Decomposition Methodology to Support Complex Decisions in Construction Application

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***Abstract*—Construction multi-project scheduling has been receiving increased attention in recent years due to its crucial role in the success of construction projects. However, most of the reported models and approaches in the literature are very difficult or impossible to implement in real construction projects. Most of the previous models and the solution approaches were constructed based on a set of assumptions to simplify the decision-making process, so they do not reflect all the dimensions of construction multi-project scheduling in real-world problems. This research aims to address one of the most complicated decision-making problems in the construction application, which is the Multi-mode Time-Cost-Quality trade-off Resource-Constrained Multi-Project Scheduling (MTCQ-RCMPS) problem, besides the adherence to the budgets and the maximum daily cost constraints. In this paper, the multi-criteria Analytical Hierarchy Process (AHP) and the Modified Genetic Algorithm (MGA) are incorporated into the (AHP-MGA) approach to obtain a near-optimal solution in a reasonable time for solving the MTCQ-RCMPS problem. Finally, the proposed AHP-MGA approach is applied to a real-life case in construction projects and benchmark problems to justify its applicability and effectiveness. The experimental results show that the proposed AHP-MGA approach is indeed able to make tremendous improvements in terms of time, cost, and quality with adherence to budgets compared to the reported results in the literature.**

***Index Terms*—Genetic Algorithm, Multi-Criteria, Construction Multi-Project Scheduling, Multi-Resource-Constrained, Time-Cost-Quality Trade-Off.**

I. Introduction

THE Multi-mode Resource-Constrained Project Scheduling (MRCPS) problem has been attracting the attention of many researchers in two fields: the decision support system and construction project management. The MRCPS is a very complicated problem because of its enormous scope in which decision-makers need to narrow-down this scope by several assumptions to find the compromise solution for a large number of constraints and conflicting objectives. Several varieties of the models and the solution approaches in the literature can be classified into four main problems as shown in Fig. 1. In the MRCPS problem, there may be only one project or multi-project, single-objective, or multi-objective. This problem is solved to improve three main objectives, which are the time, cost, and quality of the project [1], [2]. The types of resources may be renewable or non-renewable resources, or both together. The real practice of construction multi-project scheduling does not base on the mathematical models and the approaches which are grounded on the many assumptions to suggest the solutions, so scientific research in this field still needs more effort [3].

The Resource-Constrained Project Scheduling (RCPS) problem is one of the most pressing challenges in several applications, such as multimedia, production, cloud computing, and construction projects [4]- [7]. The RCPS problem is solved previously by using several types of approaches, which are the traditional, exact, heuristic, and meta-heuristic approaches. Most of the previous studies emphasize the inefficiency of the traditional and heuristic solution approaches in the context of the RCPS problems [8]. On the other hand, most researchers confirm that the meta-heuristic solution approaches that are inspired by biological evolution such as genetic algorithm (GA) and ant colony optimization (ACO) outperform all other solution approaches in this context [9]. When there is more than one mode to execute each activity, this leads to an expansion of the solution space and paves the way to find better solutions, but at the same time, the problem is becoming increasingly complex. The MRCPS problem is an NP-complete problem [10]. Also, the MRCPS problem consists of two sub-problems, which are the mode assignment problem and the project resource scheduling problem. Knowing that the Multi-mode Resource-Constrained Multi-Project Scheduling (MRCMPS) problem is a generalized case from the MRCPS problem, furthermore, the complexity rate of this problem is increasing as a result of an increased number of projects, objectives, and constraints. Hence, the decomposition methodology that bases on the idea of breaking down a complex task into simpler sub-tasks is very suitable for this problem.

In an attempt to simplify the Multi-Project Scheduling (MPS) problem, most researchers rely on the methodology of aggregating the activities of the multi-project in a single project' network to tackle the multi-project scheduling by using the Single-Project Scheduling (SPS) approach. This methodology is an easy way to find feasible solutions for MPS problems, but it has some weaknesses that prevent it from finding an optimal or a near-optimal solution in the case of multi-project scheduling [11]- [13]. Also, in another attempt to simplify the multi-project scheduling problem, several objectives are formulated as a single objective [1], [2],

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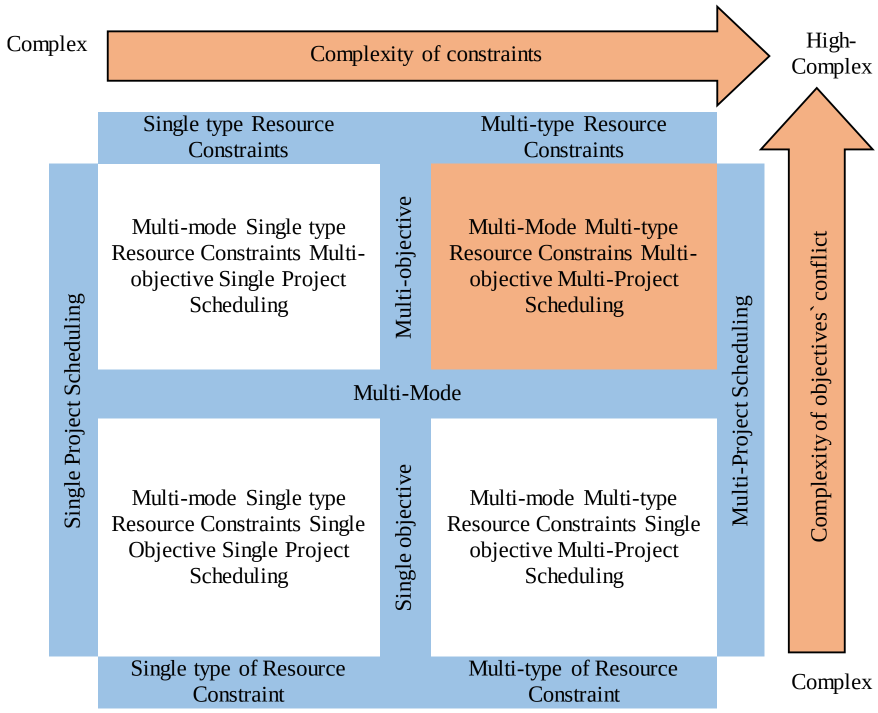

Fig. 1. Classification of multi-mode resource scheduling problem.

[14]- [17]. In most cases, only one objective function does not guarantee the achievement of all the objectives of the customers and the owners in construction companies [13]; this explains our decision to solve the MPS problem as a multi-objective problem by using the proposed AHP-MGA approach.

The time, the cost, and the quality are significant and conflicting criteria to a decision-maker in construction projects. This conflict is increased when there are several modes to execute the activities of the project. In this regard, the decision-maker may be facing difficulty to choose the best execution mode for each activity. For example, a particular execution mode may achieve the highest quality, but it is poorly in terms of the time and cost of the project. Also, another execution mode may meet the time and cost objectives, but this execution mode achieves a low quality. The decision-making of assigning the best execution mode to a particular activity is known as multi-attribute decision-making. The Analytic Hierarchy Process (AHP) that was introduced by Saaty [18] is one of the most powerful methods of Multi-Criteria Decision-Making (MCDM). MCDM processes analyze the problems that are influenced by several factors and criteria to comply with the best way the largest number of the objectives according to the requirements of the project [19]. The analytic hierarchy process has advantages and disadvantages. AHP is time-consuming with large-scale problems because the AHP bases on the pairwise comparisons. These comparisons are increasing according to the number of criteria. Also, there are more advantages for the AHP: it can deal with the problems that include different measure units, can make use of pairwise comparisons in the formulation of optimization problems according to the objectives and preferences of the decision-maker, provides a certain measure of consistency, and is simple in calculations. Because the MTCQ-RCMPS problem includes only three criteria: time, cost, and quality in addition to these criteria have different measure units, the AHP is very suitable for this problem.

The solution methodologies of the RCPSP problems have two categories: centralized and decentralized [16]. In the centralized approach, the multi-project resource scheduling is obtained by only one decision-maker for all the projects. In the centralized methodology, the decision-maker tackles the multi-project as a megaproject to simplify the problem (i.e., converting the multi-project into a single project by using dummy activities). In contrast, in the decentralized approaches, there are a set of sub-decision makers and the only main decision-maker. In most previous researches, the idea of the centralized approach is adopted due to its simplicity. This idea does not find the near-optimal solution of the total cost and the completion time for all the projects because it does not take into account the local objectives of all the projects.

In this paper, we propose three main contributions to improve the solution of the MTCQ-RCMPS problem. Firstly, we developed the decentralized methodology that was reported in [16] to include other sets of objectives and constraints in construction projects to represent more realistic purposes. Fig. 2 illustrates the framework of the proposed decentralized methodology. Secondly, we develop a novel mathematical model to solve the MTCQ-RCMPS problem. This model improves the total cost of all projects together instead of the cost of any project separately. Also, in the context of the non-renewable, the existing models handle the non-renewable resources as unlimited or limited without the reorder point during the implementation time of the construction projects. Because these two assumptions are not identical to the reality in the construction industry, we take into account the reorder points and the order quantity of the non-renewable resources in the developed model. Finally, we propose the AHP-MGA approach that is characterized by decomposing the MTCQ-RCMPS problem into two sub-problems.

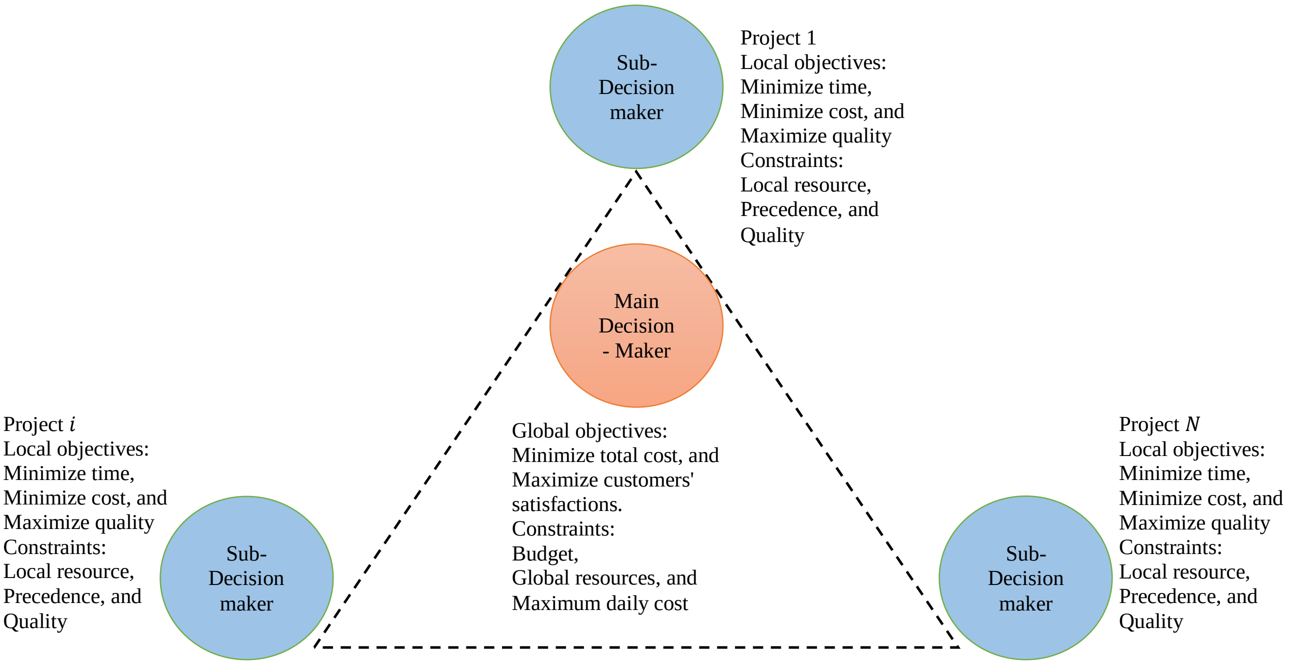

Fig. 2 Conceptual description of the proposed decentralized methodology for the MTCQ-RCMPS scheduling problem.

Each sub-problem is solved by using the appropriate approach to overcome the drawbacks of the SPS approaches in the multi-project scheduling case. Also, we develop a parallel scheduling generation scheme (PSGS) to construct a feasible solution for the RCMPS (PSGS-RCMPS) problem. The fundamental differences between the developed PSGS-RCMPS in this paper and the existing traditional PSGS that proposed in the previous study are illustrated in the section of the proposed approach.

The rest of this article is organized as follows: Section II includes a brief review of the related work. In Section III, we propose the description of the MTCQ-RCMPS problem to provide a framework for the proposed approach. The mathematical model of the MTCQ-RCMPS problem is formulated in Section IV. The proposed AHP-MGA approach is explained in Section V. Experimental results and discussion are reported in Section VI. Finally, we propose the conclusion and future work in Section VII.

II. Related Work

The resource constraints problem in both cases: the single-mode and multi-mode are two main challenges in construction project management [20]. In this section, we will tackle a review of the latest advances to solve this problem.

