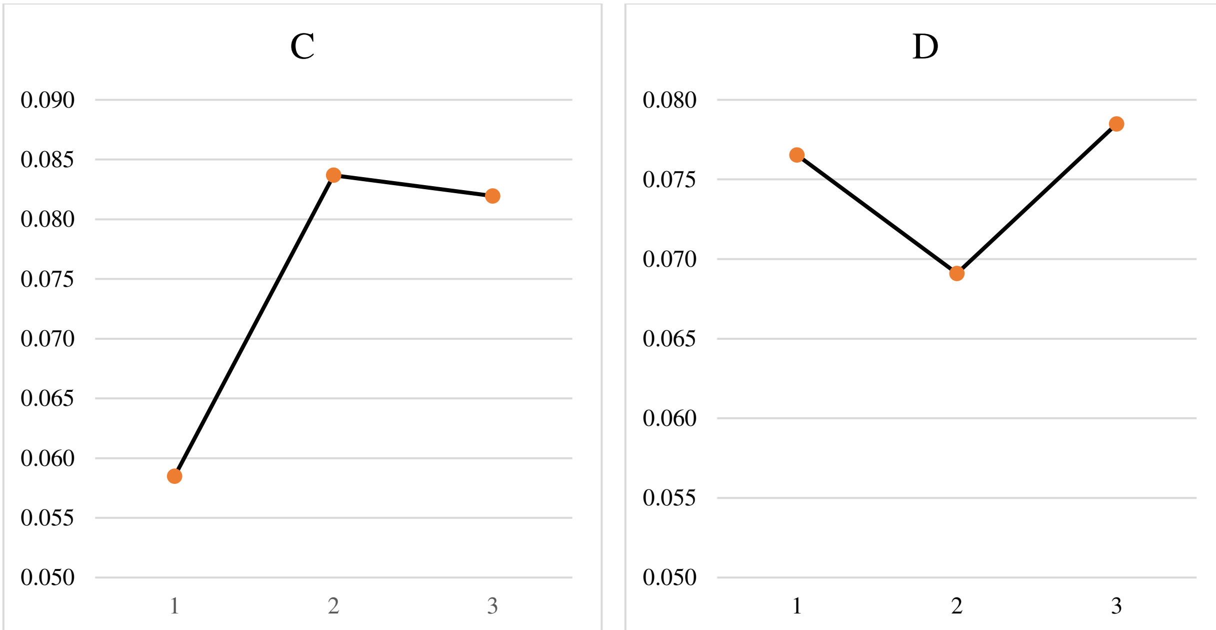


Fig. 6. The average VR for GA

5.3.2. Performance of the proposed heuristic to produce initial population

In order to test the performance of proposed heuristic for production of initial population, we compare its results with random generation method. For this purpose, each of procedures was applied 10 times on the case study. The experiments show that the results are improved by 10 percent using the proposed heuristic, while it increases CPU-time 3 percent.

5.3.3. Performance of the proposed fitness function

In order compare the proposed fitness function with a fitness function that works based on removing infeasible solution, each of them was applied 10 times on the case-study. The results in Table 9 shows that proposed fitness function improves the desirability of the solutions by 19%, while it increases CPU-time slightly.

Table 9. Performances of the proposed fitness function and the fitness function that works based on removing infeasible solutions.

	Proposed fitness function	Fitness function that works based on the removing infeasible solutions.
Total cost	980.25 $	1205$
Calculation time	13.25 minutes	12 minutes

5.3.4. Performance of the proposed GA

Similar to previous performance evaluation, in order to test the performance of proposed GA, it was run 10 times to solve the case study problem. The results are presented in Table 10. Optimum values for the case study which are computed by CPLEX solver of GAMS are considered as basis for the calculation of the average deviations.

It can be observed that the proposed algorithm can reduce computing time by 8% in comparison with the exact method and at the same time it is capable of reaching desirable solutions. In fact, although the exact method can probe the search space completely, the searching time will increase significantly. So, adopting this approach seems to be unreasonable in large scale problems because the problem is a NP-hard problem. Plus, as the inputs increase, the outputs increase exponentially. Clearly, metaheuristic approaches like GA can result in desirable results in reasonable amount of time.

