KSCE Journal of Civil Engineering (2018) 22(10):3738-3752

DOI 10.1007/s12205-017-0691-x

Construction Management

pISSN 1226-7988, eISSN 1976-3808
www.springer.com/12205

Multi-project Time-cost Optimization in Critical Chain with Resource Constraints

Mohammad Javad Taheri Amiri*, **FarshidReza Haghighi****, **Ehsan Eshtehardian*****, **and Ozeair Abessi******

Received May 29, 2017/Revised 1st: September 30, 2017, 2nd: January 1, 2018/Accepted January 20, 2018/Published Online September 14, 2018

Abstract

The simultaneous reduction of the project cost and time has paramount importance in today's competitive world; however, it is necessary to balance the project time and cost because of the reduction asymmetry of the two factors in a project. How to balance the cost and time parameters in managing construction projects is also critical and there have always been some attempts made to provide different approaches to control it. Given the immense importance of considering resource constraints for project scheduling problems, and the proximity of the study conditions to the real world, resource constraints were also included. In a project, project managers need to be aware of resource constraints. As resource constraint scheduling problem is considered NP-hard, the meta-heuristic models were developed in this paper in order to obtain results contributing to project managers' decision-making. For this purpose, a non-dominated sorting genetic algorithm method was developed to optimize a time-cost trade-off problem. Furthermore, to solve a multi-project scheduling problem, the critical chain method was used. In order to evaluate the performance of the model, the developed model was first studied in a small scale and then simultaneous projects with 7, 8 and 10 tasks were planned. Because resource availability is essential in such problems, after solving the proposed model, a sensitivity analysis was performed for daily resources and the results were discussed. Results shows the ability of the proposed model and methodology to optimize the time-cost tradeoff considering resource constraints in sample problems. Solutions obtained showed that in some cases of scheduling without this algorithm, resource consumption exceeded above resource availability. After solving the model by proposed algorithm, resource allocation is implemented considering resource constraint. This model determined these resources as crucial and helped managers to control them.

Keywords: *bi-objective time-cost optimization, resource constraints, non-dominated sorting genetic algorithm*

1. Introduction

In the competitive conditions of today's economy, the ability to minimize time and cost can have a decisive role in the profitability or even survival of a contracting company. However, since construction time is predetermined and mentioned in contract documents, the participants of the tender usually pay attention to one goal, i.e., minimizing the cost of the project, to be able to offer a lower price than competitors (Park and Chapin, 1992). During the scheduling of the project, both time and cost should be calculated and considered simultaneously. Cost minimization performed concurrently with project schedule compression forces contractors to calculate time-cost optimization before any other decisions (Alkass *et al.*, 1996). Therefore, due to the importance of time and cost factors that have also been emphasized by the standard of the Project Management Body of Knowledge (PMBOK Guide, 2013), several studies have been reported recently investigating the trade-off between these two goals. For this purpose, it is essential that the technique of simultaneous optimization be considered, which requires using a multi-objective optimization approach. It should be noted that reducing the execution time of an activity always comes at a cost, which in return reduces the project completion time. Additionally, savings will accrue for contractors and employers, and liquid capital of the project will start circulating earlier. To reduce the time of activities, resources can be increased or changes can be made in the technical methods of implementation to accelerate the execution time. In other words, for the implementation of an activity in a time shorter than normal, it is necessary to increase the volume of resources, i.e., the workforce and the amount of equipment and machinery, or employ more expensive equipment and power, and change the technical methods used (Sonmez and

*Ph.D. Student in Construction Engineering and Management, Babol Noshirvani University of Technology Babol 47148-71167, Iran (E-mail: jvd.taheri@gmail.com)
**Assistant Professor, Dept. of Civil Engineering, Babol Noshirvani University of Technology Babol 47148-71167, Iran (Corresponding Author, E-mail: haghighi@nit.ac.ir)
***Assistant Professor, Dept. of Project Management, Tarbiat Modares University, Tehran 14115-111, Iran (E-mail: eshtehardian@modares.ac.ir)
****Assistant Professor, Dept. of Civil Engineering, Babol Noshirvani University of Technology, Babol 47148-71167, Iran (E-mail: Oabessi@nit.ac.ir)

Bettemir, 2012).

Regarding the importance of the time factor in project planning, different methods for the scheduling of the projects have been developed. Among these the critical chain method has contributed more to shaping the new generation of project planning techniques. This method was developed by Goldratt while considering the application of project management in the Theory of Constraints (Goldratt, 1997). Many studies have been reported on the pros and cons of this method, which has also stirred a lot of criticism (Rand, 2000; Leach, 2000; Herroelen *et al.*, 2002; Raz *et al.*, 2003; Kuchta, 2004; Juring, 2004; Dan, 2005). According to previous studies, the critical chain method displayed better performance compared to earlier methods to reduce project execution time (Shen and Chua, 2008; Startton, 2009), by eliminating existing uncertainties in the timing of activities (Wei-Xin *et al.*, 2014) and providing a flexibility of time buffers in planning, which concluded to be accepted by the project managers (Vanhoucke, 2016; Ghoddousi, 2016). Another factor of great importance in project planning is the cost factor, which includes both indirect and direct project costs. Direct costs include costs related to all renewable and non-renewable resources for project activities, and indirect costs include fixed costs of the company during the implementation of the project.

On the other hand, contracting companies often have to manage multiple projects at the same time that involve all of the company's resources. The constraint of these resources is a common problem and may causes projects to have timing difficulties (Singh, 2013). Resource constraints are a standard problem that has been researched extensively in planning issues, specifically in multi-project planning problems (Shou *et al.*, 2013). In the majority of resource constraint problems, only the issue of whether these resources are adequate for the whole project has been well-examined (Long and Ohsato, 2008; Wei-Xin *et al*., 2014), but the condition of these resources on a daily basis has been less frequently discussed. The benefit of a daily assessment of resources is that project managers understand what resources are required every day, deficiencies of which could trouble a project's ultimate time and cost. This method helps project managers and contracting companies to focus on resources with more sensitivity and supply these resources as a priority to project managers. To determine the groups of resources of greater importance for later managers to concentrate on, the project's influential resources need to be specified by a sensitivity analysis. The purpose then is to determine the sensitivity of each resource with respect to time and the cost.

Because resource constraint problems are considered as NP-hard (Non-deterministic Polynomial-time hard) problems (Blazewicz *et al*., 1983; Chen and Zhou, 2013; Gonzalez-Pardo and Camacho, 2013, Giran, 2017), they cannot be solved using optimization methods with exact solutions and large dimensionality. Therefore, metaheuristic methods have commonly been used for this problem. Several metaheuristic algorithms, such as particle swarm optimization by Aminbakhsh and Sonmez (2016), the Tabu search algorithm by Hazir *et al.* (2011), simulated annealing algorithms by Anagnostopoulos & Kotsikas (2010) and Taheri Amiri *et al.* (2017a), and neural networks by Rumelhart *et al.* (1986) have been used to optimize such time-cost trade-off problems.

Genetic Algorithms (GA) have also been used for the optimization of time-cost trade-off problems by scholars (Leu *et al.*, 2001; Azaron *et al.*, 2005; Ke *et al*., 2009; Ke *et al.*, 2012; Ke and Ma, 2014, Taheri Amiri, 2017b). However, only a few studies have addressed solutions of the time-cost trade-off problem using multi-objective models (Eshtehardian, 2009; Ghoddousi, 2013). In multi-objective models, a set of non-prioritized Pareto solutions are obtained. This gives a decision-maker the ability to choose one of the Pareto solutions according to the conditions of the project. As long as multi-objective models are superior to single-objective models in many cases, therefore, in this paper, resource constraints using a bi-objective model of time and cost are investigated, using a Non-dominated Sorting Genetic Algorithm (NSGAII). Furthermore the application of a critical chain method has also been investigated. As previously mentioned, for p roject scheduling with resource constraints, researchers have concentrated more on the resources of the entire project. Here, the need for the project managers to know the amount of resources used each day, as well as the limitation of daily resources, has been considered, and the importance of each are investigated separately. This will help project managers to provide limited resources in a timely manner, in accordance with the importance of each resource and its insufficiency.

2. Literature Review

Chen and Tsai (2011) investigated the problem of time-cost tradeoff of a project network in the fuzzy environment. Bi-level mathematical programming has been used for specification of the upper and lower limits of total fuzzy cost. The membership function of total fuzzy cost and optimal time for each activity are obtained through specification of different α values. The time-cost tradeoff problem was solved with a number of fuzzy parameters for validation of the proposed approach.

Afrouzi *et al.* (2013) examined the planning issue of the time-cost tradeoff for projects with limited multimode resources using adjusted fuzzy dominance genetic algorithm. In this model, each activity has multi modes to be performed. In each mode, the required resources for performing the activity are different, at least in one type. In addition, each activity can be done in either normal or crashing ways in each performing mode. The project cost consists of both direct and indirect costs. In this study, some examples of small and large-scale projects are solved. Finally, in order to evaluate the algorithm efficiency, the algorithm proposed in this study was compared with NSGAII, NRGA, PAES, MOIWO algorithms. The findings indicated the better efficiency of the proposed algorithm.