Peteghem et al. [21] suggested a bi-population genetic algorithm; this algorithm is amongst the most competitive algorithms for solving the resource-constrained project scheduling problem in the case of the multi-mode, as well as it deals with both types the non-preemptive and the preemptive activities. These authors applied the non-dominated sorting genetic algorithm-II (NSGA-II) to estimate the Pareto-optimal solution set in a mining plant located in the northern Brazilian territory to improve the total time and total cost of the selected execution modes [22]. In the context of project resource scheduling, AHP has been combined with GA to solve problems involving priority setting based on a set of criteria. Singh et al. [23] used AHP with GA in a single-mode case to determine the priority of projects based on a set of criteria such as the urgency, NPV, risk, and growth. Cheng et al. [24] explored the difference between preemption and activity splitting in the MRCPS problem. Also, they modified the precedence tree-based branch-and-bound algorithm to find the optimal solution for the MRCPS problem with only the minimization of make-span objective function in the single project scheduling case. Beşikci et al. [25] proposed the two-phase and monolithic genetic algorithms to minimize the weighted tardiness cost of projects for the MRCPS problem in the case of the multi-project subject to the renewable and the non-renewable resource constraints in addition to the budget constraints and the due date constraints of projects. Chen et al. [26] developed the discrete version of the artificial bee colony algorithm. In this version, the local search operators only affect the mode of execution or the order of the activities along with their execution modes. Patience et al. [27] proposed a machine learning approach to determine the best initial solutions for the metaheuristic approach for solving multi-mode resource-constrained project scheduling problems in the case of a single objective and single project. Curitiba et al. [28] proposed the Path-Relinking (PR) algorithm to solve the RCPS problem in single-mode and multi-mode cases. Also, they added a new fitness function for the individuals who are infeasible to minimize the make-span. Afshar et al. [29] used the Simulated Annealing (SA) algorithm to obtain the global solution for the preemptive multi-mode resource-constrained project scheduling problem (P-MRCPSP) to improve the make-span of the project subject to the resource-constrained and mode changeability after preemption. Kosztyán et al. [30] proposed a hybrid approach for solving the MRCPS scheduling; This approach tackles the MRCPSP to find the optimal solution according to the

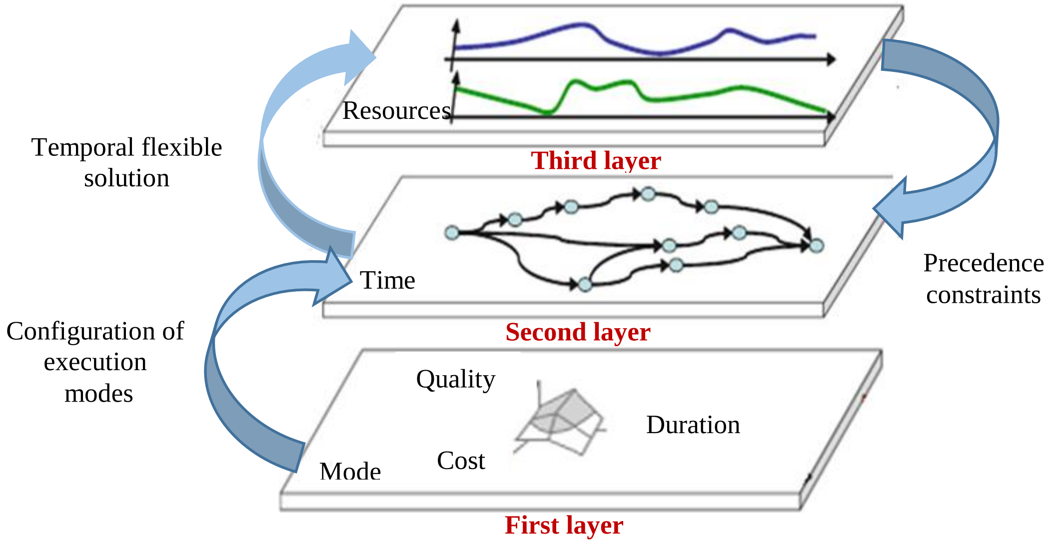

Fig. 3 Search space of the MTCQ-RCMPS scheduling problem.

predefined preferences of the time, cost, and quality. Nemati-Lafmejani et al. [31] used the AHP to determine the relative importance of performance metrics for the (NSGA-II) and multi-objective particle swarm optimization algorithm (MOPSO) that proposed to solve the multi-mode resource-constrained project scheduling and contractor selection (MRCPSP-CS). In [31], the authors showed that the proposed hybrid approach finds an adequate alternative to flexible project management. Kannimuthu et al. [2] compared the single project approach and the multi-project approach for solving the MTCQ- RCMPS problem. The results of these approaches indicate that the single-project approach is better than the multi-project approach in this context. Chakrabortty et al. [32] used the modified variable neighborhood search heuristic algorithm to minimize the completion time of the project; this algorithm was compared to the most applicable existing algorithms to solve this problem. The results of these authors showed that this algorithm is efficient, particularly with projects that include a large number of activities, but it does not take into account the cost and quality of modes besides the duration of the activities.

From the above related-works, Kannimuthu et al. [2] solved the MTCQ-RCMPS problem with the largest number of objectives and constraints. Also, they applied their approaches to real construction projects. These authors proposed two approaches to find optimal/near- optimal solutions for the MTCQ-RCMPS problem. In our research, we adopt the metaheuristic approach (MGA) and the analytic process (AHP) to find a near-optimal solution for the MTCQ-RCMPS problem. The essential differences among our approach and these approaches will be discussed in the section (VI) of the experimental results and discussion.

III. Problem Description

In the MTCQ-RCMPS problem, a set of projects are scheduled simultaneously; each project includes a set of activities; The quality, time, cost, and resources' demand of the activity are determined based on the selected mode to execute it. The MTCQ-RCMPS problem consists of two sub-problems, which are the mode assignment and RCMPS problems. The mode assignment sub-problem means a set of activities or tasks that can be executed by several alternatives of modes. Each mode has time, cost, quality, and demand from the resources to implement a particular activity. The MTCQ-RCMPS problem will become an RCMPS problem in the single-mode case after the best single-mode to execute every activity was selected. In the RCMPS problem, the feasible scheduling must adhere to the precedence constraints of activities, renewable resources, non-renewable resources constraints, the budget, due date, and quality constraints. The quality of the projects completely depends on modes assignment. On the other hand, the time and cost of the projects depend on the selected execution mode and resource scheduling together. The completion time of the project does not only depend on the activities' duration of the project but also depends on the availability of the resources that is necessary to execute these activities. Moreover, the cost of the project depends on the direct cost of the selected mode and the penalty cost as a result of the lack of resources to complete the activities. The search space of the MTCQ-RCMPS problem is illustrated in Fig 3. In this paper, the three layers search space of the MTCQ-RCMPS problem in a multi-mode case is inspired by the two layers search space of the RCPSP problem in a single-mode case that reported in precedence constraint posting schema [33]. MTCQ-RCMPS problem is a complete NP-hard problem; the search space is composed of separated three layers. The search space of the execution modes constraints is represented by the first layer; the selected mode to execute each activity affects the due date, quality, budget, penalties' costs, direct resources' cost, and indirect resources' cost. The precedence constraints and arrival date constraints are included in the second layer. All types of resource constraints are represented by the third layer. Due to the complexity of the MTCQ-RCMPS problem, the decomposition methodology and the meta-heuristic approaches are very suitable to solve it.

IV. PROBLEM FORMULATION

The MTCQ-RCMPS problem consists of a set of projects. Each project includes a set of activities. Each activity can be executed by a mode or more than executed modes. The cost, time, and quality are the criteria to generate the near-optimal solution for this problem under several sets of constraints. The mathematical model of the MTCQ-RCMPS problem is formulated as follows:

Indices and decision variables: Indices and decision variables:

i:	Project index, $i = (1, 2, \ldots, N)$
j:	Activity index of i^{th} project ($j = 1, 2, \ldots, n_i$)
T_i:	Completion time of i^{th} project
N:	Number of projects
n_i:	Number of j^{th} activity of i^{th} project
ft_{ij}^m:	Finish time of j^{th} activity of i^{th} project by assignment m^{th} mode
AD_i:	Arrival date of i^{th} project
Q_i:	Quality of i^{th} project
α_i:	Relative importance between the minimum and average quality of i^{th} project
$Q_{i,min}$:	Minimum quality of i^{th} project among the assignment activity modes
$Q_{i,avg}$:	Average quality of i^{th} project among the assignment activity modes
TC:	Total cost of all the projects
C_{i1}:	Direct and indirect costs of i^{th} project is calculated by Eq. (20)
C_{i2}:	Total cost of violated constraints of i^{th} project is calculated by Eq. (21)
D_i:	Due date of i^{th} project
C_i^{UB}:	Budget (Upper pound of cost) of i^{th} project
st_{ij}^m:	Start time of j^{th} activity of i^{th} project by assignment m^{th} mode
st_{ik}^m:	Start time of k^{th} activity of i^{th} project by assignment m^{th} mode
M_{ik}	A set of preceding activities before k^{th} activity of i^{th} project
t:	Represents a time period (a time period t is define as the time interval $[t-1, t[\ \forall(t = 1,2, \ldots T)$ where T denotes $Max_{i=1}^{N}\{T_i\}$
R:	Number types of g^{th} global renewable resources
$\mathcal{R}$:	Number types of $\mathcal{g}^{th}$ global non-renewable
g:	Index pointers to type of renewable global resources, $g = (1, 2, \ldots, R)$
$\mathcal{g}$:	Index pointers to type of global non-renewable resources, $\mathcal{g} = (1, 2, \ldots, \mathcal{R})$
R_g:	Quantity of g^{th} global renewable resources over time periods of projects
$\mathcal{V}_{\mathcal{g}}$:	Number of inventory' cycles for $\mathcal{g}^{th}$ global non-renewable resource
$\mathcal{C}_{\mathcal{g}}$:	Index pointer of inventory' cycles for $\mathcal{g}^{th}$ global non-renewable resource ($\mathcal{C}_{\mathcal{g}} = 1,2, \ldots, \mathcal{V}_{\mathcal{g}}$)
$\mathcal{R}_{\mathcal{g}}^{\mathcal{C}_{\mathcal{g}}}$:	Quantity of $\mathcal{g}^{th}$ global non-renewable resources over time of ${\mathcal{C}_{\mathcal{g}}}^{th}$ inventory cycle, ($\mathcal{C}_{\mathcal{g}} = 1,2, \ldots, \mathcal{V}_{\mathcal{g}}$)
r_i:	Number of types of l^{th} local renewable resources of i^{th} project.
$\mathcal{r}_i$:	Number of types of ℓ^{th} local non-renewable resources of i^{th} project
l:	Index pointers to types of local renewable resources, $l = (1, 2, \ldots, r_i), i \in N$
ℓ:	Index pointers to types of local non-renewable resources, $\ell = (1, 2, \ldots, \mathcal{r}_i), i \in N$
r_{i_l}:	Quantity of l^{th} local renewable resource of i^{th} project
$\mathcal{r}_{i_\ell}^{c_\ell}$:	Quantity of ℓ^{th} local non-renewable resource of i^{th} project at ${c_\ell}^{th}$ inventory cycle
$qA_{ijR_g}^m$:	Demand from global renewable resource type g to start work in j^{th} activity of i^{th} project by m^{th} mode
$\mathcal{q}A_{ij\mathcal{R}_{\mathcal{g}}}^m$:	Demand from global non-renewable resource type $\mathcal{g}$ to start work in j^{th} activity of i^{th} project by m^{th} mode
$qA_{ijr_{i_l}}^m$:	Demand from l^{th} local renewable resource type for j^{th} activity of i^{th} project by m^{th} mode
Mdc:	The maximum daily cost of resource utilization
$\mathcal{q}A_{ij\mathcal{r}_{i_\ell}}^m$:	Demand from ℓ^{th} local non-renewable resource type for j^{th} activity of i^{th} project by m^{th} mode
$\mathcal{v}_\ell$:	Number of inventory's cycles for ℓ^{th} local non-renewable resource
c_ℓ:	Index pointer of inventory' cycles for ℓ^{th} local non-renewable resource ($c_\ell = 1,2, \ldots, \mathcal{v}_\ell$)
$\mathcal{g}_{\mathcal{S}}$:	Start time of inventory' cycle for $\mathcal{g}^{th}$ global non-renewable resource
$\mathcal{g}_{\mathcal{F}}$:	End time of inventory' cycle for $\mathcal{g}^{th}$ global non-renewable resource
$\mathcal{t}$:	Index pointer of time inventory' cycle
$i\ell_{\mathcal{s}}$:	Start time of inventory' cycle for ℓ^{th} local non-renewable resource of i^{th} project
$i\ell_{\mathcal{F}}$:	End time of inventory' cycle for ℓ^{th} local non-renewable resource of i^{th} project
d_{ij}^m:	Duration of j^{th} activity of i^{th} project by assignment m^{th} mode
dc_{ij}^m:	Direct cost of j^{th} activity of the i^{th} project by assignment m^{th} mode
IC_i:	Indirect cost of i^{th} project per period (e.g. Depreciation cost)
PT_i:	Penalty cost of late i^{th} project per period
BT_i:	Bonus for an early completion time of i^{th} project
PQ_i:	Penalty cost of quality violation of i^{th} project
BQ_i:	Bonus of quality of i^{th} project

$$x_{ij}^{t} = \begin{cases} 1, & \text{if } j^{th} \text{ activity of } i^{th} \text{ project in an execution phase at time period } t \\ 0, & \text{Otherwise} \end{cases} \quad (1)$$

$$x_{ij}^{t} = \begin{cases} 1, & if\ j^{th}\ activity\ of\ project\ i^{th}\ project\ in\ an\ execution\ phase\ at\ time\ period\ t\ of\ specific\ inventory\ cycle \\ 0, & Otherwise \end{cases} \quad (2)$$

$$A_{ij}^{m} = \begin{cases} 1, & if\ j^{th}\ activity\ of\ i^{th}\ project\ is\ executed\ by\ m^{th}\ mode \\ 0, & Otherwise \end{cases} \quad (3)$$