Table 10. Performance of the proposed GA

	GA	CPLEX solver of GAMS
Average deviation	980.25 $	0
Run time	13.25 minutes	170 minutes

5. Conclusion

This research study proposes a mixed-integer linear programming (MILP) model to select subcontractors and assign available work packages to them when numerous projects need to be done at the same time. Then, the model will be solved by means of an exact method and a metaheuristic method.

The results show that:

1. When numerous projects need to be done at the same time, single project planning criteria will not result in an optimum solution.
2. The proposed MILP model also has better performance in the multiple project environment compared to the existing models.
3. The proposed heuristic method has better performance (approximately 10%) in reaching the better solutions.
4. The proposed fitness function could improve the desirability of the produced feasible solutions by 19% (at respectively the same as the approach of removing infeasible solution).
5. The proposed GA in stopping criteria of 5000 results in lower computing time (92% in comparison with the exact method). Besides, it can reach to the desirable solutions.

6. Compliance with ethical standards

Financial Disclosures. The authors have no relevant financial disclosures.

Conflict of interest. The authors declare that they have no conflict of interest.

7. Authorship contributions

Afshar. MR., Shahhosseini. V. and Sebt MH. contributed to the design and implementation of the research, to the analysis of the results and to the writing of the manuscript.

References

Monghasemi S, Nikoo MR, Fasaee MAK, Adamowski J (2015) A novel multi criteria decision making model for optimizing time–cost–quality trade-off problems in construction projects. Expert systems with applications 42 (6): 3089-3104.

Biruk S, Jaśkowski P, Czarnigowska A (2017) Minimizing Project Cost by Integrating Subcontractor Selection Decisions with Scheduling. In IOP Conference Series: Materials Science and Engineering, IOP Publishing, 072007.

Pells D (1993) The AMA Handbook of Project Management AMA-COM, New York.

Afshar MR, Shahhosseini V, Sebt MH, (2020) An interval type-2 fuzzy MCDM model for work package subcontractor prequalification. Soft Computing 1-14.

Afshar MR, Alipouri Y, Sebt MH, Chan WT (2017) A type-2 fuzzy set model for contractor prequalification. Automation in Construction 84: 356-366.

Fachrurrazi HS, Munirwansyah H (2017) The subcontractor selection practice using ANN-multilayer. International Journal of Technology 8 (4): 761-772.

Ulubeyli S, Kazaz, A (2016) Fuzzy multi-criteria decision making model for subcontractor selection in international construction projects. Technological and Economic Development of Economy 22 (2): 210-234.

Polat G (2016) Subcontractor selection using the integration of the AHP and PROMETHEE methods. Journal of Civil Engineering and Management 22 (8): 1042-1054.

Abbasianjahromi H, Rajaie H, Shakeri E (2013) A framework for subcontractor selection in the construction industry. Journal of Civil Engineering and Management 19(2): 158-168.

Pollack-Johnson B, Liberatore MJ (2006) Incorporating quality considerations into project time/cost tradeoff analysis and decision making. IEEE Transactions on Engineering Management 53 (4): 534-542.

Mungle S, Benyoucef L, Son YJ, Tiwari MK (2013) A fuzzy clustering-based genetic algorithm approach for time–cost–quality trade-off problems: A case study of highway construction project. Engineering Applications of Artificial Intelligence 26 (8): 1953-1966.

Mokhtari H, Abadi INK (2013) Scheduling with an outsourcing option on both manufacturer and subcontractors. Computers & Operations Research 40 (5): 1234-1242.

Abbasianjahromi H, Rajaie H, Shakeri E, Chokan F (2014) A new decision making model for subcontractor selection and its order allocation. Project Management Journal 45(1): 55-66.

Polat G, Kaplan B, Bingol BN (2015) Subcontractor selection using genetic algorithm. Procedia Engineering 123: 432-440.