Ghoddousi *et al.* (2013) presents the Multi-mode Resource-Constrained Discrete Time–Cost-Resource Optimization (MRC-DTCRO) model in order to select starting the time and the execution mode of each activity satisfying all the project constraints. To solve these problems, non-domination based genetic algorithm (NSGA-II) is employed to search for the non-dominated solutions considering total project time, cost, and resources moment deviation as three objectives. The results of MRC-DTCRO model presented. in this paper show that adding the resource leveling capability to the previously developed Multi-mode Resource-Constrained Discrete Time–Cost Trade-Off Problem (MRC-DTCTP) models provides more practical solutions in terms of resource allocation and leveling, which makes this research applicable to both construction industry and researchers.

Cheng and Tran (2015) develops a novel optimization algorithm, the Opposition-based Multiple Objective Differential Evolution (OMODE), to solve the Time–Cost-Utilization work shift Trade-off (TCUT) problem. This algorithm employs an opposition-based learning technique for population initialization and for generation jumping. Opposition numbers are used to improve the exploration and convergence performance of the optimization process. Two numerical case studies of construction projects demonstrate the ability of OMODE generated non-dominated solutions to assist project managers to select an appropriate plan to optimize TCUT, an operation that is otherwise difficult and time-consuming. Comparisons with the non-dominated sorting genetic algorithm (NSGA-II), multiple objective particle swarm optimization (MOPSO), and Multiple Objective Differential Evolution (MODE) verify the efficiency and effectiveness of the proposed algorithm.

Tran *et al.* (2015) presents a new hybrid approach, named Artificial Bee Colony with Differential Evolution, to handle Resource-Constrained problems (ABCDE-RC). The proposed algorithm integrates crossover operations from Differential Evolution (DE) with original Artificial Bee Colony (ABC) to balance exploration and exploitation phases of the optimization process. Furthermore, this study applies a serial method to reflect individual-vector priorities into the active schedule to calculate project duration. The ABCDE-RC algorithm is compared with benchmark algorithms considered using a real construction case study and a set of standard problem available in the literature. The experimental results demonstrate the efficiency and effectiveness of the proposed model. The ABCDE-RC is a promising alternative approach to handling resource-constrained project scheduling problems.

Ghoddousi *et al.* (2016) studied a multi-attribute buffer sizing method in order to maximize the robustness of the buffered schedule generated. The methodology presented in this study is based on the critical chain buffer management methodology. In order to prove the effectiveness of the proposed method, a simulation approach is applied.

Zhang *et al.* (2016) studied a project scheduling problem under resource tightness. They focused on project buffer sizing of a project critical chain. The Design Structure Matrix (DSM) is then adopted to analyze the information flow between activities and calculate the rework time resulting from the information interaction and the information resource tightness.

Taheri Amiri *et al.* (2017b) solved the issue of the project time-cost balance planning using the genetic meta-heuristic algorithm. In this research, the time-objective function was calculated using the critical chain method and the project buffer was obtained by cut-and-paste method. Furthermore, in order to evaluate the cost-objective function, the total cost of consumable and non-consumable resources was used. Time and cost were converted to a single objective by using the utility function and the problem was solved in a single-objective manner.

3. Methodology

3.1 Non-dominated Sorting Genetic Algorithm (NSGAII)

The NSGA-II technique (Srinivas and Deb, 1994) is one of the most common meta-heuristic methods that obtain multiple optimal Pareto solutions for multi-objective optimization problems. It has the following three features:

1. Observes the principle of elitism.
2. Has a special mechanism for maintaining diversity in the population.

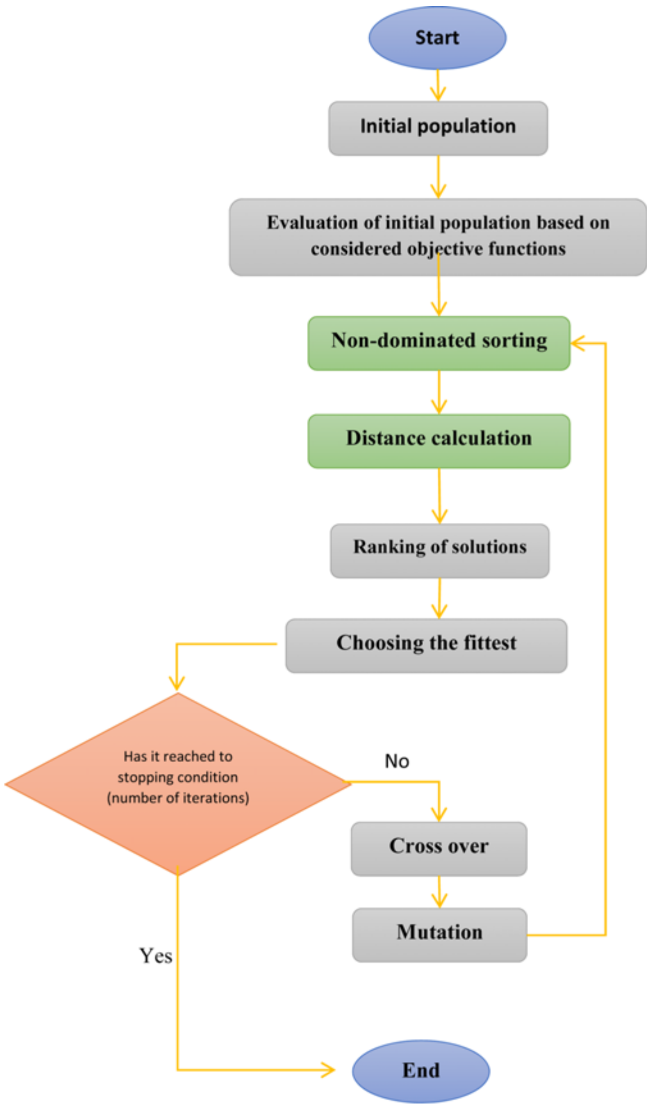

Fig. 1. Flowchart of Proposed Algorithm

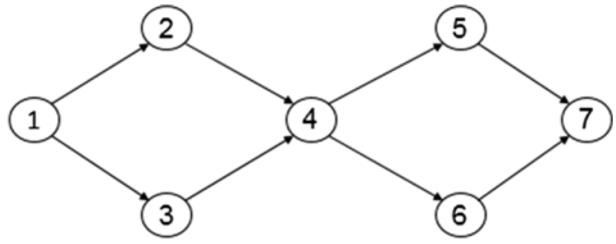

Fig. 2. View a Node Network

3. Emphasizes non-dominated solutions.

The flowchart of NSGAII approach is shown as Fig. 1 below:

The structure of the proposed NSGAII algorithm is described below and exhibited in a graph in Fig. 2. The NSGAII structure includes how to generate an initial response and new generations using two operators, i.e., crossover and mutation. Fig. 2 contains a sample graph for explaining the proposed structure.

In this graph, activity 1 is the first activity for implementation, and until this activity ends, it is not possible to perform subsequent activities. After performing activity 1, it is time for the implementation of activities 2 and 3. If resources are available, both activities can be performed simultaneously; otherwise, one of these activities is randomly selected and executed, and after the completion of the selected activity, the next activity will be done. To execute, activity 4, in addition to needing resources, should wait for activities 2 and 3 to complete. Upon completion of activity 4, activities 5, 6, or both are selected with regard to resource constraints. Activity 7 is the last activity to be performed that cannot be executed until activities 1 to 6 are executed.

3.1.1 Solution Presentation

The purpose of this study is to find the best sequence of activities that consider the prerequisite relations, and reduce costs and time. The first step in meta-heuristic algorithms is to consider a structure to show the justified answers. This used a continuous structure to encode the responses, and after two stages of modifying this response, the intended response was generated.

Step 1: Generating a chromosome for n size activity with values f rom 0 to 1.

Step 2: Sorting the chromosome in an ascending order and finding the position of each element after sorting.

After sorting and considering the position of each element, a permutation of the elements is created. The permutation of the elements brings about a non-duplication of elements.

Step 3: Modification of the chromosome considering pre-requisite relations

After creating the initial response, it is necessary to correct this response based on the pre-requisite conditions described in the previous section. The pseudo-code 1as shown in Fig. 3 is defined to correct prerequisite relations.

3.1.2 Producing the New Generation

The parent selection mechanism in this study is a roulette wheel. To generate neighboring responses in the NSGAII algorithm,

```
function newX=PrecedenceCheck(x,Precedence)
newX=[];
while true
    for i=x
        if all(ismember(cell2mat(Precedence(i)),newX));
            break;
        end
    end
    [newX]=[newX i];
    [j]=find(x==i);
    x(j)=[];
    if isempty(x)
        break;
    end
end

end
```

Fig. 3. The Pseudo-code 1 to Correct Pre-requisite Relations

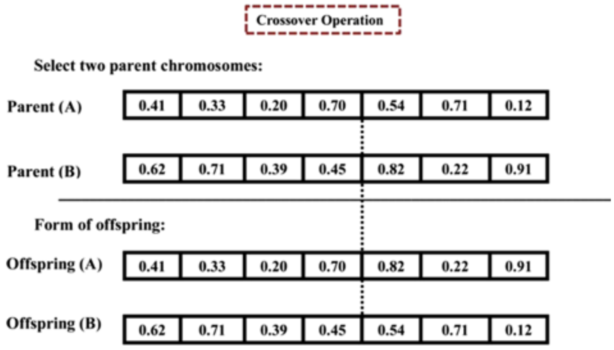

Fig. 4. Crossover Operation to Generate Offspring Genes

Fig. 5. Mutation Operation to Generate Offspring Genes

two crossover and mutation operators are used. For this purpose, a single-point crossover operator was used, and a mutation operation with a mutation rate of 0.02 was applied. After applying the desired changes and generating new responses, all responses were updated according to the second step and pseudo-code 1. The method of applying the crossover and mutation operator is shown in Figs. 4 and 5.