Objective functions:

$$Minimize\ T_i = max_{j=1}^{n_i}\{ft_{ij}^{m}\} - AD_i \quad, \forall\ (i \in N) \quad (4)$$

$$\text{Maximize } Q_i = \propto_i Q_{i,min} + (1 - \propto_i) Q_{i,avg}, \forall\ (i \in N) \quad (5)$$

$$Minimize\ TC = \sum_{i=1}^{N}(C_{i1} + C_{i2}) \quad (6)$$

Subject to:

$$T_i \le D_i \quad (7)$$

$$TC \le \sum_{i=1}^{N} C_i^{UB} \quad (8)$$

$$st_{ij}^{m} \le st_{ik}^{m} - d_{ij}^{m}, \forall i \in N;\ \forall\ j \in M_{ik} \quad (9)$$

$$\sum_{j=1}^{n_i} x_{ij}^{t} q A_{ijr_{i_l}}^{m} \le r_{i_l}, \forall (l \in r_i), \forall (i \in N), \forall (t \in T) \quad (10)$$

$$\sum_{i=1}^{N}\sum_{j=1}^{n_i} x_{ij}^{t} q A_{ijR_g}^{m} \le R_g, \forall (g \in R), \forall (t \in T) \quad (11)$$

$$\sum_{t=i\ell_s}^{i\ell_{\mathcal{F}}}\sum_{j=1}^{n_i} x_{ij}^{t} q A_{ijr_\ell}^{m} \le r_{i_\ell}^{c_\ell}, \forall\ (\ell \in r_i), \forall\ (i \in N), \forall\ (c_\ell \in v_\ell) \quad (12)$$

$$\sum_{t=g_s}^{g_{\mathcal{F}}}\sum_{i=1}^{N}\sum_{j=1}^{n_i} x_{ij}^{t} q A_{ij\mathcal{R}_g}^{m} \le \mathcal{R}_g^{c_g}, \forall\ (g \in \mathcal{R}), \forall\ (i \in N), \forall\ \mathcal{C}_g \in \mathcal{V}_g) \quad (13)$$

$$st_{ij}^{m} \ge AD_i, \forall (j \in n_i), \forall (i \in N) \quad (14)$$

$$\sum_{i=1}^{N}\sum_{j=1}^{n_i}\left(\frac{dc_{ij}^{m}}{d_{ij}^{m}}\right) A_{ij}^{m}\left(x_{ij}^{t}\right) \le Mdc \quad (15)$$

$$\sum_{m=1}^{M} A_{ij}^{m} = 1 \quad (16)$$

$$A_{ij}^{m} \in \{0,1\}, \forall (i \in N, j \in n_i, m \in M) \quad (17)$$

$$d_{ij}^{m} \ge 0, \forall (i \in N, j \in n_i, m \in M) \quad (18)$$

$$t \in [0, T] \quad (19)$$

The above model includes a set of objective functions to minimize the completion time and maximize the quality for the i^{th} project. They are represented by Eq. (4) and Eq. (5), respectively. Only a single objective function to minimize the total cost of all the projects together is formulated in Eq. (6) where C_{i1} *and* C_{i2} are defined by Eq. (20) and Eq. (21) as follows:

$$C_{i1} = \sum_{j=1}^{n_i}\sum_{m=1}^{M}(A_{ij}^{m}\ dc_{ij}^{m}) + (IC_i * T_i) \quad (20)$$

$$C_{i2} = \left(Y_i\left(PT_i(T_i - D_i)\right)\right) + \left(y_i\left(BT_i(D_i - T_i)\right)\right) + (Z_i(PQ_i(Q_i^{LB} - Q_i))) + (z_i(BQ_i(Q_i - Q_i^{LB}))) \quad (21)$$

where

$$Y_i = \begin{cases} 1, & if\ T_i > D_i \\ 0, & Otherwise \end{cases} \quad (22)$$

$$y_i = \begin{cases} -1, & if\ D_i > T_i \\ 0, & Otherwise \end{cases} \quad (23)$$

$$Z_i = \begin{cases} 1, & if\ Q_i^{LB} > Q_i \\ 0, & Otherwise \end{cases} \quad (24)$$

$$z_i = \begin{cases} -1, & if\ Q_i > Q_i^{LB} \\ 0, & Otherwise \end{cases} \quad (25)$$

The MTCQ-RCMPS problem is restricted by a set of constraints. Eq. (7) represents the due date constraints for every i^{th} project. The budget's constraint is formulated in Eq. (8). Eq. (9) shows the precedence constraints for every project. The local and global renewable resource constraints are presented by Eq. (10) and Eq. (11), respectively. Eq. (12) and Eq. (13) indicate the local and global non-renewable resource. The arrival date constraints of projects are present in Eq. (14). The daily cost constraint is formulated in Eq. (15). Eq. (16) and Eq. (17) guarantee that every j^{th} activity of i^{th} project is executed by only one mode. Eq. (18) indicates the non-negative constraints for any duration of activity by any execution mode. The time step is specified by Eq. (19).

V. Proposed Approach

MTCQ-RCMPS problem includes two complicated sub-problems. The first sub-problem is to make the appropriate decisions for assigning the best execution mode for each activity. The second sub-problem is to make the appropriate decisions to find the best start time for each activity based on the available resources, maximum daily cost, and budget. The two approaches AHP and MGA are integrated to solve this problem. The general steps of the proposed AHP-MGA approach are explained as follows:

- Step 1 Identify the feasible execution modes that satisfy the constraints of the daily renewable resources and the maximum daily cost from the first layer of the search space.
- Step 2 Determine the best configuration of execution modes from the list of feasible modes by using the AHP based on a scheme of pairwise comparisons; the mode with higher priority for each activity is selected as the best execution mode for this activity.
- Step 3 Identify a set of non-dominated project resource scheduling for the best-selected execution modes from the feasible resources scheduling of layer 2 and layer 3 of the search space together by using the MGA approach.
- Step 4 Select the compromise solution according to the preference of the decision-maker from the non-dominated solutions.
- Step 5 If the compromise solution does not satisfy the budget constraint: this means the preferences of criteria are conflicted with the budget constraint (infeasible solution); do (update the preference of the criteria by the decision-maker and go to step 1) or (update the budget value).

The details of pseudo-code of constructing the feasible execution modes in the first step is shown as follows:

Construct the feasible execution modes

Begin
1: Feasible-modes {} ← ∅ *// begin with empty feasible modes*
2: For i ← 1 to(N) do *// projects*
3: For j ← 1 to (n_i) do *// activities of the project*
4: For m ← 1 to (M_{ij}) do *// available modes of activity*
5: If $\left(\frac{dc_{ij}^m}{d_{ij}^m}\right) > Mdc$ then $m \leftarrow m+1$ *//check daily cost*
6:: Break *// ignore infeasible mode*
7: Else
8: If ($qA_{ijr_{i_l}}^m \le r_{i_l}$ $\forall l \in r_i$) is not satisfied then
$m \leftarrow m+1$ *// check daily local renewable resources*
9: Break *// ignore infeasible mode*
10: Else
11: If $(qA_{ijR_g}^m \le R_g$ $\forall g \in R)$ is not satisfied then
$m \leftarrow m+1$ *// check daily global renewable resources*
12: Break *// ignore infeasible mode*
13: Else
14: Feasible-modes {} ← A_{ij}^m *//add to the feasible mode*
15: End
16: Return Feasible-modes{}
End

In the second step, the decision-maker chooses among the alternatives of the execution modes of the activity based on how well they meet various objectives in terms of time, cost, and quality. The structure of the modes selection problem (MTCQ problem) in terms of the project, activities, alternatives of execution modes, and criteria is illustrated in Fig 4. For example, when assigning an execution mode to implement a particular activity, a decision-maker might choose among the offered modes by determining how well each one meets three objectives. The 1st objective is the direct cost of a mode, the 2nd objective is the quality of the resources by used this mode, and the 3rd objective is the duration of activity by used this mode.

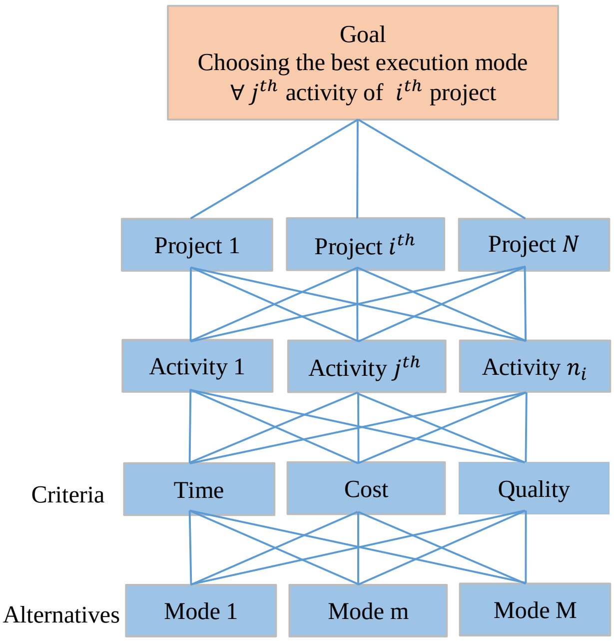

Fig. 4 Structure of the MTCQ problem.

The algorithm of the AHP to assign the best execution mode for each activity is shown as follows:

Alg. of AHP to solve the MTCQ problem

Inputs:
$\mathrm{N}, \mathrm{n_i}$, information of modes $\forall$ (i ∈ N), $\forall$ (j ∈ $\mathrm{n_i}$)
Outputs: best $\mathrm{A_{ij}^m}$ $\forall$ (i ∈ N), $\forall$ (j ∈ $\mathrm{n_i}$)
Begin
0: While $(i \le \mathrm{N})$ do
1: While $(j \le n_i)$ do
2: Construct the pairwise comparison matrix to establish the priorities for the three criteria (time, cost, and quality) based on the preference of the decision-maker.
3: Normalize each column in the pairwise comparison matrix.
4: Calculate the averages of the elements for each row in the normalized pairwise comparison matrix; these averages represent the priorities of the time, cost, and quality criteria.
5: Check the consistency of the above pairwise comparison matrix if the degree of consistency is unacceptable then change the preference of criteria by the decision-maker and go to step 3.
6: $w_t, w_c, w_q \leftarrow$ the priority of time, cost, and quality criterion, respectively.
7: Construct the three pairwise comparisons for the decision alternatives of execution modes of j^{th} activity of i^{th} project; the pairwise comparisons of these alternatives are expressed by the available information of the execution modes; this information is previously estimated by the experts /judges in the construction projects during the estimation phase of the project scheduling management.
8: Apply step 3 and step 4 on the three pairwise comparison matrices which are constructed in step 6 to establish the priorities for all alternatives of m^{th} execution modes of j^{th} activity of i^{th} project.
9: For $m \leftarrow 1$ to (number of execution modes of j^{th}activity of i^{th} project) do:
   a. $r_{ij}^{m_t} \leftarrow$ the priority value of time of alternative m^{th} mode of j^{th} activity of i^{th} project
   b. $r_{ij}^{m_c} \leftarrow$ the priority value of the cost of the alternative m^{th} mode of j^{th} activity of i^{th} project.
   c. $r_{ij}^{m_q} \leftarrow$ the priority value of the quality of the alternative m^{th} mode of j^{th} activity of i^{th} project.
   d. $A_{ij}^m\ overall\ priority = W_t(\ r_{ij}^{m_t}) + W_c(\ r_{ij}^{m_c}) + W_q\left(r_{ij}^{m_q}\right)$
   e. $if\ A_{ij}^m$ has a $\underset{m \in M_{ij}}{Max}\{A_{ij}^m\ overall\ priority\}$ then $best\ A_{ij}^m \leftarrow A_{ij}^m$
End

To illustrate how the execution mode is assigned to a particular activity by the AHP approach, let's suppose that a particular activity has three execution modes as illustrated in Table 1. We use the objectives' priority (weights) W_b and the priority of each mode on each b^{th} objective, $b = 1,2,3$ (i.e.

time, cost, and quality) to determine the best execution mode for a particular activity A_{ij}. We compute mode offer $A_{ij}^{m`s}$ overall priority by Eq. (26).

$$\sum_{b=1}^{3} W_b \text{ (mode offer } A_{ij}^{m`s} \text{ priority on } b^{th} \text{ objective)} \quad (26)$$

The objectives' weights W_b are explicitly or implicitly defined in the problem. The objectives' weights (priority of criteria) W_b are determined by the preference of the decision-makers based on the pairwise comparison matrix; for convenience, always by Eq. (27).

$$\sum_{b=1}^{3} W_b = 1 \quad (27)$$

When the preferences of a decision-maker are equal (i.e. we search on the compromise solution among the time, cost, and quality) in this case $W_b = \left(\frac{1}{3}, \frac{1}{3}, \frac{1}{3}\right)$. When the preference of the decision-maker only the time or cost or quality in such cases the weights of the objectives are defined as $W_b = (1, 0, 0)\ or\ (0, 1, 0), or\ (0, 0,1)$, respectively. In table I, there is no mode which has the best offers for the three objectives (e.g., the first mode best meets the cost objective, but it is worst on the time and the quality objectives), so we determine the scores of each mode on all the objectives based on the offers of all the alternative modes for the particular activity. To determine the best mode for each activity, we apply the steps of pseudo- code of the MTCQ based on AHP. The priority of each mode on all the objectives is illustrated in Table II. The overall score gives more weight to a mode offer's priority on the more important objectives. The priorities for each mode using time, cost, and quality criteria are illustrated in Table III, Table IV, and Table V, respectively. The overall priority for each mode is illustrated in Table VI.

TABLE I
SEVERAL MODES OF A PARTICULAR ACTIVITY

Alternatives	Criteria		
	Time	Cost	Quality
Mode 1	6	2	%70
Mode 2	2	7	%75
Mode 3	4	5	%80

TABLE II
THE CRITERIA PAIRWISE COMPARISON MATRIX

	Time	Cost	Quality	Priority
Time	1	1	1	1/3
Cost	1	1	1	1/3
Quality	1	1	1	1/3

TABLE III
PRIORITIES FOR EACH MODE USING TIME CRITERION

	Mode 1	Mode 2	Mode 3	Priority
Mode 1	6/6	2/6	4/6	0.1818
Mode 2	6/2	2/2	4/2	0.5454
Mode 3	6/4	2/4	4/4	0.2727

TABLE IV
PRIORITIES FOR EACH MODE USING COST CRITERION

	Mode 1	Mode 2	Mode 3	Priority
Mode 1	2/2	7/2	5/2	0.5932
Mode 2	2/7	7/7	5/7	0.1694
Mode 3	2/5	7/5	5/5	0.2372

TABLE V
PRIORITIES FOR EACH MODE USING QUALITY CRITERION

	Mode 1	Mode 2	Mode 3	Priority
Mode 1	0.70/0.70	0.70/0.75	0.70/0.80	0.3111
Mode 2	0.75/0.70	0.75/0.75	0.75/0.80	0.3333
Mode 3	0.80/0.70	0.80/0.75	0.80/0.80	0.3555

TABLE VI
PRIORITIES FOR EACH MODE USING EACH CRITERION

Alternatives	Criteria			Overall Priority
	Time 1/3	Cost 1/3	Quality 1/3	
Mode 1	0.1818	0.5932	0.3111	0.3620.
Mode 2	0.5454	0.1694	0.3333	0.3494
Mode 3	0.2727	0.2372	0.3555	0.2885

In the case of $W_b = \left(\frac{1}{3}, \frac{1}{3}, \frac{1}{3}\right)$, each mode's overall priority is computed as follows:
Mode 1 overall priority =0.1818(1/3) + 0.5932(1/3) + 0.3111 (1/3) =0.3620.
Mode 2 overall priority = 0.5454 (1/3) + 0.1694 (1/3) + 0.3333 (1/3) = 0.3494.
Mode 3 overall priority = 0.2727(1/3) + 0.2372(1/3) + 0.3555 (1/3) = 0.2885.
Finally, we choose the best execution mode (mode 1) that has the highest overall priority to execute the activity.