Afshar MR, Shahhosseini V, Sebt MH (2020) Optimal sub-contractor selection and allocation in a multiple construction project: Project portfolio planning in practice. Journal of the Operational Research Society: 1-14.

El-Abbasy MS, Elazouni A, Zayed T (2017) Generic scheduling optimization model for multiple construction projects. Journal of Computing in Civil Engineering 31 (4): 04017003.

Sonmez R, Gürel M, (2016) Hybrid Optimization Method for Large-Scale Multimode Resource-Constrained Project Scheduling Problem. Journal of Management in Engineering 32(6): 04016020.

Beşikci U, Bilge Ü, Ulusoy G (2015) Multi-mode resource constrained multi-project scheduling and resource portfolio problem. European Journal of Operational Research 240 (1): 22-31.

Lee K, El-Sharkawi M (2008) Modern Heuristic Optimization Techniques: Theory and Applications to Power Systems. IEEE Press Series on Power Engineering. New York:Wiley-IEEE Press.

Józefowska J, Mika M, Różycki R, Waligóra G, Węglarz J (2001) Simulated annealing for multi-mode resource-constrained project scheduling. Annals of Operations Research 102(1-4): 137-155.

Montgomery DC (2005) Design and Analysis of Experiments. 6th ed. Hoboken, NJ: JohnWiley & Sons.