By creating the chromosome of each response and obtaining the sequence of activities, based on the time of each activity and the amount of resources required for carrying them out, the completion time of the project and its total cost are obtained.

4. Analysis of Objective Function in Critical Chain Multi-project Scheduling

In this study two factors, time and cost, were considered to assess critical chain multi-project scheduling. In terms of time, the project aimed to minimize duration using the critical chain method. In terms of cost, the study aimed to minimize the total cost of the project, including direct and indirect costs. Direct costs involve costs related to renewable and nonrenewable resources employed for all project operations. On the other hand, indirect costs include fixed costs of the company during the project implementation period. In order to provide the objective function for the proposed problem, its associated notation was first presented.

• Notations

N: Total number of projects

i: Project index i = 1, 2, 3, …, N

J: Project activities j = 1, 2, 3, …, J

K: Renewable resources k = 1, 2, 3, …, K

r_{ijk}: $_{Renewable}$ *resources, K, required for accomplishing activity j in project i*

i = 1, 2, 3, …, N & j = 1, 2, 3, …, J & k = 1, 2, 3, …, K

C_k: *Unit cost of renewable resources k = 1, 2, 3, …, K*

t_{ij}: *Duration of activity j in project i i = 1, …, N, j = 1, …, J*

P: Non-renewable resources

nr_{ijp}: *The renewable non-renewable resource, P, required for accomplishing activity j in project i*

i = 1, 2, 3, …, N & j = 1, 2, 3, …, J & p = 1, 2, 3, …, p

C_p: *Unit cost of non-renewable resources p*

p = 1, 2, 3, …, p

E_{e_0}: *Ending time of a virtual activity*

PB: Project buffer

T: Total project time with the critical chain method

R_k: *Amount of unusable resources available*

k = 1, 2, 3, …, K

S: Sum of critical chain activities

T_{ts}: *Total duration of critical chain activities*

S_i: *Indirect cost for project i per day i = 1, …, N*

$t_{i:}$ *Completion time of project i*

$t_{ij:}$ *Duration time of activity j in project i*

$E_{ij:}$ *Start time of activity j in project i*

4.1 Proposed Multi-project Critical Chain Scheduling Model Considering Resource Constraints

A bi-objective multi-project scheduling problem was studied. The two objective functions of our mathematical model are presented in Eqs. (1) and (2).

$$\min T = E_{e_0} + PB \qquad (1)$$

$$\min C = \sum_{i=1}^{N}\left(\sum_{j=1}^{J}\left(\sum_{k=1}^{K} r_{ijk}C_k t_{ij} + \sum_{p=1}^{p} nr_{ijp}C_p\right)\right) + (S_i t_i) \qquad (2)$$

The constraints of our model are shown in Eqs. (3)-(5).

s.t.

$$E_{ij} - E_{i(j-1)} \geq t_{ij} \qquad (3)$$

$$PB = \frac{T_{ts}}{2} \qquad (4)$$

$$\sum_{i=1}^{N}\sum_{j=1}^{J} r_{ijk} \leq R_k \qquad \forall t \in T \qquad (5)$$

4.1.1 Model Explanation

Equation (1) shows the total time of the project using the critical chain method. A multi-project critical chain planning and control process is complex, and project executors and employers are always focusing on the project's total time. Therefore, multi-project critical chain scheduling aims to minimize the project time. In Eq. (1), the Project Buffer (PB) was calculated on the basis of a cut-and-paste method. To clarify the way in which the project buffer is calculated and the difference between the critical path and critical chain methods, an example with three activities A (14 days), B (10 days), and C (4 days) was considered. The prerequisite relationships between the activities are such that activity A has no prerequisites, activity B depends on activity A, and activity C depends on activity B. If the project is scheduled with the critical path method, the total project time will equal the sum of the times of activities A, B, and C, i.e., 28 days. In the critical chain method, based on the philosophy behind the method, which states that 50 percent of activity time consists of uncertainty, this time is eliminated from the initial time of the activity, and half of the eliminated time is allocated to the project buffer (this method of calculating project buffer is referred to as the cut-and-paste method). Thus, the times of activities A, B and C have been assumed to be 7, 5, and 2, respectively, and the project buffer time has been assumed to be 7 ((7 + 5 + 2)/2). Fig. 6 shows how project time is calculated using the critical path and critical chain methods.

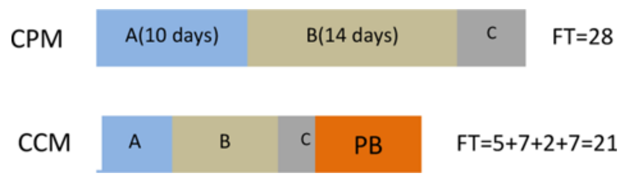

Fig. 6. Project Buffer Calculation

Equation (2) shows the project's total cost. The total cost of multi-project management includes the costs associated with renewable and nonrenewable resources as well as overhead costs per day. Eq. (3) shows the predecessors and successors in this project, suggesting that successors' operations cannot be implemented until the completion of the current prerequisite operations, and that an operation cannot be stopped after initiation because of continuity. Eq. (4) shows how to calculate the project buffer and Eq. (5) reflects the resource constraints in this model, expressing that the use of a resource for operations implemented in a day cannot exceed the amount of the resource available in that day.

5. Designing Non-dominated Sorting Genetic Algorithm

In this study, the NSGAII was used to optimize multi-project critical chain scheduling with regard to resource constraints. Using this algorithm for the problem, the best sequence of operations would be found to meet the best utility value. The solution-finding procedure with NSGAII is explained in the following steps:

- Input model and project parameters such as:
- Number of objectives
- Constraints
- Activities execution time and resources requirement
- Precedence relationship of activities
- Renewable and non-renewable resources

The NSGA II parameters are selected as below:

Generations: maxiter = 100

Initial population: npop = 100

Intersection rate: 70% of initial population

Mutation rate: 30% of initial population

The algorithm formed primary chromosomes that show operation implementation sequences with regard to precedence relationships among resource constraints.

Non-dominated sorting was performed, the crowding distance was calculated for each front, and then the best chromosomes were selected.

Finally, the Pareto solution is selected as the optimal scheduling program.

In order to verify and validate the model, two sample instances were included in this research.

5.1 Sample 1

First, for model validation, the problem was studied in small dimensions. For this purpose, the example proposed by (Zheng and Ng, 2005) was solved by making changes to the structure of the model. The example in question, and resources required for each activity (including consumable and non-consumable resources), are shown in Table 1.

In order to solve the optimization model in this study, four types of renewable resources and two types of non-renewable resources were used. The unit cost estimated for each resource is as follows:

$$C_k^1 = 30 \quad C_k^2 = 50 \quad C_k^3 = 45 \quad C_k^4 = 40 \quad C_p^1 = 5 \quad C_p^2 = 3 \tag{6}$$

The project overhead cost per day is

$$S = 200 \tag{7}$$

The above example was solved with the MATLAB software using the proposed algorithm. The results showed that the proposed algorithm could achieve the optimal solution considering the dimensions of the problem and input parameters. The optimal value of the time objective function is equal to 46 units (31 units are related to the end time of the last project activity and 15 units belong to the project buffer), and the optimal value of the cost is 24892 units. The sequence of conducting activities along with the start and finish time of activities and the cost of renewable and non-renewable resources are presented in Table 2.

To further analyze the model, the limited amount of available resources changed each day, and the effect of the change on the values o f the objective function was evaluated.

Considering the results obtained, the method of changing time and cost objective functions relative to changes of the values of the daily resource limitations are shown in the Figs. 7 and 8.

In order to illustrate the model performance, the problem was solved in two different modes with or without restricting resources and the differences between the two solutions were compared. In order to apply the resource constraints in the project, the available resource was 6 units per day. The results obtained for these two modes are represented in Figs. 9 and 10.