In the third step, we develop a parallel scheduling generation scheme for solving the resource-constrained multi-project scheduling (PSGS-RCMPS) problem. The PSGS-RCMPS and the MGA approach are integrated to identify the best solution to the RCMPS problem. PSGS-RCMPS determines how a feasible schedule is constructed by assigning start times to the projects' activities. Also, it iterates over the time horizon of the projects the scheme starts at a time point $t = 0$ and schedules all the possible activities before the time pointer is increased. At each decision point t, the eligible activities are selected based on the availability of the renewable and non-renewable resources and maximum daily cost, then the scheduling sequence of these eligible activities is assigned according to the priority list. The priority list is generated by MGA (i.e. each chromosome represents a priority list). At each decision point, the eligible activities are scheduled with a starting time equal to the decision point. The activities that cannot be scheduled due to the resources' conflicts are skipped and become eligible at the next decision point $\acute{t} > t$, which equals the earliest completion time of all activities active at the current decision point t or the closest reorder point t to meet a lack of some non-renewable resources. Table VII shows the fundamental differences between the existing traditional PSGS in the previous study and the developed PSGS-RCMPS in this work.

TABLE VII
FUNDAMENTAL DIFFERENCES BETWEEN THE
TRADITIONAL PSGS AND THE DEVELOPED PSGS-RCMPS.

	Traditional PSGS	PSGS-RCMPS
Non-renewable resources	Unlimited or limited at the total time of projects.	Limited at a set of interval times of projects
The eligible activities at each decision point t	Based on the non-contradiction of the renewable resources and its priority	Based on the non-contradiction of the renewable and non-renewable resources, maximum daily cost, and its priority
The next decision point $\acute{t}$	Equals the earliest finish time of all activities active at the current decision point t	Equals the earliest finish time of all activities active at the current decision point t or the closest reorder points to meet a lack of some non-renewable resources.

In the PSGS-RCMPS, the set E_t of the eligible activities at each decision point t is constructed by Eq. 28.
Where the eligible activities set E_t at each decision point t contains all unscheduled activities of all projects which are valid to all precedence constraints. the precedence set PA_{ij} includes all activities after j^{th} activity in i^{th} project. C_t includes a set of the activities that were completed at the decision point t. Also, all local and global constraints of renewable and non-renewable resources of A_{ij} are valid as well as the daily cost of A_{ij} is valid. The set of completed activities C_t and the set of the active activities A_t at each decision point t are updated by Eq. (29) and Eq. (30) as follows.

$$E_t = \Big\{A_{ij} \in n_i \backslash (C_t \cup A_t) \Big| (PA_{ij} \subseteq C_t) \wedge (t \geq AD_i) \wedge ((qA^m_{ijr_{i_l}} \leq \overline{r_{i_lt}})\forall l \in r_i) \wedge ((qA^m_{ij\mathscr{r}_\ell} \leq \overline{\mathscr{r}_{i_\ell t}})\forall (\ell \in \mathscr{r}_i) \wedge ((qA^m_{ijR_g} \leq \overline{R_{gt}})\forall g \in R) \wedge ((qA^m_{ij\mathcal{R}_{\mathscr{g}}} \leq \overline{\mathcal{R}_{\mathscr{g}t}})\forall \mathscr{g} \in \mathcal{R}) \wedge \left(\left(\frac{dc^m_{ij}}{d^m_{ij}}\right) \leq \overline{Mdc}\right) \Big\}, \forall (i \in N), \forall (j \in n_i) \quad (28)$$

$$C_t = \{A_{ij} \in n_i \mid ft^m_{ij} \leq t\}, \forall (i \in N), \forall (j \in n_i) \quad (29)$$

$$A_t = \{A_{ij} \in n_i \mid st^m_{ij} \leq t < ft^m_{ij}\}, \forall (i \in N), \forall (j \in n_i) \quad (30)$$

The available quantities of the local renewable $\overline{r_{i_lt}}$ and non-renewable $\mathscr{r}_{i_\ell t}$ resources at each decision point t are calculated by Eq. (31) and Eq. (32).

$$\overline{r_{i_lt}} = \{r_{i_l} - \textstyle\sum_{A_{ij} \in A_t} qA^m_{ijr_{i_l}}\}, \forall (l \in r_i) \quad (31)$$

$$\overline{\mathscr{r}_{i_\ell t}} = \{\mathscr{r}^{c_\ell}_{i_\ell} - \textstyle\sum_{A_{ij} \in A_{c_\ell}} qA^m_{ijr_{i_l}} \mid (i\ell_s \geq t < i\ell_{\mathcal{F}})\}, \forall (\ell \in \mathscr{r}_i) \quad (32)$$

Where A_{c_ℓ} represents the list of active activities at $c_\ell{}^{th}$ inventory cycle of ℓ^{th} local non-renewable resource of i^{th} project; A_{c_ℓ} is constructed by Eq. (33).

$$A_{c_\ell} = \{A_{ij} \in n_i \mid ((st^m_{ij} \geq i\ell_s) \wedge (ft^m_{ij} < i\ell_{\mathcal{F}}))\}, \forall (i \in N), \forall (j \in n_i), \forall (\ell \in \mathscr{r}_i) \quad (33)$$

The available quantities of the global renewable R_{gt} and non-renewable $\mathcal{R}_{\mathscr{g}t}$ resources at each decision point t are identified by Eq. (34) and Eq. (35).

$$\overline{R_{gt}} = \left\{ R_g - \textstyle\sum_{i=1}^{N} \sum_{A_{ij} \in A_t} qA^m_{ijR_g} \right\}, \forall (g \in R) \quad (34)$$

$$\overline{\mathcal{R}_{\mathscr{g}t}} = \{\mathcal{R}^{\mathcal{C}_{\mathscr{g}}}_{\mathscr{g}} - \textstyle\sum_{i=1}^{N} \sum_{A_{ij} \in A_{\mathcal{C}_{\mathscr{g}}}} qA^m_{ij\mathcal{R}_{\mathscr{g}}} \mid (\mathscr{g}_s \geq t < \mathscr{g}_{\mathcal{F}})\}, \forall (\mathscr{g} \in \mathcal{R}) \quad (35)$$

The set of the active activities at the time of $\mathcal{C}_{\mathscr{g}}{}^{th}$ inventory cycle of $\mathscr{g}^{th}$ global non-renewable resources is constructed by Eq. (36).

$$A_{\mathcal{C}_{\mathscr{g}}} = \{A_{ij} \in n_i \mid ((st^m_{ij} \geq \mathscr{g}_S) \wedge (ft^m_{ij} < \mathscr{g}_{\mathcal{F}}))\}, \forall (i \in N), \forall (j \in n_i), \forall (\mathscr{g} \in \mathcal{R}) \quad (36)$$

The remaining money to reach the maximum daily cost $\overline{Mdc}$ is calculated by Eq. (37).

$$\overline{Mdc} = Mdc - \textstyle\sum_{A_{ij} \in A_t} \left(\frac{dc^m_{ij}}{d^m_{ij}}\right) A^m_{ij}(x^t_{ij}) \quad (37)$$

In the PSGS-RCMPS, the next decision point $\acute{t}$ is updated by Eq. (38) as follows:

$$\acute{t} = Min\,\{ \min_{ft^m_{ij}\forall(A_{ij} \in A_t)}\{ft^m_{ij}\}, \min_{\forall(\mathscr{g} \in \mathcal{R})}\{rp_{\mathscr{g}}\}, \min_{\forall(\ell \in \mathscr{r}_i)}\{rp_{i_\ell}\}\} \quad (38)$$

Where $rp_{\mathscr{g}}$ is the reorder point of the $\mathscr{g}^{th}$ global non-renewable resources, $qr_{\mathscr{g}}$ is the quantity of an order of the $\mathscr{g}^{th}$ global non-renewable resources, rp_{i_ℓ} represents the reorder point of the ℓ^{th} local non-renewable resource of i^{th} project, and qr_{i_ℓ} represents the quantity of an order of the ℓ^{th} local non-renewable resource of i^{th} project.

The developed PSGS-RCMPS is applied to construct a feasible solution for each chromosome in the MGA approach, the chromosomes of this approach are represented as depicted in Fig. 5. The pseudo-code of the developed PSGS-RCMPS to construct the feasible scheduling of RCMPS problem is illustrated as follows:

Pseudo-code of PSGS-RCMPS

Inputs: Chromosome {}
Outputs: Feasible resource scheduling for the best configuration of execution modes
1: decision point $t \leftarrow 0$
2: construct the eligible activities {} of all projects at the current decision point t by Eq. (28)
3: If the eligible activities {} is empty then update the decision point by Eq. (38) and go to step 2
4: $A_{ij} \leftarrow$ activity from the eligible activities {} with higher priority for resources in the chromosome {}
5: $st^m_{ij} \leftarrow$ decision point t *//assign start time*
6: $ft^m_{ij} \leftarrow st^m_{ij} + d^m_{ij}$ *//assign finish time*
7: *while* $(|A_t \cup C_t| \leq \sum_{i=1}^{N} n_i)$ go to step 2
// stopping criteria all activities of all projects are scheduled
8: Return best st^m_{ij}, $\forall(i \in N), \forall(j \in n_i)$)

	Project1			Project i			Project N		
Activity	A_{11}	A_{1j}	A_{1n_1}	A_{i1}	A_{ij}	A_{in_i}	A_{N1}	A_{Nj}	A_{Nn_N}
Mode	best A^m_{11}	best A^m_{1j}	best $A^m_{1n_i}$	best A^m_{i1}	best A^m_{ij}	best $A^m_{in_i}$	best A^m_{N1}	best A^m_{Nj}	best $A^m_{Nn_N}$
Priority	1	3	8	5	7	9	6	4	2
	Sub-chromosome 1			Sub-chromosome i			Sub-chromosome N		

Chromosome

Fig. 5 Representation of chromosome

Each chromosome consists of a set of genes. Each gene in the chromosome presents the priority to execute a particular activity in a particular project. The crossover and mutation operators of MGA are illustrated in Fig. 6 and 7. In the MGA, the OBX crossover is applied with probability (0.95) to generate a large number of solutions in a reasonable amount of time as it has an incredible ability to generate a large number of children for any pair of parents. For example, if there is a problem that includes five activities, the search space of this problem is represented by 125 chromosomes. The number of children for each pair of generated parents by OBX crossover equals $2^5 = 32$ chromosomes.

Parent 1

A_{11}	A_{1j}	A_{1n_1}	A_{i1}	A_{ij}	A_{in_i}	A_{N1}	A_{Nj}	A_{Nn_N}
best A_{11}^m	best A_{1j}^m	best $A_{1n_1}^m$	best A_{i1}^m	best A_{ij}^m	best $A_{in_i}^m$	best A_{N1}^m	best A_{Nj}^m	best $A_{Nn_N}^m$
1	2	3	4	5	6	7	8	9

Parent 2

A_{11}	A_{1j}	A_{1n_1}	A_{i1}	A_{ij}	A_{in_i}	A_{N1}	A_{Nj}	A_{Nn_N}
best A_{11}^m	best A_{1j}^m	best $A_{1n_1}^m$	best A_{i1}^m	best A_{ij}^m	best $A_{in_i}^m$	best A_{N1}^m	best A_{Nj}^m	best $A_{Nn_N}^m$
7	5	8	4	2	9	3	1	6

Binary Crossover (Mask)

A_{11}	A_{1j}	A_{1n_1}	A_{i1}	A_{ij}	A_{in_i}	A_{N1}	A_{Nj}	A_{Nn_N}
best A_{11}^m	best A_{1j}^m	best $A_{1n_1}^m$	best A_{i1}^m	best A_{ij}^m	best $A_{in_i}^m$	best A_{N1}^m	best A_{Nj}^m	best $A_{Nn_N}^m$
0	1	0	1	1	0	0	0	0

Offspring 1

A_{11}	A_{1j}	A_{1n_1}	A_{i1}	A_{ij}	A_{in_i}	A_{N1}	A_{Nj}	A_{Nn_N}
best A_{11}^m	best A_{1j}^m	best $A_{1n_1}^m$	best A_{i1}^m	best A_{ij}^m	best $A_{in_i}^m$	best A_{N1}^m	best A_{Nj}^m	best $A_{Nn_N}^m$
7	2	8	4	5	9	3	1	6

Offspring 2

A_{11}	A_{1j}	A_{1n_1}	A_{i1}	A_{ij}	A_{in_i}	A_{N1}	A_{Nj}	A_{Nn_N}
best A_{11}^m	best A_{1j}^m	best $A_{1n_1}^m$	best A_{i1}^m	best A_{ij}^m	best $A_{in_i}^m$	best A_{N1}^m	best A_{Nj}^m	best $A_{Nn_N}^m$
1	5	3	4	2	6	7	8	9

Fig. 6 OBX crossover of MGA

After applying the crossover operator, the mutation Swapping Mutation is applied to the offspring with probability (0.3) as follows:

Before mutation

A_{11}	A_{1j}	A_{1n_1}	A_{i1}	A_{ij}	A_{in_i}	A_{N1}	A_{Nj}	A_{Nn_N}
best A_{11}^m	best A_{1j}^m	best $A_{1n_1}^m$	best A_{i1}^m	best A_{ij}^m	best $A_{in_i}^m$	best A_{N1}^m	best A_{Nj}^m	best $A_{Nn_N}^m$
7	2	8	4	5	9	3	1	6

After mutation

A_{11}	A_{1j}	A_{1n_1}	A_{i1}	A_{ij}	A_{in_i}	A_{N1}	A_{Nj}	A_{Nn_N}
best A_{11}^m	best A_{1j}^m	best $A_{1n_1}^m$	best A_{i1}^m	best A_{ij}^m	best $A_{in_i}^m$	best A_{N1}^m	best A_{Nj}^m	best $A_{Nn_N}^m$
7	2	8	3	5	9	4	1	6

Fig. 7 Swapping Mutation of MGA

Pseudo-code of the MGA approach to identify the best solution for the RCMPS problem is interpreted as follows:

Pseudo-code of MGA

1: Randomly generate the chromosomes of the initial population
2: Construct feasible scheduling for each chromosome by using the developed PSGS-RCMPS
3: Evaluate each chromosome according to a set of objectives: by using Eq. (4), Eq. (5), and Eq. (6)
4: Find the chromosomes which represent the non-dominated solution
5: if the termination criterion (max-iteration) is met, then go to step 9
6: Rank the individual based on the strength value which represents the number of solutions that dominated by the individual (fitness function).
7: Apply the genetic operators (roulette wheel selection, OBX crossover, and swapping mutation) to generate a new offspring
8: Go to step 2
9: Return the non-dominated solutions

Finally, the compromise solution is selected according to the preference of the decision-maker from the non-dominated solutions according to Eq. (39).

$$Minimize\ z = (TC/\sum_{i=1}^{N} C_i^{UB})(w_C) + \sum_{i=1}^{N}((T_i/D_i(w_{T_i})) - (Q_i/Q_i^{UB}(w_{Q_i}))) \quad (39)$$

The two main goals for each construction company are the benefit of the owners and the benefit of the customers. the benefit of the owners is represented by minimizing the total cost of all projects and the benefit of each customer is represented by minimizing the time and maximizing the quality of its project, so we assign the weights of objectives in Eq. (39) as follows:

$(w_C, w_{T_i}, w_{Q_i}) = \left(\left(\frac{1}{N}\right), \left(\frac{1-\left(\frac{1}{N}\right)}{N*2}\right), \left(\frac{1-\left(\frac{1}{N}\right)}{N*2}\right)\right)$ where N is the number of the projects, w_C represents the weight of the total cost, w_{T_i} is time's weight of i^{th} project, w_{Q_i} represents the weight of quality of i^{th} project. For example, in the case of three projects

$(w_C, w_{T_1}, w_{T_2}, w_{T_3}, w_{Q_1}, w_{Q_2}, w_{Q_3})$ are $(\frac{3}{9}, \frac{1}{9}, \frac{1}{9}, \frac{1}{9}, \frac{1}{9}, \frac{1}{9}, \frac{1}{9})$

VI. Experimental Results and Discussion

The proposed AHP-MGA approach was verified to demonstrate its performance in the first part of this section. In the second part, the discussion of the results is clarified.