Figures

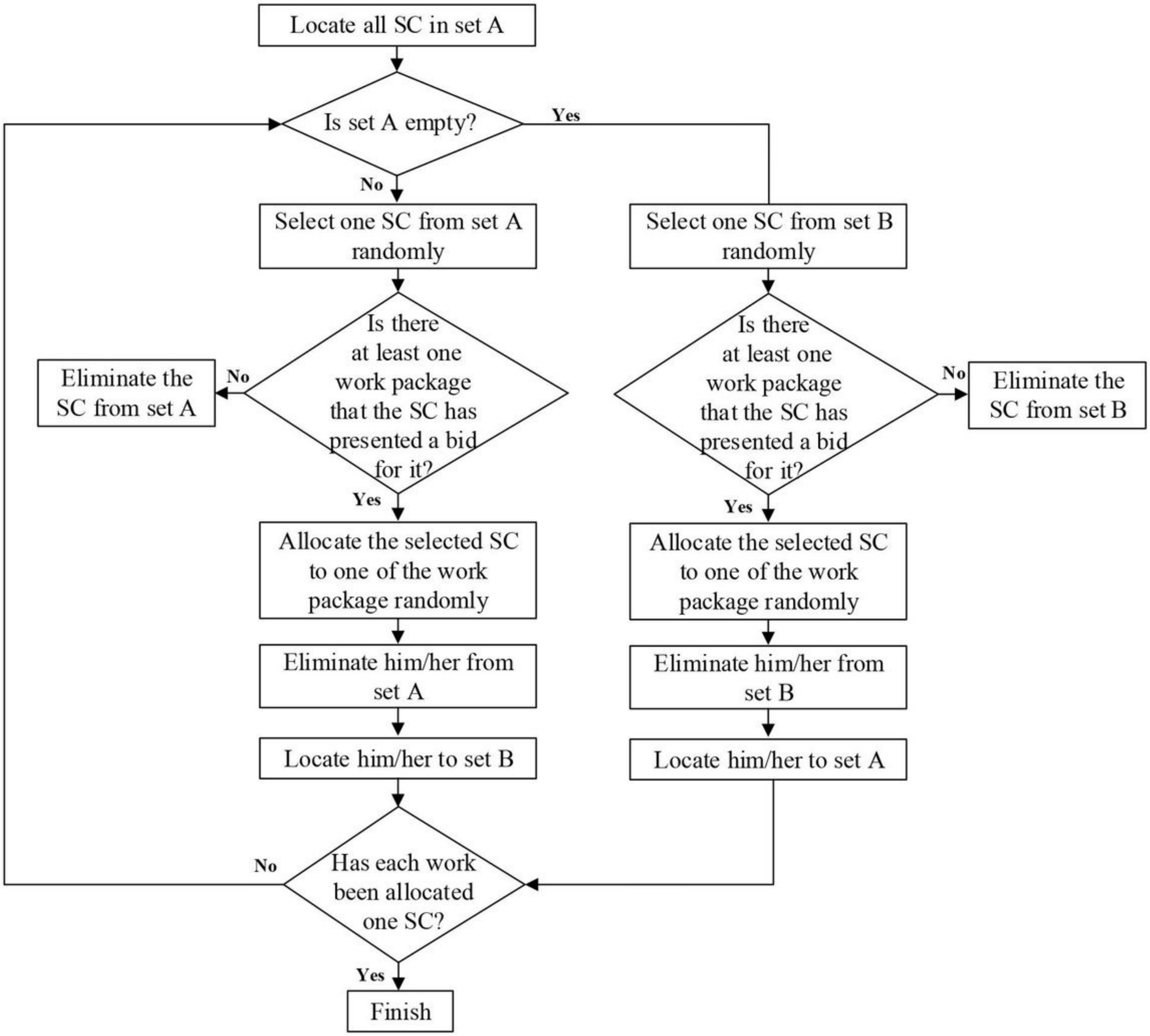


Figure 1

Generation and development of initial solutions

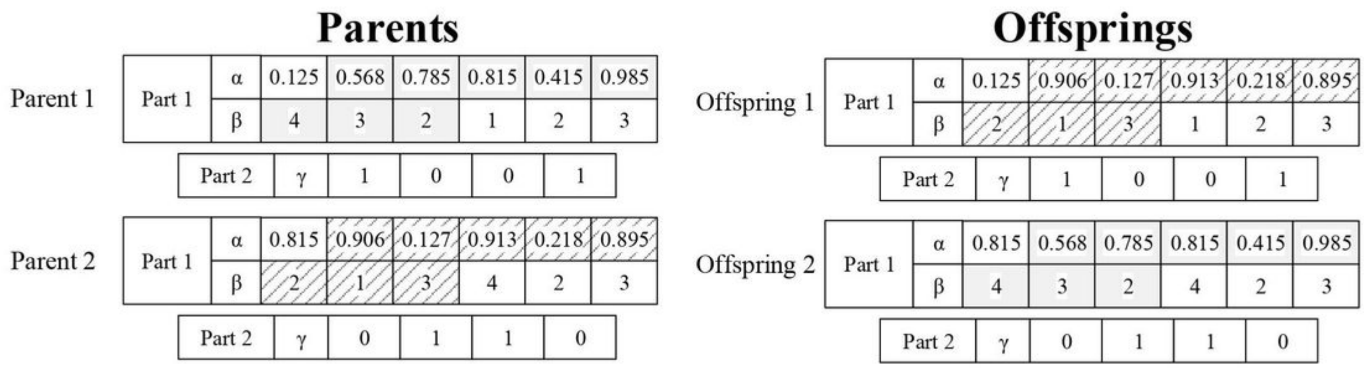


Figure 2

Proposed crossover operator (part 1 of the solution is chosen for the application of crossover operator).

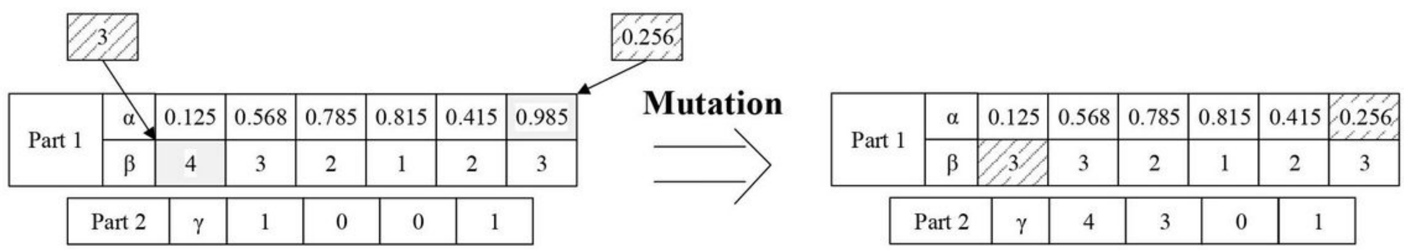


Figure 3

Proposed mutation operator (part 1 of the solution is selected for the application of mutation operator).