An example is presented to illustrate the proper performance of the model. As shown in Figs. 9 and 10, if the resource constraint of 6 units per day is concerned, Fig. 9 evidently depicts that the K1 restriction during the days 13th to 20th requires 8 units of resource, which exceeds the amount of resources available in this

Table 2. Outputs Obtained from the First Example

Sequence	Start time	Duration time	Finish time	Renewable resource cost	Non-Renewable resource cost
1	1	7	7	800	2240
2	8	8	15	800	2920
3	8	8	15	670	1440
4	8	6	13	960	2320
5	16	11	26	1350	7150
6	14	7	20	810	1925
7	27	5	31	510	975

Table 3. Objective Function Values

Renewable resource per day	Project completion time	Total cost
6	57	24901
8	46	24892
10	46	24892
12	46	24892

Table 1. Sample 1 Information

Activity name	Precedence	Time	Resource					
			K_1	K_2	K_3	K_4	P_1	P_2
1-Site preparation	-	14	2	3	2	1	100	100
2-Forms and rebars	1	15	2	2	2	2	120	120
3-Excavation	1	15	3	2	3	2	100	100
4-Precast concrete girders	1	12	1	2	2	1	80	90
5-Pour foundation and piers	2,3	22	5	4	4	5	150	200
6-Deliver precast girders	4	14	3	2	1	2	90	120
7-Erect girders	5,6	9	1	2	1	1	60	70

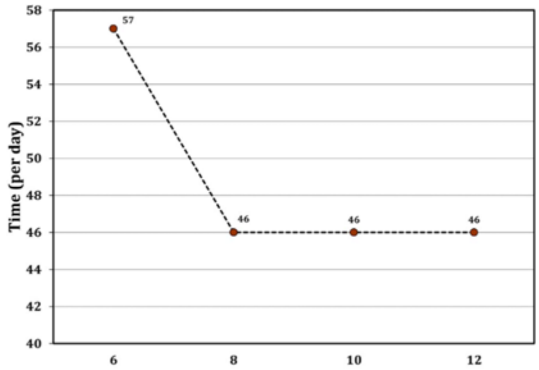

Fig. 7. Completion Time Changes Trend

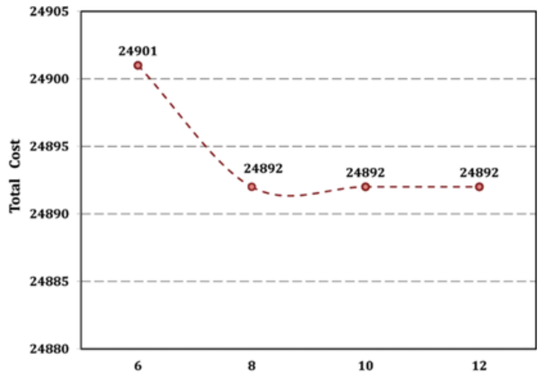

Fig. 8. Cost Changes Trend

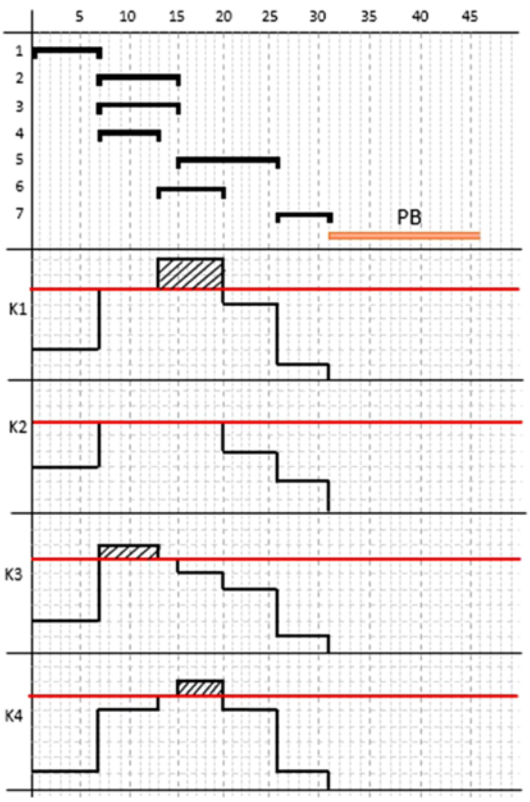

Fig. 9. Gantt Chart and Resources Required in Unrestricted Resources Mode

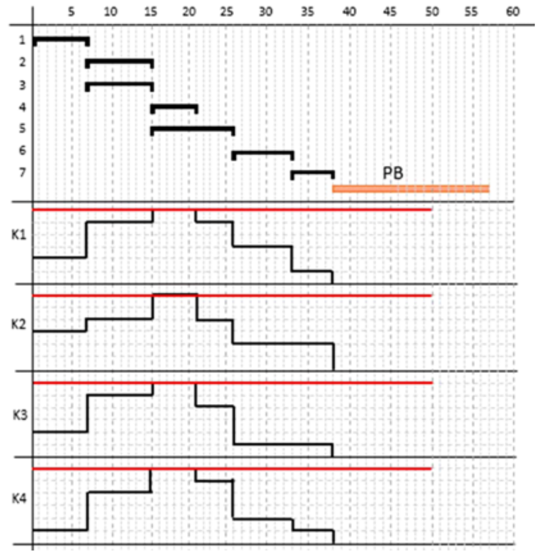

Fig. 10. Gantt Chart and Resource Allocation with a Resource Limit of Six Units

day. Hence, the resource constraints should be planned in a way to have fewer than 6 units per day. Given that the amount of resources required for Tasks 5 and 6 during the days 15th to 20th involves 8 units of resources, which is above the level of the available resources, the tasks in the resource-restricted mode are planned not to be implemented simultaneously (Task 5 is scheduled on the days 15th to 26th and Task 6 is scheduled on the days 27th to 31st). As shown in Fig. 10, all activities are planned in such a way that the amount of resources required for tasks does not exceed the available amount of resources (6 unit units per day), indicating the appropriate efficiency of the algorithm.

5.2 Sample 2

In second sample, three projects were simultaneously planned. The number of operations in these three projects was 7, 8, and 10. Information on the operations and prerequisite relations are given below for each project:

• Project 1:

The project includes 7 operations, and prerequisite relations of operations are provided in Table 4:

Table 4. Prerequisite Relations of Operations in Project 1

Activity Name	Duration	Prerequisite relations	Resources					
			k_1	k_2	k_3	k_4	p_1	p_2
A1	5	-	0	3	1	3	90	40
B1	8	A1	0	6	0	5	90	100
C1	9	A1	1	0	6	0	100	10
D1	8	A1	3	1	2	3	90	0
E1	6	B1-C1	2	2	0	3	50	10
F1	12	D1	0	2	2	1	90	90
G1	8	E1-F1	5	5	0	0	20	10

Table 5. Prerequisite Relations of Operations in Project 2

Activity Name	Duration	Prerequisite relations	Resources					
			k_1	k_2	k_3	k_4	p_1	p_2
A2	9	-	2	0	4	1	40	40
B2	6	-	2	4	2	0	80	80
C2	11	-	1	0	5	4	30	80
D2	7	A2	4	6	0	1	70	20
E2	8	B2	2	6	1	0	90	80
F2	5	B2	0	3	5	0	60	10
G2	8	C2	1	3	6	5	90	40
H2	7	D2-E2	0	3	3	3	30	80
I2	6	F2	1	1	1	6	100	90
J2	7	G2	3	1	3	1	10	80

Table 6. Prerequisite Relations of Operations in Project 3

Activity Name	Duration	Prerequisite relations	Resources					
			k_1	k_2	k_3	k_4	p_1	p_2
A3	5	-	4	4	5	3	60	40
B3	7	-	2	2	2	0	80	60
C3	8	-	1	4	0	3	50	70
D3	8	B3	3	0	0	2	100	70
E3	7	B3	0	3	4	1	70	10
F3	4	A3-D3	3	1	0	6	20	90
G3	8	B3	3	3	0	2	90	70
H3	6	C3-E3	0	3	6	2	80	80

• Project 2:

The project includes 10 operations, and prerequisite relations of operations are provided in Table 5:

• Project 3:

The project contains 8 operations, and prerequisite relations of operations are provided in Table 6:

Information about the cost of resources and overhead cost per day for all projects is the same as the previous sample.

Concerning the resource constraints in the model, different scenarios were defined to analyze the significance of each resource. In the first 4 scenarios, identical amount of resources was assigned per day (6, 8, 10 and 12 units were considered for each resource per day). In the next 3 scenarios, 1-3 resources were released simultaneously, and therefore, no resource constraint existed for released resources. In these cases, the effect of released resources on total time and cost project scheduling was investigated. Table 7 shows different scenarios for resource constraints. In the following, each scenario is described and the resource sensitivity of the proposed bi-objective model is reported.

Table 7. Different Scenarios Specification

Scenarios	Characteristic
1	Considering 6 resource constraint units for each resource per day
2	Considering 8 resource constraint units for each resource per day
3	Considering 10 resource constraint units for each resource per day
4	Considering 12 resource constraint units for each resource per day
5	Release of individual resources (4 cases)
6	Release of two resources simultaneously (6 cases)
7	Release of three resources simultaneously (4 cases)

Table 8. Time and Cost of Projects Considering 6 Resource Constraint Units for Each Resource per Day

Solution No.	Overall project completion cost	Overall project completion time
1	48332.6	97
2	48342	92
3	48334.2	95
4	48333.5	96
5	48333.5	96

• Scenario 1

After solving the above problem in the MATLAB Software with regard to 6 resource constraint units for each resource per day, the obtained Pareto responses are shown in Table 5. In this table, the first column represents the response number, and the second and third columns show the project completion time and total cost of the project, respectively. The most appropriate time duration to implement projects in this case was 92 days with a cost of 48342. The most acceptable project implementation cost was 48332.6 with an implementation time of 97 days. Depending on the project conditions and the significance of the parameters of time and cost, each of the following Pareto responses that contain a sequence of operation implementations can be selected. The sequence of operations associated with each Pareto response is presented in Table 9. In Table 9, the first column shows the Pareto solution number while the second column displays the sequence of activities' execution.

The overall project completion cost and time for each Pareto response are shown in Fig. 11.