A. Experimental results

The computational experiments were conducted by using six cases. The first case includes three real construction projects. All data of these projects can be downloaded from the following URL link (https://bit.ly/2To6TMh). Also, the proposed AHP-MGA approach was applied to a set of cases from the PSPLIB that were modified by Kannimuthu et .al [2] to include the cost and quality aspects of projects. These cases can be found by the following URL link (https://shorturl.at/ixCEK). In this section, the results of the first five cases (from portfolio instance #1 to portfolio instance #5) are presented. Also, these authors proposed the single-project approach (SPA) and the multi-project approach (MPA) for solving the MTCQ-RCMPS problem. The main idea of the SPA approach is to collect a set of the multi-projects in a single project's network to deal with them as a single project. To evaluate the performance of the proposed AHP-MGA approach, we compared its results with these approaches.

Case 1:

This problem includes 3 real projects X, Y, and Z. These projects include 32, 28, and 18 activities, respectively. Each activity can be executed by 3 execution modes. Each mode has a set of demands from the available resources of the construction company. The company has 22 types of resources. Each type is available as a limited quantity at each time point. The maximum daily cost of resources and the utilization of all types of resources over time for all projects by using the proposed AHP-MGA approach are illustrated in Fig. 8, 9, 10, and 11, respectively. The completion time, the cost, the quality, and the total cost of the three real building construction projects are illustrated in Fig.12, 13, 14, and 15, respectively. The solutions of the proposed AHP-MGA approach, the SPA, and the MPA for the scheduling of the three real building construction projects X, Y, and Z are illustrated in Table VIII.

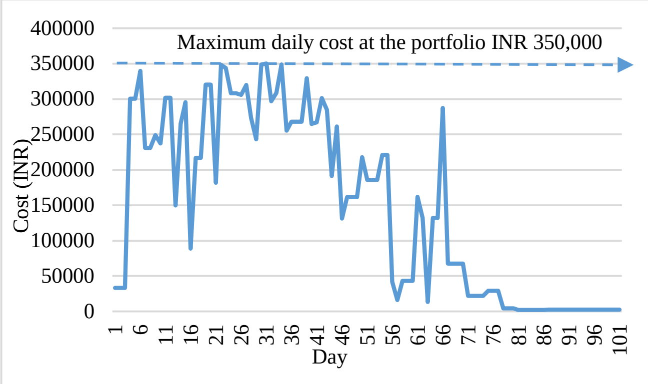

Fig. 8 Maximum daily cost over time of the first case.

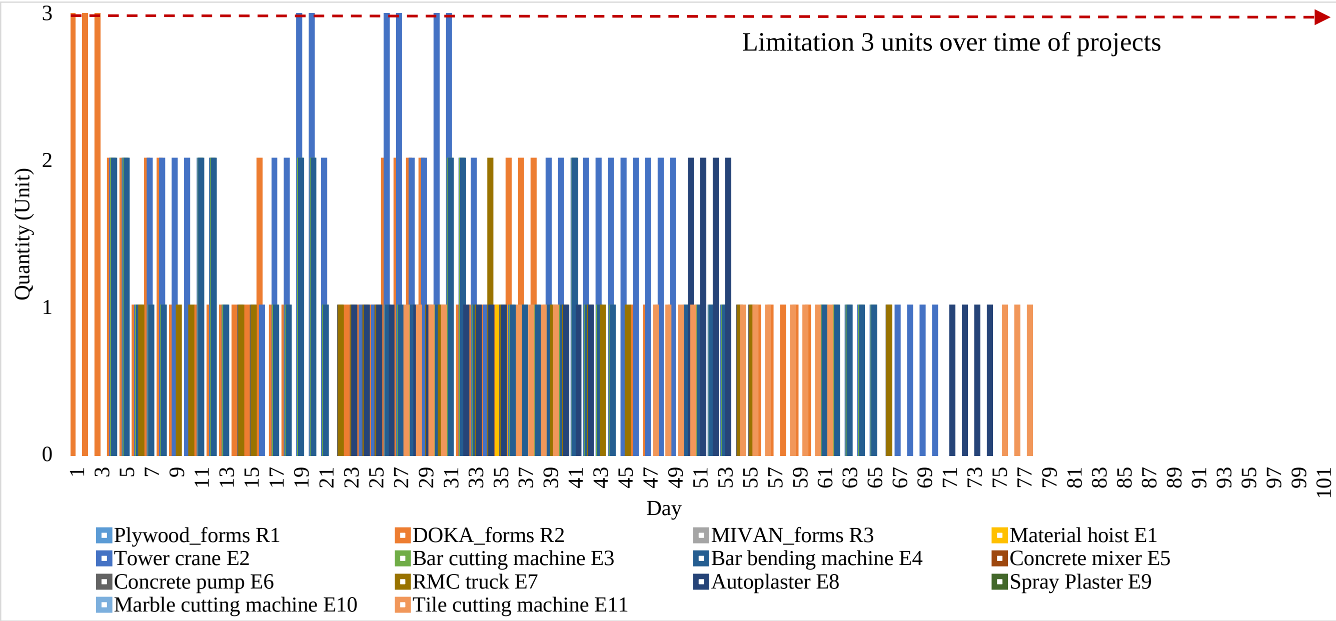

Fig. 9 Utilization of Plywood_forms R1, Doka_forms R2, Mivan_forms R3, Material hoist E1, Tower crane E2, Bar cutting machine E3, Bar bending machine E4, Concrete mixer E5, Concrete pump E6, RMC truck E7, Autoplaster E8, Spray plaster E9, Marble cutting machine E10, Tile cutting machine E11.

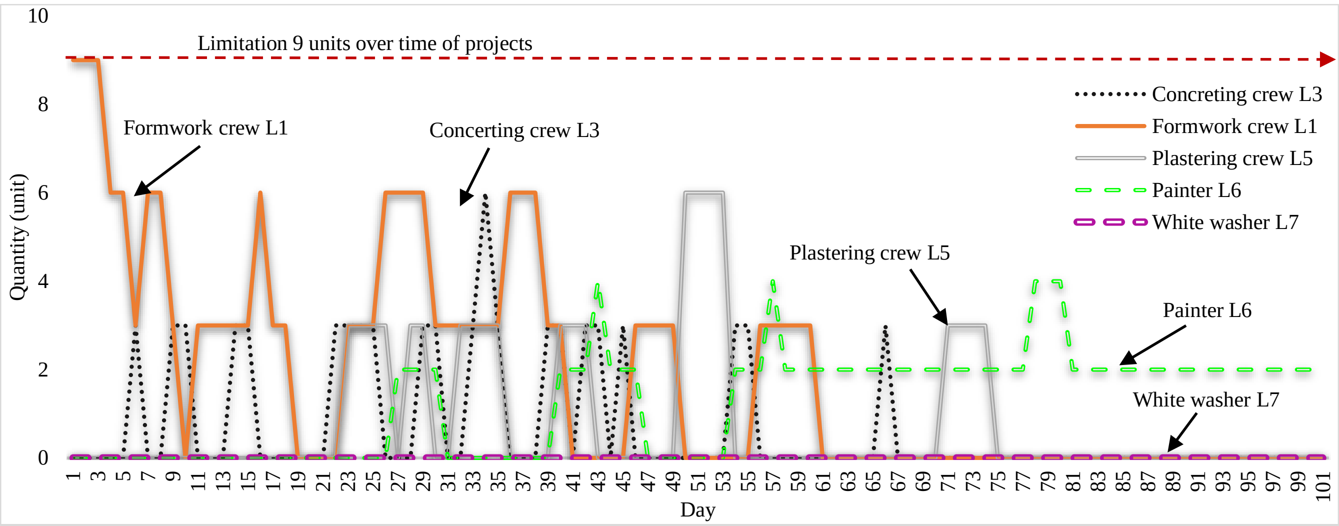

Fig. 10 Utilization of Concerting crew L3, Formwork crew L1, Plastering crew L5, Painter L6, and White washer L7 over time of the of the first case.

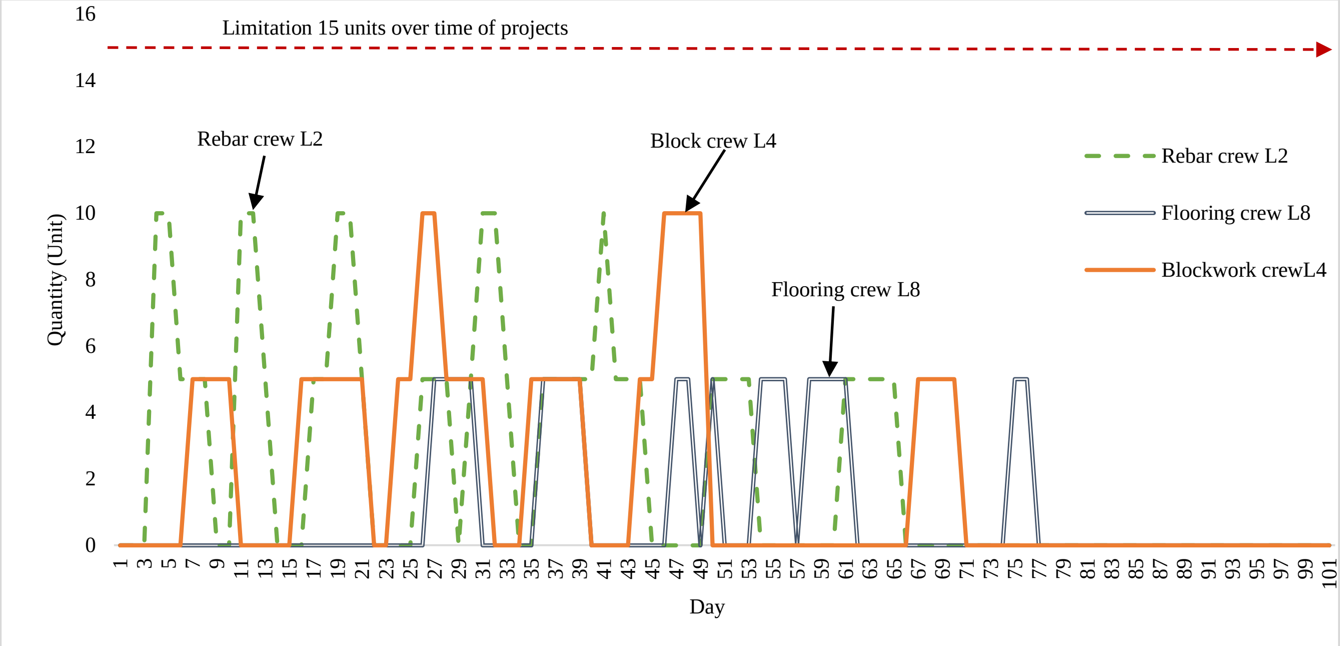

Fig. 11 Utilization of Rebar crew L2, Flooring crew L8, and Block crew L4 over time of the first case.

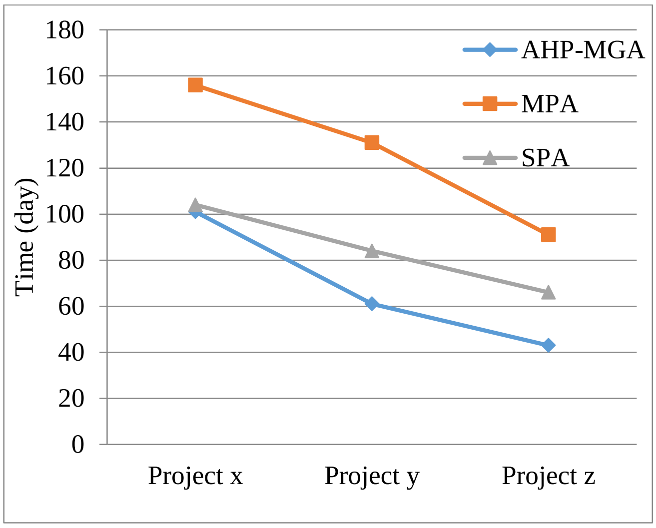

Fig. 12 The completion time of the first case.