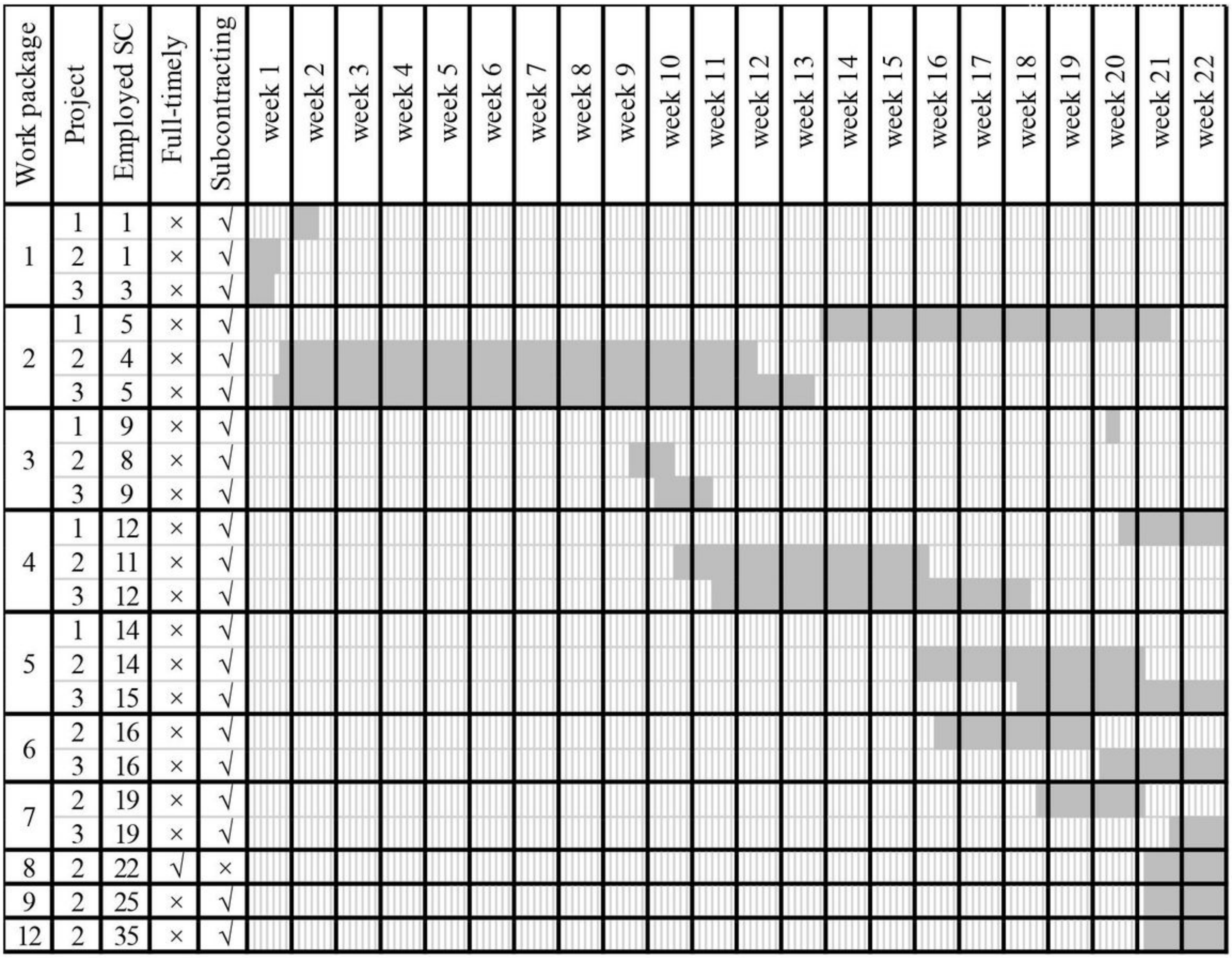


Figure 4

The optimal schedule of the case study which is computed by CPLEX solver of GAMS, 6.