• Scenario 2

Regarding 8 resource constraint units for each resource per day, the obtained Pareto responses are shown in Table 10. In this

Table 9. Implementation Sequence of Various Options Considering 6 Resource Constraint Units for Each Resource per Day

Solution No.	Implementation sequence of activities																								
1	1	3	2	5	4	6	7	9	13	8	11	10	14	12	17	15	16	18	20	19	23	22	21	24	25
2	1	2	3	5	4	6	7	9	8	20	11	12	10	14	13	16	15	17	18	19	21	22	23	24	25
3	1	2	3	4	6	5	9	13	8	7	10	11	12	14	16	15	17	18	19	21	20	22	23	24	25
4	1	3	2	4	6	5	9	7	10	8	11	13	14	12	15	16	17	19	21	18	20	22	23	24	25
5	1	2	3	4	6	5	7	9	10	8	11	12	13	14	15	16	17	20	18	19	21	22	23	24	25

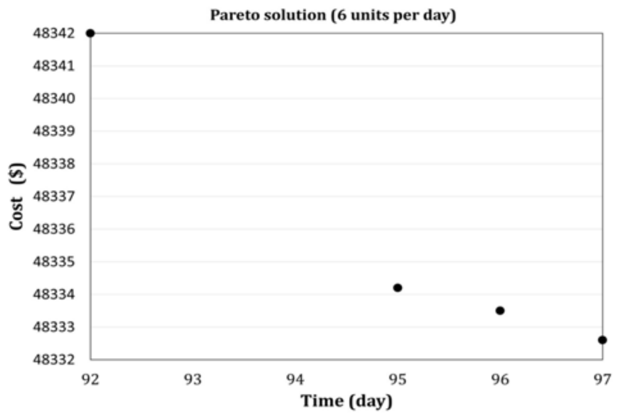

Fig. 11. Pareto Response Considering 6 Resource Constraint Units for Each Resource per Day

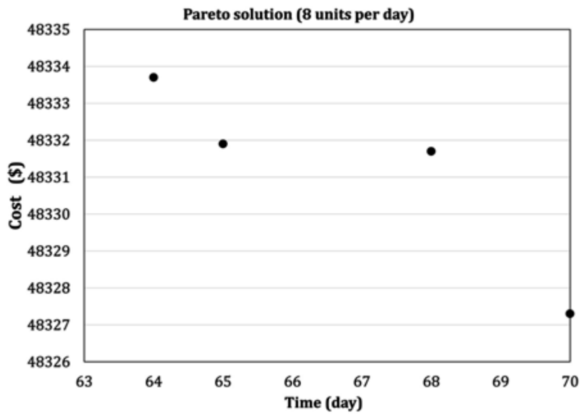

Fig. 12. Pareto Response Considering 8 Resource Constraint Units for Each Resource per Day

Table 10. Time and Cost of Projects Considering 8 Resource Constraint Units for Each Resource per Day

Solution No.	Overall project completion cost	Overall project completion time
1	48333.7	64
2	48331.9	65
3	48331.9	65
4	48331.9	65
5	48331.9	65
6	48331.9	65
7	48331.9	65
8	48331.7	68
9	48331.7	68
10	48331.7	68
11	48327.3	70
12	48327.3	70
13	48327.3	70

Table 11. Time and Cost of Projects Considering 10 Resource Constraint Units for Each Resource per Day

Solution No.	Overall project completion cost	Overall project completion time
1	48324.5	53
2	48323	54
3	48323	54

table, the first, second, and third columns represent the response number, total cost of the project, and project completion time, respectively. The most appropriate time duration to implement projects in this case was 64 days with a cost of 48333.7. The most acceptable project implementation cost was 48327.3 and implementation time of 70 days.

The overall project completion cost and time for each Pareto response are shown in Fig. 12.

• Scenario 3

Table 11 shows the Pareto responses obtained for 10 resource constraint units for each resource per day. The most appropriate time duration to implement projects in this case was 53 days with a cost of 48324.5. The most acceptable project implementation cost was 48323 and implementation time of 54 days.

The overall project completion cost and time for each Pareto response are shown in Fig. 13.

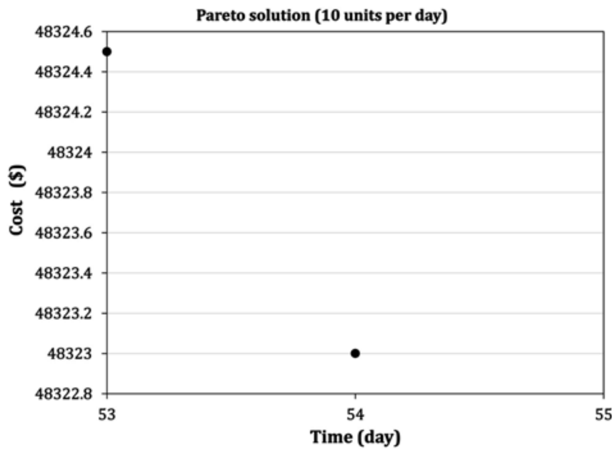

Fig. 13. Pareto Response Considering 10 Resource Constraint Units for Each Resource Per Day

• Scenario 4

When using 12 resource constraint units for each resource per day, the Pareto responses are presented in Table 12. The most appropriate time duration to implement projects in this scenario was 64 days with an implementation cost of 48323.5. The most acceptable project implementation cost was 48322.6 and implementation time of 47 days.

The overall project completion cost and time for each Pareto response are shown in Fig. 14.

• Scenario 5

In this scenario, each of four resources was separately released, and time and cost variations are shown in Figs. 15 and 16. To release each resource, the proportion of the allocated resource

Table 12. Time and Cost of Projects Considering 12 Resource Constraint Units for Each Resource Per Day

Solution No.	Overall project completion cost	Overall project completion time
1	48323.5	46
2	48322.6	47

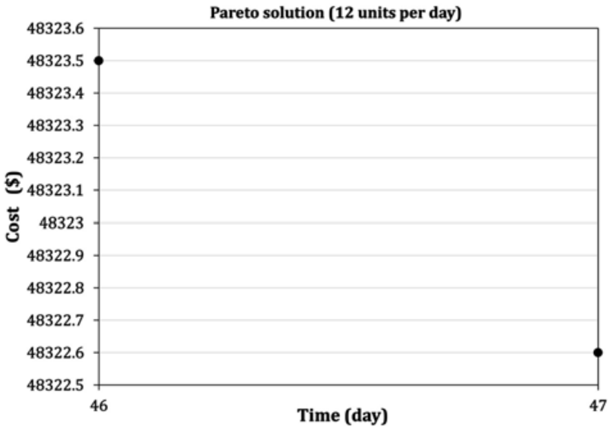

Fig. 14. Pareto Response Considering 12 Resource Constraint Units for Each Resource Per Day

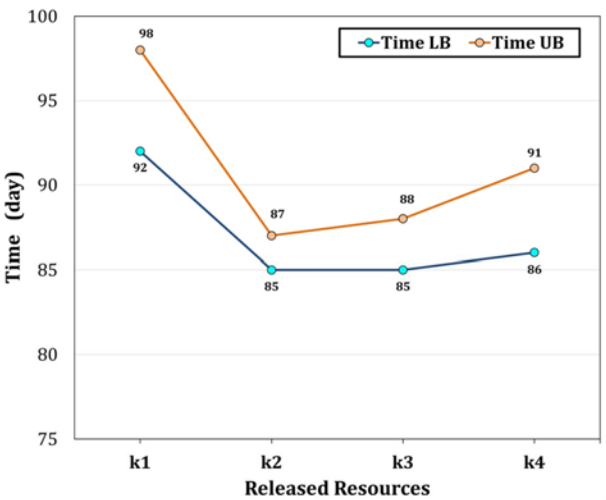

Fig. 15. Project Completion Time Variation for the Release of Individual Resources

to the released resource was considered to be high and other resources were set at the lowest value (6 resources units per day).

According to Fig. 15, the project completion time varies with the release of each resource. In this regard, it seems that the resources K2 and K3 are of greater importance, since the project, with the release of these two resources, completes in the shortest time possible.

As shown in Fig. 16, the project completion cost varies with the release of each resource. The results show that no significant difference exists in the project total cost with the release of resources separately.

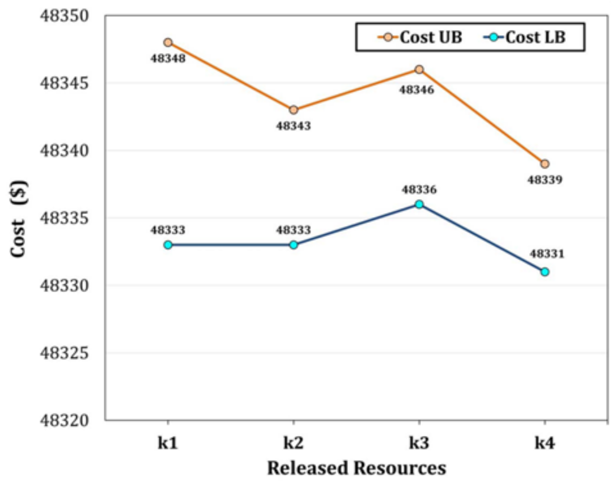

Fig. 16. Project Completion Cost Variation for the Release of Individual Resources

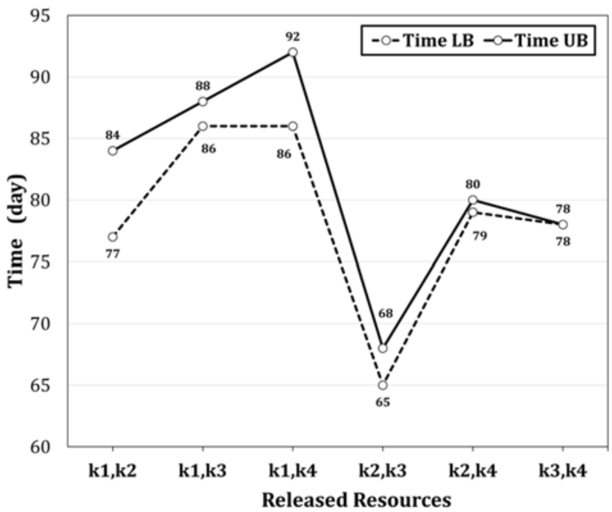

Fig. 17. Project Completion Time Variation for the Release of Resources in Pairs

• Scenario 6

In this phase, two resources were alternatively released, with the time and cost variation illustrated in Figs. 17 and 18. Large amounts of two released resources were considered.