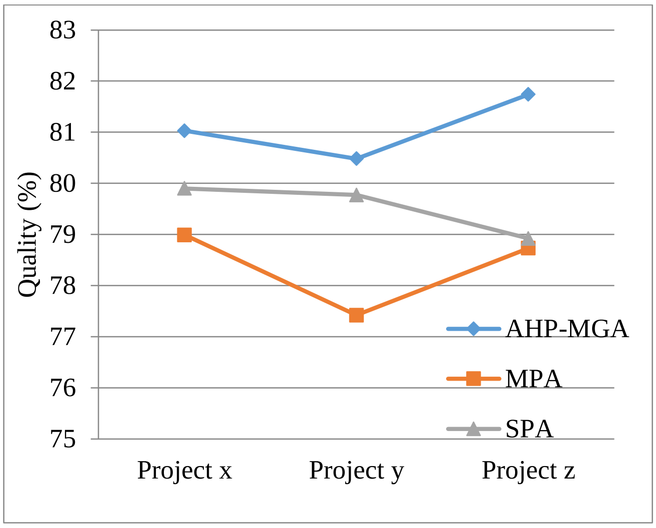

Fig. 14 construction projects' quality of the first case.

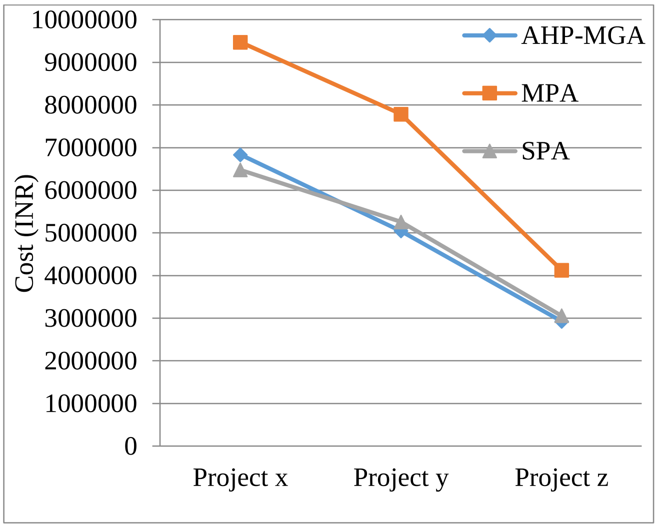

Fig. 13 The cost of the first case.

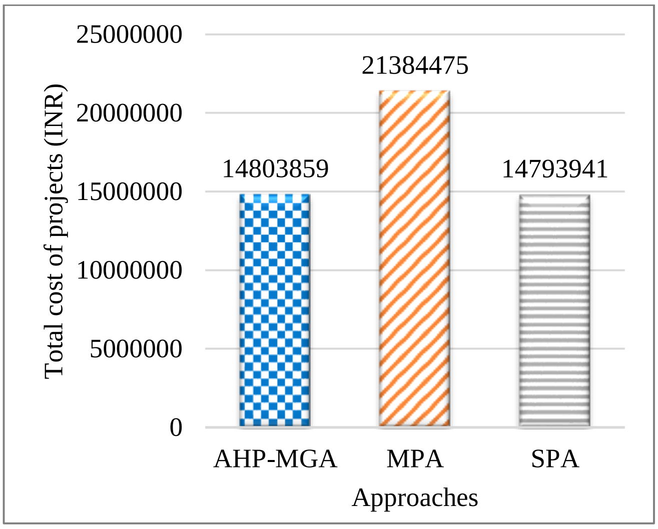

Fig. 15 The total cost of first case.

The above results of the three real construction projects by using the proposed AHP-MGA approach clear that most of the completion time and the quality of the projects are modified by using the AHP-MGA approach by a slight increase in the total cost of the projects (see Table VIII). The suggested solution of the real construction projects obtained by the AHP-MGA approach does not include the minimum total cost, but it provides the compromise solution of the time, cost, and quality of the projects without violating the budget, the maximum daily cost, and the resources constraints.

Case 2:

The values of the time, cost, and quality of the projects according to the proposed AHP-MGA, MPA, and SPA in case 2 are illustrated in Fig. 16,17, and 18, respectively. Also, the details of the improved solutions for this case are illustrated in Table IX.

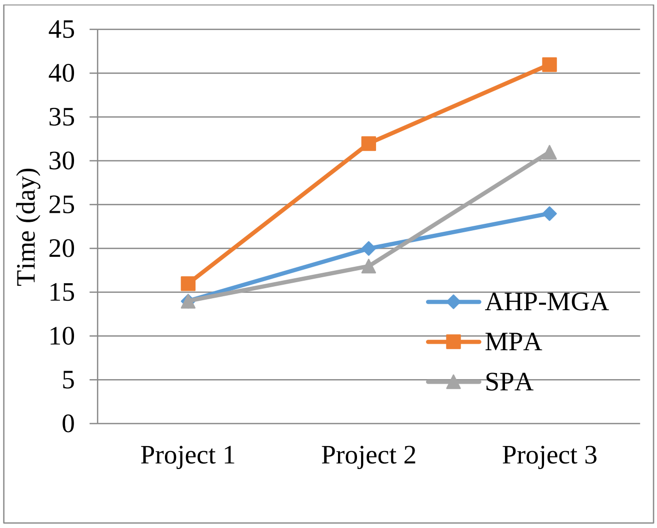

Fig. 16 The completion time of the second case.

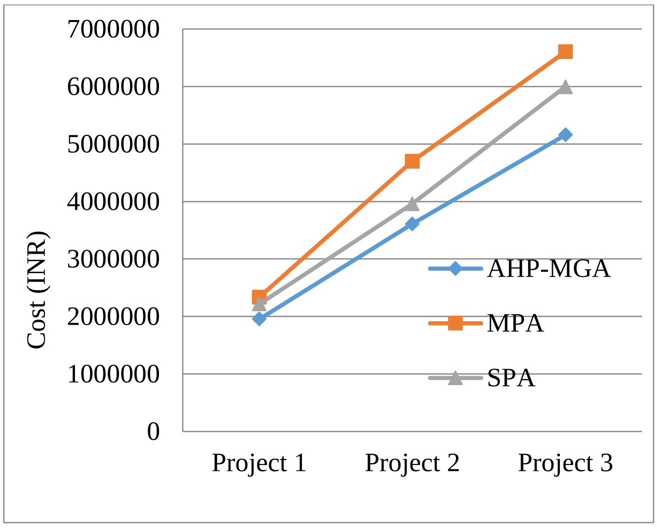

Fig. 17 The projects' cost of the second case.

The second case shows that the results of the proposed AHP-MGA approach achieved the best performance compared with the SPA, MPA in terms of time, cost, and quality for most projects, but the proposed AHP-MGA approach sometimes allows delays in some projects or a slight decrease in quality compared with SPA and MPA approaches (see Fig 16, 18). This is because the time and quality of the projects are soft constraints (i.e. the due date and quality of projects are constraints that can be violated in exchange for some penalties). On the other hand, budget constraints are hard constraints that can't be violated. In this case, the cost of the projects by using SPA and MPA approaches violate the budget constraints while the proposed AHP-MGA achieves budget surplus (see Fig. 19).

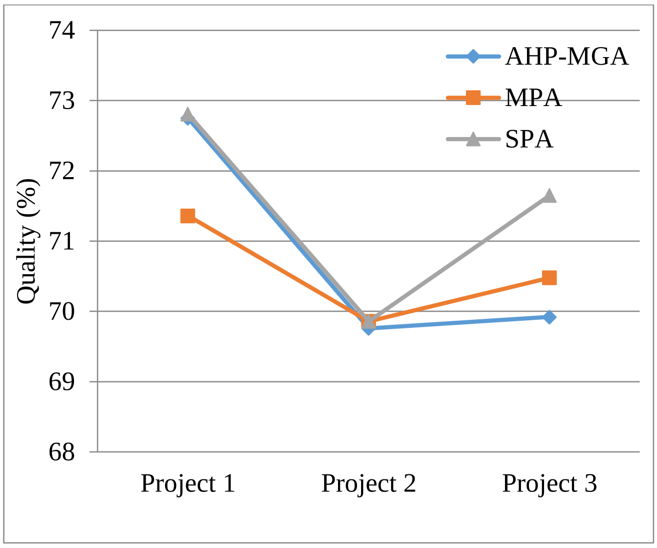

Fig. 18 Construction projects' quality of the second case.

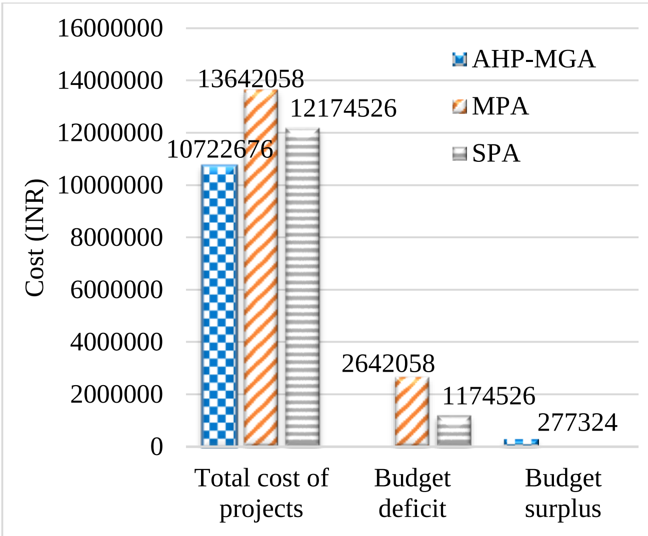

Fig. 19 The total cost and budget surplus of the second case.

Case 3:

The values of the time, cost, and quality of the projects according to the proposed AHP-MGA, MPA, and SPA in case 3 are illustrated in Fig. 20, 21, and 22, respectively. Also, the details of the improved solutions for this case are illustrated in Table X. In this case, the proposed AHP-MGA approach improved the cost of all projects and improved the time of the first and second projects with a slight decrease in the quality of projects. The proposed AHP-MGA approach overcome the budget deficit that is proposed by the solutions of the MPA and SPA approaches. Also, the proposed AHP-MGA approach achieved the budget surplus see Fig. 23.

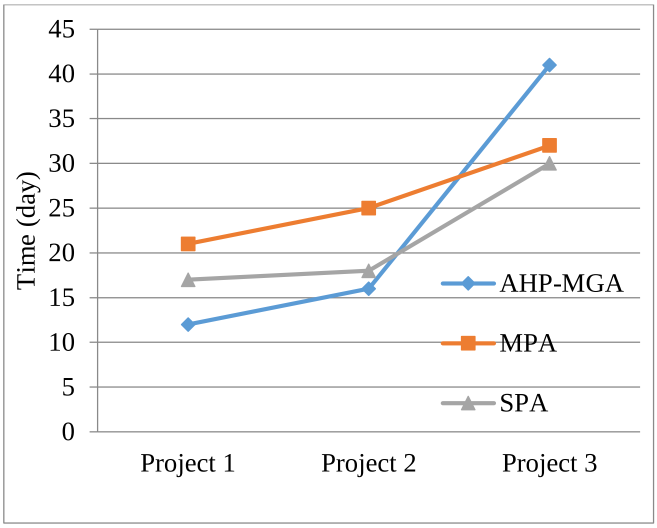

Fig. 20 Completion time of projects in case 3.

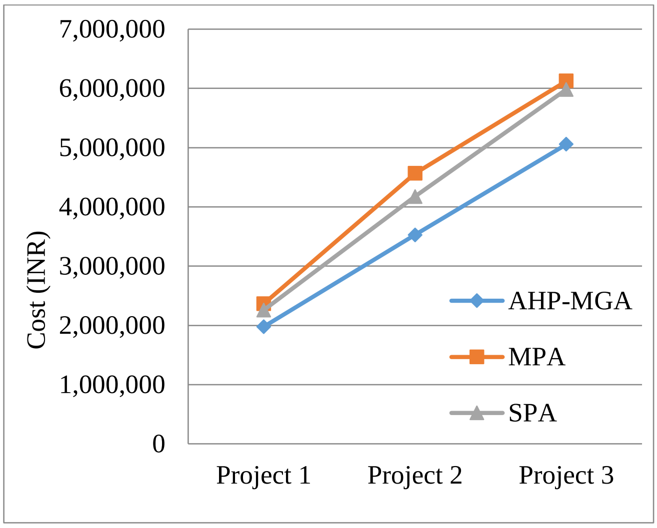

Fig. 21 The projects' cost of case 3.

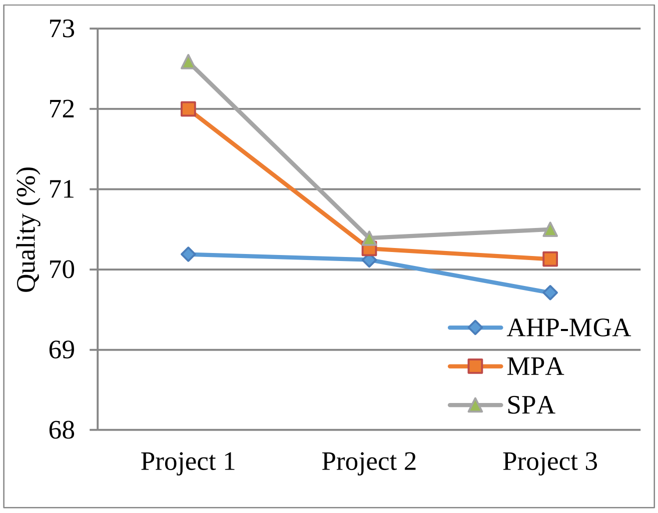

Fig. 22 Construction projects' quality of case 3.

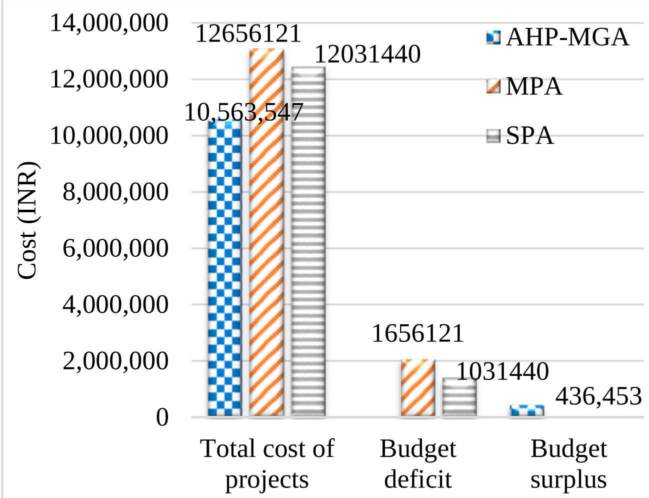

Fig. 23 The total cost and budget surplus of case 3.