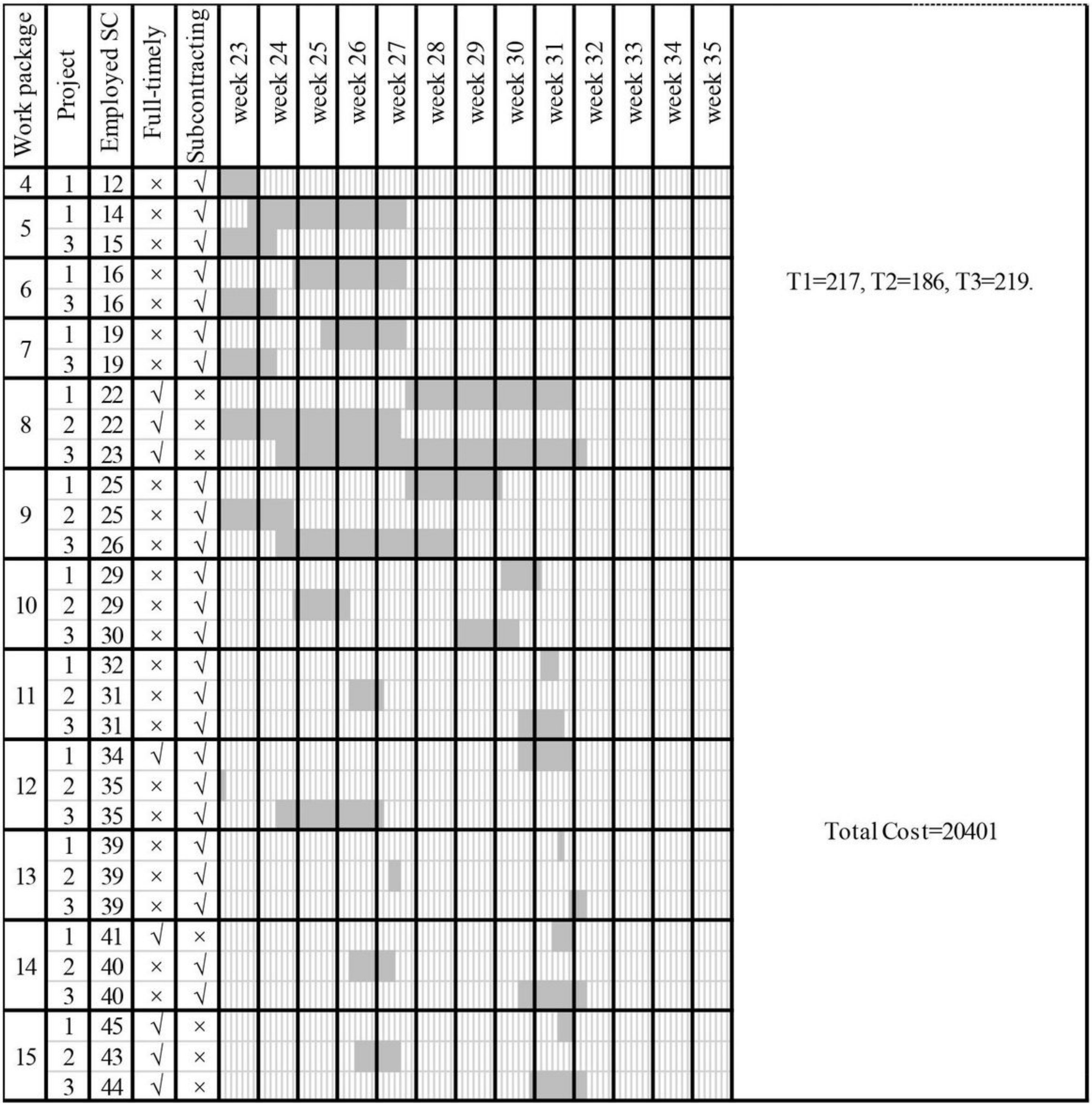


Figure 5

The optimal schedule of the case study which is computed by CPLEX solver of GAMS (continued).