Figure 17 suggests that the project completion time was reduced more with the release of two resources K2 and K3. This means that the project completed within a shorter period of time via simultaneous release of both resources when compared to their individual release or the release of both other resources.

According to the results obtained in Fig. 18, the lower bound of the total cost is not sensitive to the release of two resources at different states, but considering the cost upper bound, the states (K1 and K3) and (K2 and K4) had the highest costs and the state (K3 and K4) had the lowest cost.

• Scenario 7

Finally, three resources were alternatively released, with the

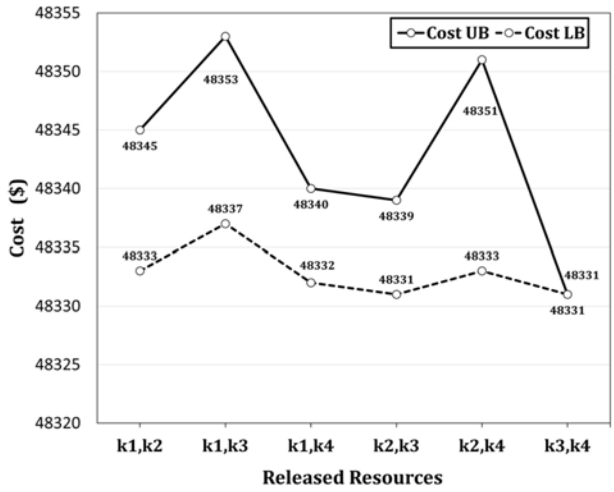

Fig. 18. Project Completion Cost Variation for the Release of Resources in Pairs

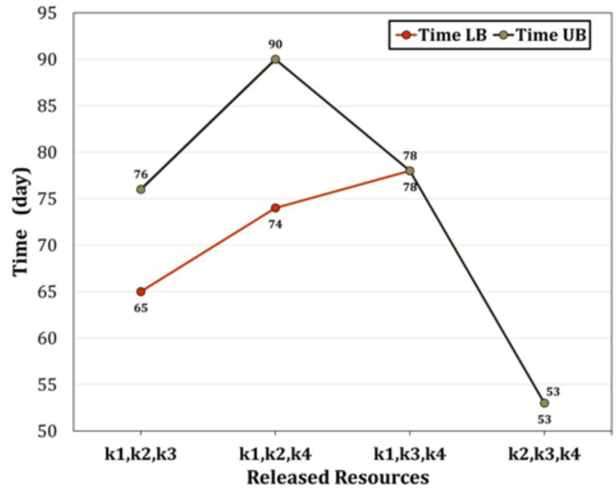

Fig. 19. Project Completion Time Variation for Ternary Release of Resources

time and cost variation illustrated in Figs. 19 and 20. Large amounts of two released resources were considered.

Figure 19 reveals that the project completion time reduced more with the release of the three resources K2, K3 and K4. It should be noted that upper and lower bounds of the obtained time were equal in two states (K1 and K3 and K4) and (K2 and K3 and K4). This means that the sensitivity to the project completion time disappears with the release of these three resources.

With regard to Fig. 20, the total project cost is minimized with the release of resources (K2, K3 and K4). It is worth noting that the project completion time decreases with the simultaneous release of four resources. This is evident since there are enough resources available and there would be no delay caused by the resources constraint.

6. Discussion

Analyzing the values obtained f rom computational results,

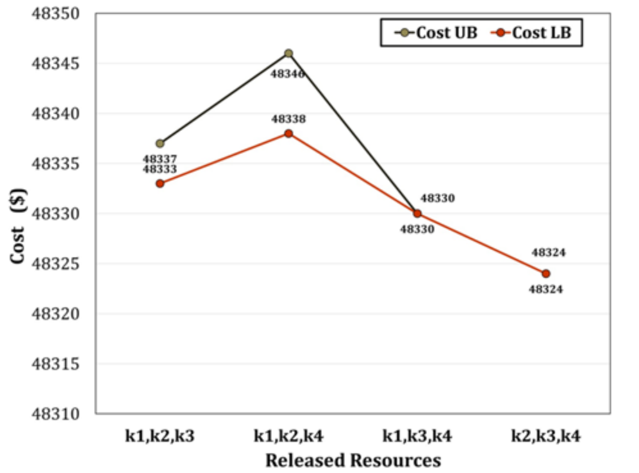

Fig. 20. Project Completion Cost Variation for Ternary Release of Resources

the following results were achieved:

- First, the model was examined in small-scale instances. The results of the change in daily resources values indicate that with the increase in daily resources, the project completion time and the cost of its implementation have decreased as shown in Figs. 7 and 8.

After running sample 2 in MATLAB, 6, 8, 10, and 12 constraint units were included in the model for each resource per day and their relevant outputs were analyzed.

- In scenario 1, five Pareto responses were obtained. Considering different implementation sequences, each of these responses provided the project manager with various implementation options. The best options can be selected with respect to project conditions. The output obtained shows that the most appropriate time duration to implement projects in this case was 92 days with a cost of 48342. The most acceptable project implementation cost was 48332.6 with an implementation time of 97 days.
- In scenario 2, 13 Pareto responses were obtained. The output obtained shows that the most appropriate time duration to implement projects in this case was 64 days with a cost of 48333.7. The most acceptable project implementation cost was 48327.3 with an implementation time of 70 days. The best options can be selected with respect to project conditions and the significance of cost and time parameters.
- In scenario 3, three Pareto responses were obtained. The output obtained shows that the most appropriate time duration to implement projects in this case was 53 days with a cost of 48324.5. The most acceptable project implementation cost was 48323 with an implementation time of 54 days. The best options can be selected with respect to project conditions and the significance of cost and time parameters.
- In scenario 4, two Pareto responses were obtained. The output obtained shows that the most appropriate time duration to implement projects in this case was 64 days with a cost of 48323.5. The most acceptable project implementation cost

was 48322.6 with an implementation time of 47 days. The best options can be selected with respect to project conditions and the significance of cost and time parameters.

- In scenario 5, resources K2 and K3 were more important than others in the project, which with their release, completes at the shortest time possible.
- The project completion cost varies with the release of each resource. The results show that no significant difference exists in the project total cost with the release of resources separately.
- Scenario 6 suggests that simultaneous release of two resources reduced the project completion time more than other scenarios. The result reflected the proper performance of the proposed algorithm. The project completion time was significantly reduced with the release of two resources K2 and K3. This reflects the great importance of these two resources. Therefore, it can be concluded that when the project completion time is of paramount importance in a project, the release of two resources K2 and K3 (i.e. providing these two resources completely and removing resource constraints relevant to them) can contribute significantly in decreasing the project completion time.
- According to the results obtained in Fig. 18, the lower bound of the total cost is not sensitive to the release of two resources at different states, but considering the cost upper bound, the states (K1 and K3) and (K2 and K4) had the highest costs while the state (K3 and K4) had the lowest cost.
- Scenario 7 shows that the project completion time was reduced more with the release of three resources K2, K3 and K4. It should be noted that upper and lower bounds of the obtained time were equal in two states (K1 and K3 and K4) and (K2 and K3 and K4). This means that their sensitivity to the project completion time disappears with the release of these three resources.
- According to Fig. 20, the total project cost was minimized with the release of resources (K2, K3 and K4).
- The project completion time decreased with the simultaneous release of four resources. This is evident since there are enough resources available and there would be no delay caused by any resource constraint.
- Several Pareto responses were obtained for each resource constraint. Here, the objective functions achieved from each response are analyzed. Of the different Pareto responses for each problem with specified resource constraints per day, responses having the lowest cost and shortest time were selected. It should be noted that the responses with the lowest cost led to the longest total project implementation time, while those responses with the shortest time resulted in projects with the highest project implementation costs. Hence, ranges of time and cost were obtained for each problem with daily resource constraints. Figure 21 represents the lower and upper bounds of the total execution time for projects with different daily resource constraints.