Case 4:

The values of the time, cost, quality, and the total cost of the projects according to the proposed AHP-MGA, MPA, and SPA in case 4 are illustrated in Fig. 24, 25, 26, and 27 respectively. Also, the details of the improved solutions for this case are illustrated in Table XI.

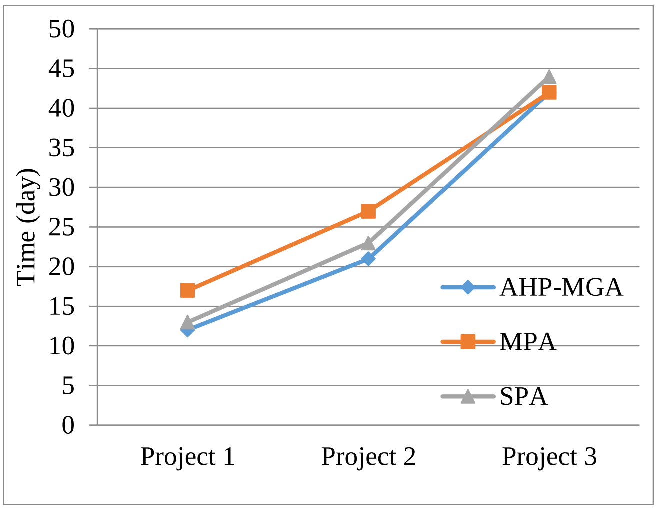

Fig. 24 Completion time of projects in case 4.

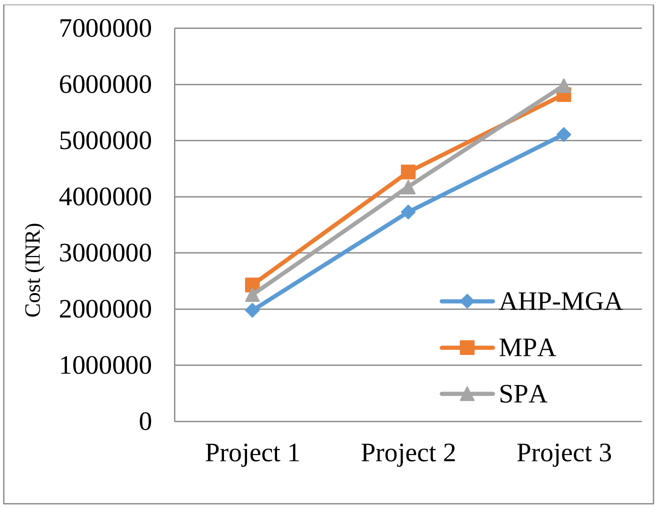

Fig. 25 The projects' cost of case 4.

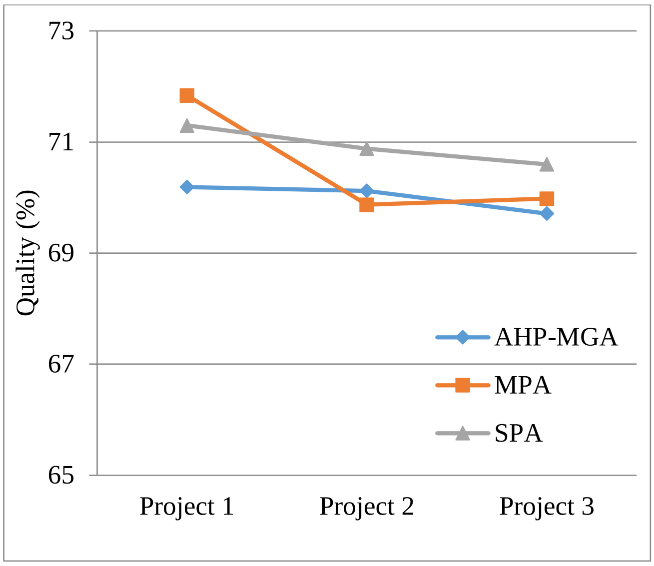

Fig. 26 Construction projects' quality of case 4.

From the results of this case, it is clear that the SPA and MPA often violate the budget constraints while the proposed AHP-MGA approach provides solutions within the limits of the permitted budget for projects. In addition to that, it achieves a budget surplus (see Fig 27), as well as the time and cost that are prominently improved by a slight decrease in the quality of projects around (1%), as a result of the design of our proposed approach, which is inclined toward the balancing between the benefits of the customers and the owners of the companies.

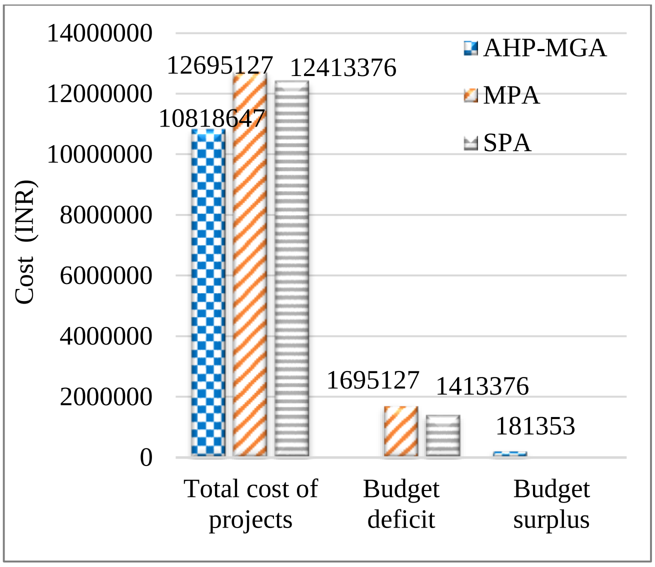

Fig. 27 The total cost and budget surplus of case 4.

Case 5:

The values of the time, cost, quality, and total cost of the projects according to the proposed AHP-MGA approach, MPA, and SPA in case 5 are illustrated in Fig. 28, 29, 30, and 31, respectively. Also, the details of the improved solutions for this case are illustrated in Table XII.

Fig. 28 Completion time of projects in case 5

Fig. 29 The projects' cost of case 5.

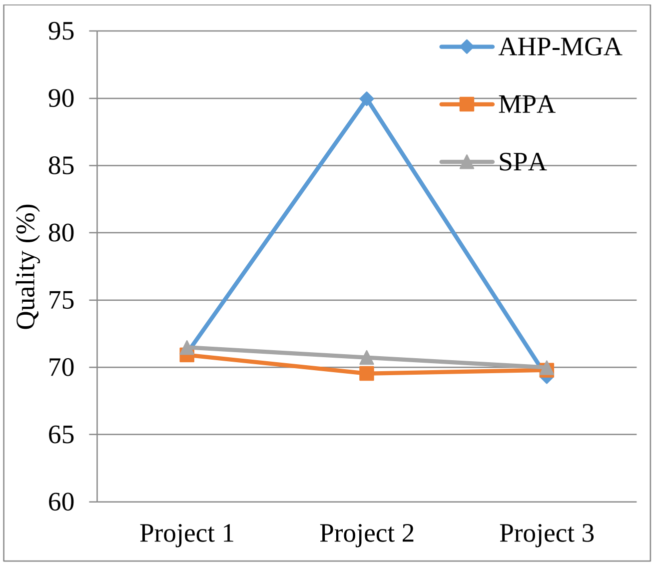

Fig. 30 Construction projects' quality of case 5.

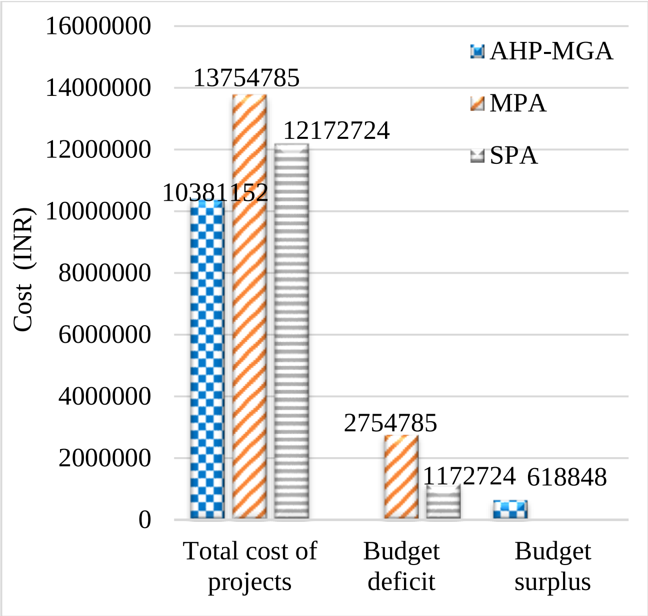

Fig. 31 The total cost and budget surplus of case 5.

Case 6:

The values of the time, cost, quality, and total cost of the projects according to the proposed AHP-MGA approach, MPA, and SPA in case 6 are illustrated in Fig. 32, 33, 34, and 35, respectively. From this case results, it is clear that the proposed AHP-MGA approach outperforms the MPA and the SPA in the time and cost, and quality of all projects in addition to that, it achieves a budget surplus (see Fig 35). The details of the solutions by using the proposed AHP-MGA, MPA, and SPA are illustrated in Table XIII.

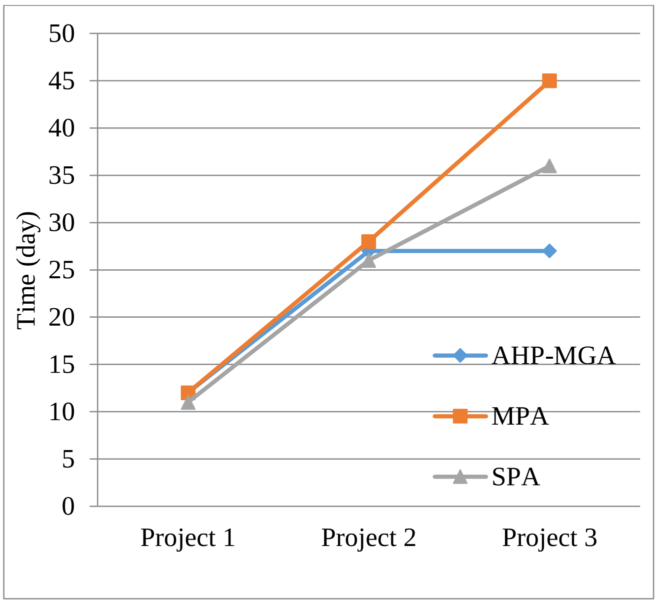

Fig. 32 Completion time of projects in case 6.

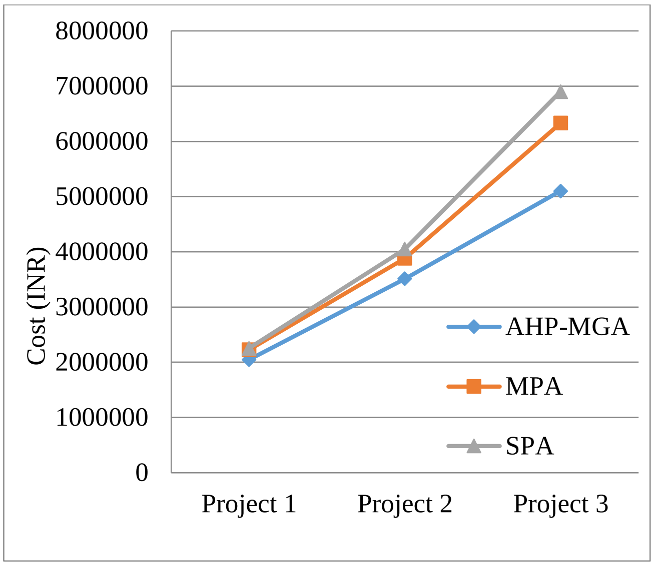

Fig. 33 The projects' cost of case 6.

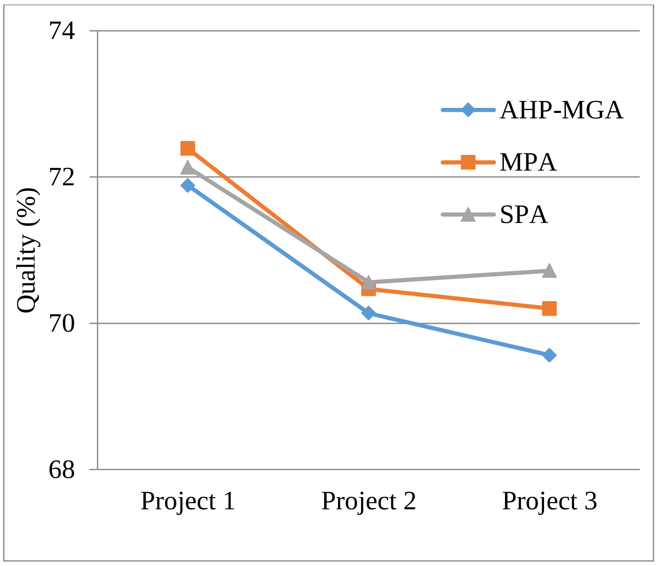

Fig. 34 Construction projects' quality of case 6.

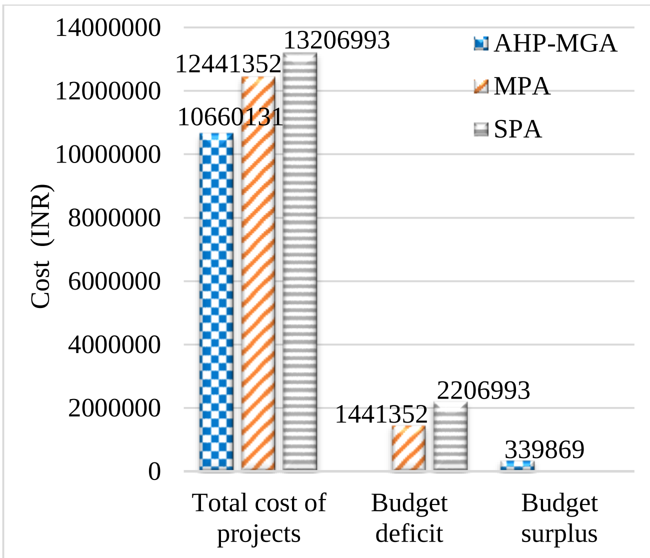

Fig. 35 The total cost and budget surplus of case 6.