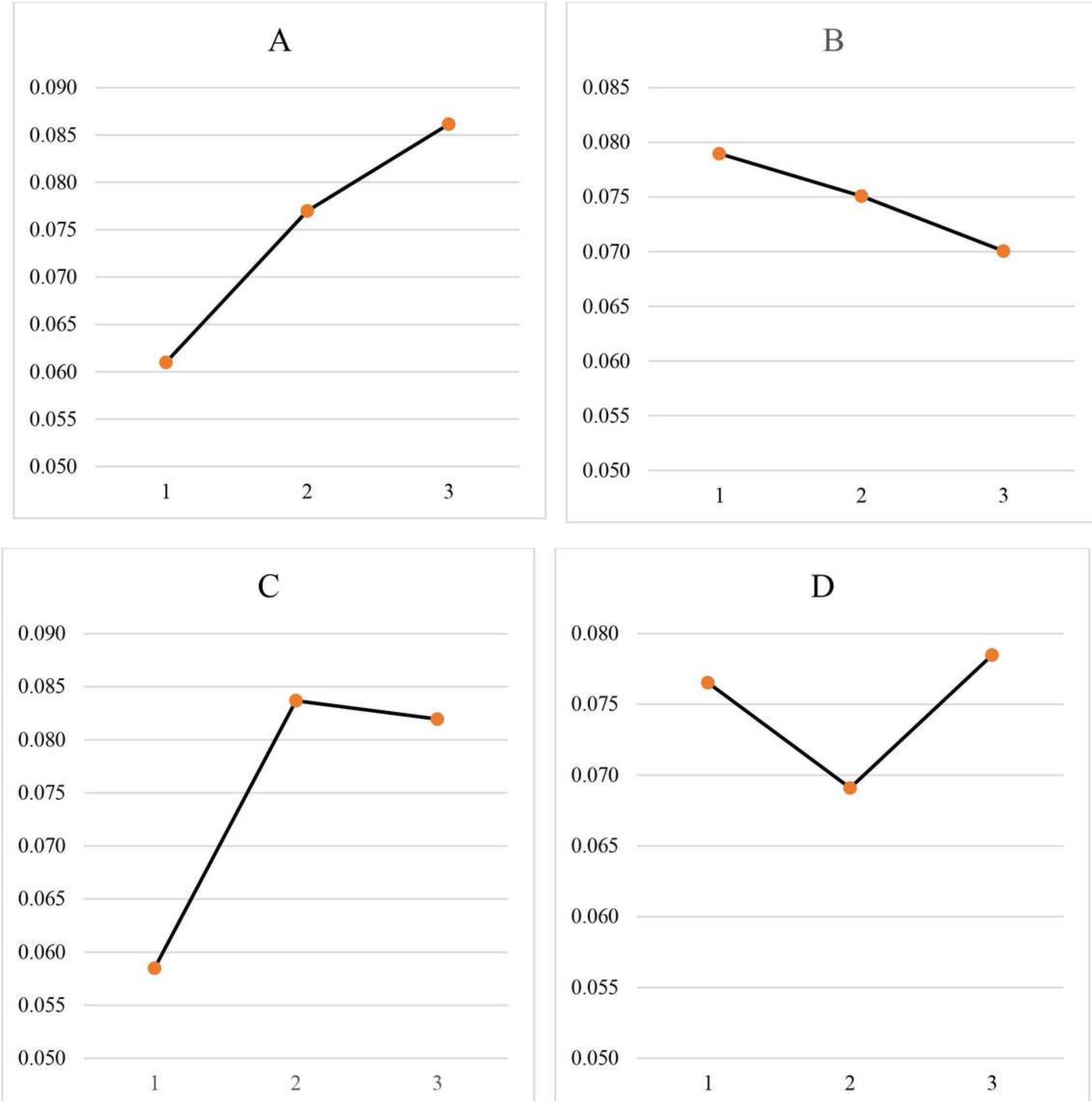


Figure 6

The average VR for GA