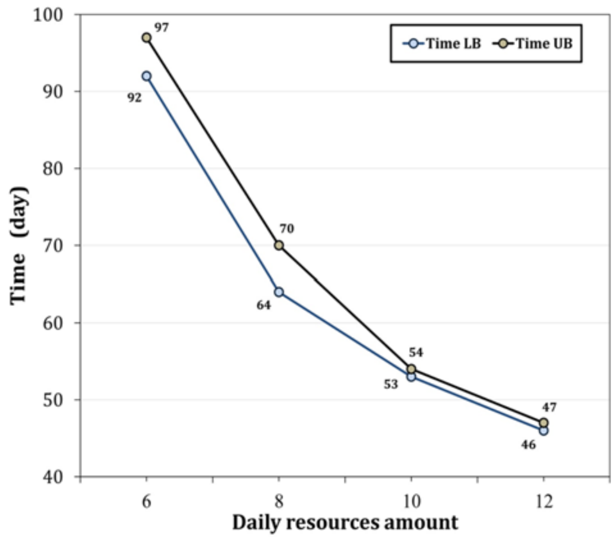

Fig. 21. Lower and Upper Bounds of the Total Implementation Time for Different Daily Resource Constraints

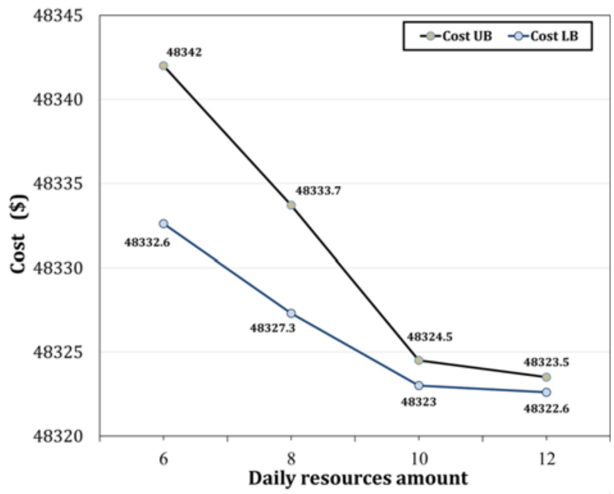

Fig. 22. Lower and Upper Bounds of the Total Implementation Cost for Different Daily Resource Constraints

According to Fig. 21, the greater the amount of resources available per day, the shorter the total project completion time will be. This process is clear and indicates the appropriateness of the proposed algorithm. It can also be observed that the time interval changes are reduced as the amount of daily resources increases. This shows that increasing the daily resources reduces time sensitivity. In other words, the constrained access to resources is decreased, and not leads to dramatic changes in the project completion time. Fig. 22 represents the lower and upper bounds of the total implementation cost for projects with different daily resource constraints.

Since an increase in the amount of the daily project resources decreased the project completion time, overhead costs are affected that are directly related to the project time. Hence, the greater the amount of available resources, the lower the project completion time and, consequently, the lower the overhead costs

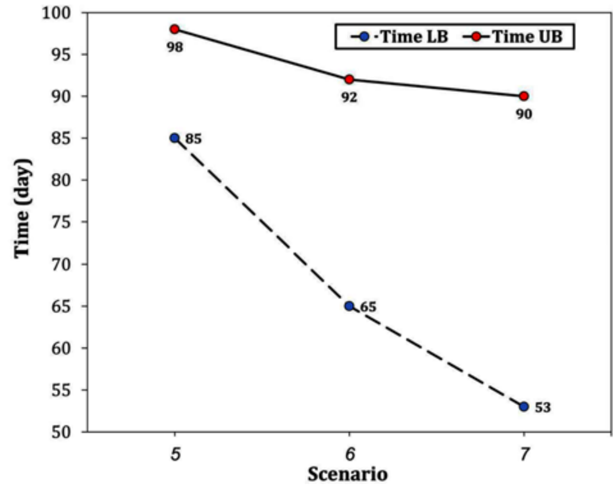

Fig. 23. Lower and Upper Bounds of the Total Implementation Time for Releasing Resources Scenarios

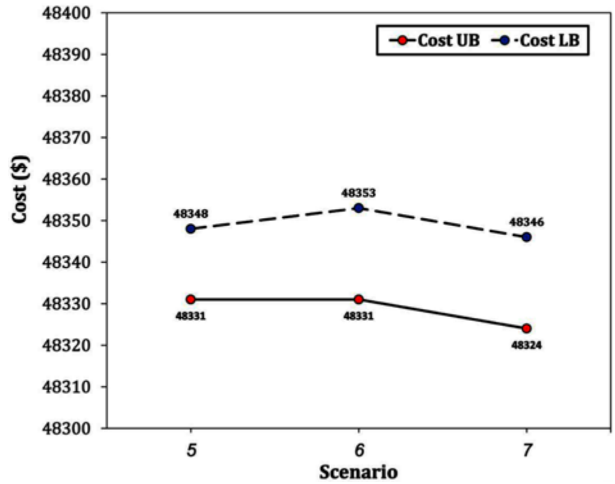

Fig. 24. Lower and Upper Bounds of the Total Implementation Cost for Releasing Resources Scenarios

(Fig. 22).

- In scenarios with released resources, time and cost are reduced by increasing the number of released resources. As shown in Fig. 22, when two resources are released simultaneously, the project can be finished 20 days earlier than when one resource is released according to a time lower bound. Also, releasing three resources led to decreased project completion time. This trend exists on the time upper bound but the difference between them is negligible. Furthermore, according to the cost lower and upper bound variation trend, increasing the number of released resources have a negligible impact on the project's cost (Fig. 23).

In summary, after releasing different resources, resources K2 and K3 are more sensitive than others, and project completion time and cost will be decreased rapidly by releasing these resources. Thus, managers can reduce project time and cost by supplying resources K2, K3 while the two other resources do not prominently affect the project's objectives. Generally, it can be concluded that this model helps managers analyze various aspect of projects and determine its most important and effective elements, such as resources, before starting the project in order to better manage them during its execution.

7. Conclusions

The main objective of this study was to provide a time-cost trade-off model to explore optimal responses. In this regard, a non-dominated sorting genetic algorithm was used to provide project managers with different Pareto responses. Better responses will be obtained if there is a correct definition of the problem to achieve the optimal solution and the project parameters are properly applied. For this purpose, the fundamental principles of non-dominated sorting genetic algorithm were created, then the time-cost trade-off problem were solved by the proposed algorithm, which was applied to several scenarios. Finally, the results obtained from scenarios were analyzed. According to the scenarios related to resource constraints and results obtained from solving them, several Pareto solutions are given with different time, cost, and varying number of resources, so that managers, based on their facilities and conditions, can be able to choose one of these cases. Results show that project completion time will be reduced if more resources are available, but the total project cost will not be significantly changed.

Also, to analyze the sensitivity of each resource and measure their importance, each resource was excluded from the resource constraint mode in a single, double, and triple form so that the importance of these resources for the project manager was determined. Following the analysis, it was revealed that the resources K2 and K3 are of great importance and have a great impact on the project time and cost. Thus, the supply of these two resources in the concerned projects would improve the project time and cost.

Due to the complexity of the discussion of project scheduling with resource constraints, the proposed model faces challenges. Among these cases, one may consider other goals in addition to time and cost. In addition, although the prioritization for the resource allocation is based on the profitability of projects, in this study, the same level of profitability was considered among the projects. In this research, the input parameters of the problem, such as the time and cost of each activity, are fixed and predefined, whereas in the real world they can be uncertain.

Given the above issues, one may consider various alternatives to carry out future studies based on the proposed model in this research. Among other goals considered for these issues, one can identify the quality and diversion of available resources.

In addition, to make the proposed model realistic, one can consider various coefficients for the projects. Finally, various approaches, such as the fuzzy theory approach and stochastic modeling, can be used to apply uncertainty to the problem.

Also, n this study, maximum number of activities in multiple project was 10. In future study, this model can be applied for large scale projects or mega project which has lots of activities such as high-rise buildings and skyscrapers. Considering the approach used in this research to assess the significance of each resource, this effect is better demonstrated in larger projects and would improve the performance of such projects. Once the weight of each resource is identified, the supply of resources of greater importance would prevent the occurrence of time delays in large-scale projects.

References

Afrouzi, N. E., Roghanian, E., Najafi, A. A., and Mazinani., M. (2013). "A multi-mode resource-constrained discrete time-cost tradeoff problem solving using an adjusted fuzzy dominance genetic algorithm." *Scientia Iranica*, Vol. 20, No. 3, pp. 931-44, DOI: 10.1016/j.scient. 2012.12.024.

Alkass, S., Mazerolle, M., and Harris, F., (1996). "Construction delay analysis techniques." *Construction Management Economics*., Vol. 14, No. 5, pp. 375-394, DOI: 10.1080/014461996373250.

Aminbakhsh, S. and Sonmez, R. (2016). "Discrete particle swarm optimization method for the large-scale discrete time-cost trade-off problem." *Expert Systems with Application*, Vol. 51, pp. 177-185, DOI: 10.1016/j.eswa.2015.12.041.

Anagnostopoulos, K. P. and Kotsikas, L. (2010). "Experimental evaluation of simulated annealing algorithms for the time–cost trade-off problem." *Applied Mathematics and Computation*, Vol. 217, No. 1, pp. 260-270, DOI: 10.1016/j.amc.2010.05.056.

Azaron, A., Perkgoz, C., and Sakawa, M. (2005). "A genetic algorithm approach for the time-cost trade-off in PERT networks." *Applied Mathematics and Computation*, Vol. 168, No. 2, pp. 1317-1339, DOI: 10.1016/j.amc.2004.10.021.

Blazewicz, J., Lenstra, J., and Rinnooy Kan, A. (1983). "Scheduling subject to resource constraints: Classification and complexity." *Discrete Applied Mathematics*, Vol. 5, No. 1, pp. 11-24, DOI: 10.1016/0166-218X(83)90012-4.

Chen, S. P. and Tsai, M. J. (2011). "Time–cost trade-off analysis of project networks in fuzzy environments." *European Journal of Operational Research*, Vol. 212, No. 2, pp. 386-397, DOI: 10.1016/j. ejor.2011. 02.002.

Chen, T. and Zhou, G. (2013), "Research on project scheduling problem with resource constraints." *Journal of Software*, Vol. 8, No. 8, pp. 2058-2063, DOI: 10.4304/jsw.8.8.2058-2063.

Cheng, M. Y. and Tran, D. H. (2015). "Opposition-based Multiple Objective Differential Evolution (OMODE) for optimizing work shift schedules." *Automation in Construction*, Vol. 55, pp. 1-14, DOI: 10.1016/ j.autcon.2015.03.021.

Eshtehardian, E., Afshar, A., and Abbasnia, R. (2009). Fuzzy-based MOGA approach to stochastic time–cost trade-off problem, *Automation in Construction*, Vol. 18, No. 5, pp. 692-701, DOI: 10.1016/ j.autcon.2009.02.001.

Ghoddousi, P., Ansari, R., and Makui, A. (2016). "A risk-oriented buffer allocation model based on critical chain project management." *KSCE Journal of Civil Engineering*, pp. 1-13, DOI: 10.1007/ s12205-016-0039-y.

Ghoddousi, P., Eshtehardian, E., Jooybanpour, S., and Javanmardi, A. (2013). "Multi-mode resource-constrained discrete time-cost-resource optimization in project scheduling using non-dominated sorting genetic algorithm." *Automation in construction*, Vol. 30, pp. 216-227, DOI: 10.1016/j.autcon.2012.11.014.

Giran, O., Temur, R., and Bekdas, G. (2017). "Resource constrained project scheduling by harmony search algorithm." *KSCE Journal of Civil Engineering*, Vol. 21, No. 2, pp. 479-487, DOI: 10.1007/s12205-017-1363-6.

Goldratt, E. M. (1997). *Critical Chain*, North River Press, Great Barrington, MA, United States.

Gonzalez-Pardo, A. and Camacho, D. (2014). "A new CSP graph-based representation to resource-constrained project scheduling problem." *2014 IEEE Congress on Evolutionary Computation (CEC)*, IEEE, Beijing, China, pp. 344-351, DOI: 10.1109/ CEC.2014.6900543.

Hazir, O., Erel, E., and Gunalay, Y. (2011). "Robust optimization models for the discrete time/cost trade-off problem." *International Journal f Production Economics*, Vol. 130, No. 1, pp. 87-95, DOI: 10.1016/j.ijpe.2010.11.018.

Herroelen, W., Leus, R., and Demeulemeester, E. (2002). "Critical chain project scheduling do not oversimplify." *Project Management Journal*, Vol. 33, No. 4, pp. 48-60.

Juring, J. (2004). "Benefits of a critical chain – a system dynamics based study." *Second World Conference on POM and 15th Annual POM Conference*, Cancun, Mexico.

Ke, H. and Ma, J. (2014). "Modeling project time–cost trade-off in fuzzy random environment." *Applied Soft Computing*, Vol. 19, pp. 80-85, DOI: 10.1016/j.asoc.2014.01.040.

Ke, H., Ma, J., and Chen, X. (2012). "Modeling stochastic project time–cost trade-offs with time-dependent activity durations." *Applied Mathematics and Computation*, Vol. 218, No. 18, pp. 9462-9469, DOI: 10.1016/j.amc.2012.03.035.

Ke, H., Ma, J., and Ni, Y. (2009). "Optimization models and a GA-based algorithm for stochastictime-cost trade-off problem." *Applied Mathematics and Computation*, Vol. 215, No. 1, pp. 308-313, DOI: 10.1016/j.amc.2009.05.004.

Kuchta, D. (2004). "The critical chain method in project management-A formal description." *Badania Operacyjneide I Decyzje*, Vol. 1, pp. 37-51.

Leach, L. (2000). "Critical chain project management improves project performance." *Preiect Management Journa*, Advanced Project Institute, DOI: 10.1177/875697289903.0000207.

Leu, S. S, Chen, A. T., and Yang, C. H. (2001). "A GA-based fuzzy optimal model for construction time-cost trade-of." *International Journal of Project Management*, Vol. 19, No. 1, pp. 47-58, DOI: 10.1016/S0263-7863(99)00035-6.

Long, L. D. and Ohsato, A. (2008). "Fuzzy critical chain method for project scheduling under resource constraints and uncertainty." *International Journal of Project Management*, Vol. 26, No. 6, pp. 688-698, DOI: 10.1016/j.ijproman.2007.09.012.

Park, W. R. and Chapin, W. B. (1992). *Construction bidding: Strategic pricing for profit*,Wiley, New York, United States.

PMI (2013). *A guide to the project management body of knowledge: PMBOK Guide*, *5th ed*., Project Management Institute Inc., PA, United States.

Rand, K. (2000). "Critical chain: The Theory of constraints applied to project management." *International Journal of Project Management*, Vol. 18, No. 3, pp. 173-177, DOI: 10.1016/S0263-7863(99)00019-8.

Raz, T., Barnes, R., and Dvir, D. (2003). "A critical look at critical chain project management." *Project Management Journal*, Vol. 34, No. 4, 24-32, DOI: 10.1109/EMR.2004.25048.

Rumelhart, D. E., Hinton, G. E., and Williams, R. J. (1986). "Learning representations by backpropagating errors." *Nature*, Vol. 323, pp. 533-536, DOI: 10.1038/323533a0.

Shen, L. and Chua, D. (2008). "An investigation of critical chain and lean project scheduling." *16th Annual Conference of the International Group for Lean Construction*, Manchester, UK.

Shou, Y., Xiang, W., Li, Y., and Yao, W. (2013). "A multi-agent evolutionary algorithm for the resource-constrained project portfolio selection and scheduling problem." *Conference: Proceedings of the 15th annual conference companion on Genetic and evolutionary computation*, Amesterdam, Netherland.

Singh, A. (2013). "Resource Constrained Multi-Project Scheduling with Priority Rules & Analytic Hierarchy Process." *24th DAAAM International Symposium on Intelligent Manufacturing and Automation*, Zadar, Crotia.

Sonmez, R. and Bettemir, O. H. (2012). "A hybrid genetic algorithm for the discrete time–cost trade-off problem." *Expert Systems with Applications*, Vol. 39, No. 13, pp. 11428-11434, DOI: 10.1016/j.eswa.2012.04.019.

Srinivas, N. and Deb, K. (1994). "Multi-objective function optimization using non-dominated sorting genetic algorithm." *Evolutionary Computation Journal*, Vol. 2, No. 3, pp. 221-248, DOI: 10.1162/evco.1994.2.3.221.

Startton, R. (2009). "Critical chain project management theory and practice." *POMS 20th Annual Conference*, Orlando Florida, United States.

Taheri Amiri, M. J., Haghighi, F., Eshtehardian, E., and Abessi, O. (2017a). "Optimization of time, cost, and quality in critical chain method using simulated annealing." *International Journal of Engineering*, Vol. 30, No. 5, pp. 705-713, DOI: 10.5829/idosi.ije.2017.30.05b.00.

Taheri Amiri, M. J., Haghighi, F., Eshtehardian, E., Hematian, M., and Kordi, H. (2017b). "Optimization of time and costs in critical chain method using genetic algorithm." *Journal of Engineering and Applied Sciences*, Vol. 12, No. 4, pp. 871-876, DOI: 10.3923/jeasci.2017.871.876.

Tran, D. H. Cheng, M. Y., and Cao, M. (2015). "Solving resource-constrained project scheduling problems using hybrid artificial bee colony with differential evolution." *Journal of Computing in Civil Engineering*, Vol. 30, Issue 4, 04015065, DOI: 10.1061/(ASCE)CP.1943-5487.0000544.

Trietsch Dan (2005). "Why a Critical path by any other name would smell less sweet." *Project Management Institute*, Vol. 36, No. 1, pp. 27-36, DOI: 10.1.466.9308.

Vanhoucke, M. (2016). *Buffer management*, Integrated Project Management Sourcebook, Springer International Publishing, pp. 155-193.

Wei-Xin, W., Xu, W., Xian-Long, G., and Lei, D. (2014). "Multi-objective optimization model for multi-project scheduling on critical chain." *Advances in Engineering Software*, Vol. 68, pp. 33-39, DOI: 10.1016/j.advengsoft.2013.11.004.

Zhang, J., Song, X., and Diaz, E. (2016). "Project buffer sizing of a critical chain based on comprehensive resource tightness." *European Journal of Operational Research*, Vol. 248, Issue 1, pp. 174-182, DOI: 10.1016/j.ejor.2015.07.009.

Zheng, D. X. M. and Ng, S. T. (2005). "Stochastic time–cost optimization model incorporating fuzzy sets theory and nonreplaceable front." *Journal of Construction Engineering and Management,* Vol. 131, No. 2, pp. 176-186, DOI: 10.1061/(ASCE)0733-9364(2005)131:2(176).