TABLE VIII. COMPARISON OF SCHEDULING FOR THE FIRST CASE (MAXIMUM DAILY COSTS AT THE PORTFOLIO INR 350,000)

Project information	Budget	Project performances	AHP-MGA (decentralized multi-project scheduling)	MPA	SPA (portfolio optimization)	Comparison of AHP-MGA against the MPA	Comparison of AHP-MGA against the SPA (portfolio optimization)
Project no.1 (X)	8,500,000	Time	101	156	104	Improvement in time (35.25%)	Improvement in time (2.88%)
		Cost	6,831,931	9,470,743	6,476,854	Improvement in cost (27.86%)	Increase in cost (5.48%)
		Quality	81.03	78.99	79.90	Improvement in quality (2.51%)	Improvement in quality (1.39%)
Project no. 2 (Y)	6,500,000	Time	61	131	84	Improvement in time (53.43%)	Improvement in time (27.38%)
		Cost	5,044,780	7,787,510	5,259,044	Improvement in cost (35.21%)	Improvement in cost (4.07%)
		Quality	80.48	77.42	79.77	Improvement in quality (3.8%)	Improvement in quality (0.88%)
Project no. 3 (Z)	4,000,000	Time	43	91	66	Improvement in time (52.74%)	Improvement in time (34.84%)
		Cost	2,927,148	4,126,222	3,058,043	Improvement in cost (29%)	Improvement in cost (4.28%)
		Quality	81.74	78.73	78.92	Improvement in quality (3.68%)	Improvement in quality (3.44%)
Total (budget/cost)	19,000,000		14,803,858	21,384,475	14,793,941	Improvement in total cost (30.77%)	Increasing in total cost (0.067%)
Budget deficit			-	2,384,475	-		
Budget surplus			4,196,141	-	4,206,059		

TABLE IX. COMPARISON OF SCHEDULED SOLUTIONS FOR THE SECOND CASE (MAXIMUM DAILY COSTS AT THE PORTFOLIO INR 900,000)

Project information	Budget	Project performances	AHP-MGA (decentralized multi-project scheduling)	MPA	SPA (portfolio optimization)	Comparison of AHP-MGA against the MPA	Comparison of AHP-MGA against the SPA (portfolio optimization)
Project no.1 (j103_10)	2,000,000	Time	14	16	14	Improvement in time (12%)	Are equal
		Cost	1,954,126	2,336,041	2,216,546	Improvement in cost(16%)	Improvement in cost (11%)
		Quality	72,75	71.36	72.81	Improvement in quality (2%)	Decreasing in quality (0.08%)
Project no. 2 (j209_8)	3,500,000	Time	20	32	18	Improvement in time (37%)	Increasing in time (11.11%)
		Cost	3,609,785	4,700,886	3,961,024	Improvement in cost (23%)	Improvement in cost (8%)
		Quality	69.76	69.73	69.86	Decreasing in quality (0.14%)	Decreasing in quality (0.14%)
Project no. 3 (j309_10)	5,500,000	Time	24	41	31	Improvement in time (41%)	Improvement in time (22%)
		Cost	5,158,765	6,605,131	5,996,956	Improvement in cost (22%)	Improvement in cost (14%)
		Quality	69.92	70.48	71.65	Decreasing in quality (0.79%)	Decreasing in quality (2.41%)
Total (budget/cost)	11,000,000		10,722,676	13,642,058	12,174,526	Improvement in total cost (21%)	Improvement in total cost (12%)
Budget deficit			-	2,642,058	1,174,526		
Budget surplus			277,324	-	-		

TABLE X. COMPARISON OF SCHEDULED SOLUTIONS FOR CASE 3 (MAXIMUM DAILY COSTS AT THE PORTFOLIO INR 600,000)

Project information	Budget	Project performances	AHP-MGA (decentralized multi-project scheduling)	MPA	SPA (portfolio optimization)	Comparison of AHP-MGA against the MPA	Comparison of AHP-MGA against the SPA (portfolio optimization)
Project no.1 (j108_3)	2,000,000	Time	12	21	17	Improvement in time (42%)	Improvement in time (29%)
		Cost	1,979,141	2436390	2246480	Improvement in cost(18%)	Improvement in cost (11%)
		Quality	70.19	72	72.59	Decreasing in quality (0.02%)	Decreasing in quality(3.03%)
Project no.2 (j2017_9)	3,500,000	Time	16	25	18	Improvement in time (36%)	Improvement in time (11%)
		Cost	3,526,857	4387573	4044133	Improvement in cost (19%)	Improvement in cost (12%)
		Quality	70.12	70.26	70.39	Decreasing in quality (0.19 %)	Decreasing in quality (0.38%)
Project no.1 (j3012_4)	5,500,000	Time	41	32	30	Increasing in time (28%)	Increasing in time (36%)
		Cost	5,057,549	5832158	5740827	Improvement in cost (13%)	Improvement in cost (11%)
		Quality	69.71	70.13	70.50	Decreasing in quality (0.59%)	Decreasing in quality (1.12%)
Total (budget/cost)	11,000,000		10,563,547	12656121	12031440	Improvement in total cost (16%)	Improvement in total cost (12%)
Budget deficit			-	1656121	1031440		
Budget surplus			436,453	-	-		

TABLE XI. COMPARISON OF SCHEDULING FOR CASE 4 (MAXIMUM DAILY COSTS AT THE PORTFOLIO INR 800,000)

Project information	Budget	Project performances	AHP-MGA (decentralized multi-project scheduling)	MPA	SPA (portfolio optimization)	Comparison of AHP-MGA against the MPA	Comparison of AHP-MGA against the SPA (portfolio optimization)
Project no.1 (j1011_3)	2000000	Time	12	17	13	Improvement in time (29.41%)	Improvement in time (7.69%)
		Cost	1980091	2431116	2257187	Improvement in cost (18.55%)	Improvement in cost (12.27%)
		Quality	70.19	71.84	71.3	Decreasing in quality (2.29%)	Decreasing in quality (1.55%)
Project no. 2 (j2023_9)	3500000	Time	21	27	23	Improvement in time (22.22%)	Improvement in time (8.69%)
		Cost	3727457	4440675	4175132	Improvement in cost (16%)	Improvement in cost (10.72%)
		Quality	70.12	69.87	70.88	Improvement in quality (1.4%)	Decreasing in quality (1.06%)
Project no. 3 (j3016_2)	5500000	Time	42	42	44	Are equal	Improvement in time (4.54%)
		Cost	5111099	5823336	5981057	Improvement in cost (12.23%)	Improvement in cost (14.54%)
		Quality	69.71	69.98	70.6	Decreasing in quality (0.38%)	Decreasing in quality (1.25%)
Total (budget/cost)	11000000		10818647	12695127	12413376	Improvement in total cost (14.78%)	Improvement in total cost (12%)
Budget deficit			-	1695127	1413376		
Budget surplus			181353	-	-		

TABLE XII. COMPARISON OF SCHEDULING FOR CASE 5 (MAXIMUM DAILY COSTS AT THE PORTFOLIO INR 700,000)

Project information	Budget	Project performances	AHP-MGA (decentralized multi-project scheduling)	MPA	SPA (portfolio optimization)	Comparison of AHP-MGA against the MPA	Comparison of AHP-MGA against the SPS (portfolio optimization)
Project no.1 (j1014_8)	2000000	Time	19	36	18	Improvement in time (47%)	Increasing in time (5.55%)
		Cost	1956654	3023452	2330559	Improvement in cost (35%)	Improvement in cost (16%)
		Quality	71.02	70.92	71.48	Improvement in quality (0.14 %)	Decreasing in quality (0.63%)
Project no. 2 (j2031_7)	3500000	Time	20	31	17	Improvement in time (35%)	Increasing in time (17.64%)
		Cost	3154076	4376772	3823893	Improvement in cost (27.9%)	Improvement in cost (17.5%)
		Quality	89.95	69.54	70.73	Improvement in quality (29%)	Improvement in quality (27%)
Project no. 3 (j3026_9)	5500000	Time	24	33	27	Improvement in time (27%)	Improvement in time (11%)
		Cost	5270422	6354561	6018272	Improvement in cost (17%)	Improvement in cost (12.4%)
		Quality	69.30	69.79	69.99	Decreasing in quality (0.69%)	Decreasing in quality (0.98%)
Total (budget/cost)	11000000		10381152	13754785	12172724	Improvement in total cost (24.5%)	Improvement in total cost (14%)
Budget deficit			-	2754785	1172724		
Budget surplus			618848	-	-		

TABLE XIII. COMPARISON OF SCHEDULING FOR CASE 6 (MAX DAILY COSTS AT THE PORTFOLIO INR 900,000)

Project information	Budget	Project performances	AHP-MGA (decentralized multi-project scheduling)	MPA	SPA (portfolio optimization)	Comparison of AHP-MGA against the MPA	Comparison of AHP-MGA against the SPA (portfolio optimization)
Project no.1 (j1020_8)	2000000	Time	12	12	11	Are equal	Increasing in time (9.09%)
		Cost	2045937	2227063	2252370	Improvement in cost (8.13%)	Improvement in cost (9.16%)
		Quality	71.88	72.39	72.13	Decreasing in quality (0.69%)	Decreasing in quality (0.34%)
Project no. 2 (j2040_8)	3500000	Time	27	28	26	Improvement in time (3.57%)	Increasing in time (3.84)
		Cost	3513039	3881208	4050992	Improvement in cost (9.48%)	Improvement in cost (13%)
		Quality	70.13	70.47	70.56	Decreasing in quality (0.47%)	Decreasing in quality 0.60%
Project no. 3 (j3034_6)	5500000	Time	27	45	36	Improvement in time (40%)	Improvement in time (25%)
		Cost	5101155	6333081	6903631	Improvement in cost (19.45%)	Improvement in cost (26%)
		Quality	69.56	70.2	70.72	Decreasing in quality (0.90%)	Decreasing in quality (1.63%)
Total (budget/cost)	11000000		10660131	12441352	13206993	Improvement in total cost (14%)	Improvement in total cost (19%)
Budget deficit			-	1441352	2206993		
Budget surplus			339869	-	-		

B. Discussion

The AHP-MGA approach has been verified against the SPA and MPA approaches from the literature [2]. According to the results in the experimental results section, it is clear that the proposed AHP-MGA approach outperforms the SPA and MPA in most of the cases, due to several reasons that can be summarized as follows:

1) In the MPA and SPA, the original multi-objective (time, cost, and quality) of the resource scheduling optimization problem has been transformed into a single-objective optimization problem by the weighted sum method. The weighted sum method is one of the most widely used multi-objective methods for solving multi-objective problems due to its simplicity. However, this method has several drawbacks, such as in some of the cases, it is difficult to generate a good set of points that are uniformly distributed on the Pareto front. Also, this method only works for convex Pareto fronts. Moreover, the objectives' proper normalization is frequently needed so that their ranges/values should be comparable. Otherwise, the weight coefficients will be poorly distributed, leading to biased sampling on the Pareto front [34].
2) In the SPA, the original multi-project scheduling optimization problem has been transformed into a single-project optimization problem by the dummy activities. This methodology is an easy way to find a feasible solution for the multi-project scheduling problem, but it has several drawbacks that prevent it from finding the optimal or a near-optimal solution in the case of the multi-project scheduling [11]-[13].
3) In the MPA, each project is optimized individually while in the proposed AHP-MGA, a set of projects are optimized simultaneously to maximize the utilization of resources.
4) The AHP-MGA approach can improve several dimensions of the problem. The AHP contributes to optimize the time, the direct cost, the quality of activities, and the quality of projects. On the other hand, the MGA contributes to optimizing the completion time and total cost of the projects.
5) The main problem, the multi-mode multi-objective resource-constrained multi-project scheduling problem, includes two sub-problems: the modes assignment problem and the multi-objective resource-constrained multi-project scheduling problem. These two problems belong to Multi-Criteria Decision Making (MCDM), but the first problem belongs to the class of multi-attribute decision making (MADM) of MCDM. The MADM problem refers to making preference decisions by evaluating and prioritizing a limited set of alternatives based on multiple conflict attributes [35], so we base on the AHP as one of the most powerful methods of MADM. It is used to rank the alternatives of modes and select or assign the best alternative to execute each activity. On the other hand, the multi-objective resource-constrained multi-project scheduling problem belongs to the class of multi-objective decision making (MODM) of MCDM, so we used the multi-objective genetic algorithm as one of the best MODM to solve this problem. According to the reasons that have been mentioned, any single optimization approach is not sufficient to solve the main problem.

VII. Conclusion and Future Work

The MTCQ-RCMPS problem represents a difficult challenge in construction projects due to the strong conflict among the three objectives: the time, cost, and quality, in addition to the conflicts of resources. There are conflicts in the context of the local resources at the level of the activities of the projects. Also, there are conflicts in global resources at the level of the projects. The proposed AHP-MGA approach consists of two sub-approaches: the multi-criteria analytical hierarchy process and the modified genetic algorithm. Also, the MTCQ-RCMPS problem is composed of two sub-problems, which are the MTCQ trade-off problem and the RCMPS problem. Firstly, the execution modes of the activities are compared by the three criteria of each execution mode: the time, cost, and quality; the best execution mode of each activity is allocated based on the highest weight of the execution modes for each activity by using the AHP. Secondly, the RCMPS problem is solved by the MGA algorithm. Also, we developed PSGS-RCMPS to construct feasible solutions to the RCMPS problem for each individual of the population. We have compared the proposed AHP-MGA with the existing approaches and observed the average (28.53%), (20.37%), and (2.36%) improvement in terms of the time, cost, and quality of projects, respectively compared with the MPA. And we observed the average (10.53%), (11.49%), and (1.81%) improvement in terms of the time, cost, and quality of projects, respectively compared with the SPA. Furthermore, the solution by the proposed AHP-MGA approach does not include any budget deficit while the budget constraint was violated in the provided solutions by using the MPA and SPA approaches in the related work. In addition to that, the proposed AHP-MGA achieves the budget surplus at a rate of (3.32%).

In terms of future studies for this work, more multi-criteria decision-making approaches should be applied to evaluate the alternatives of the execution modes instead of the mathematics and meta-heuristic approaches. These approaches would be useful because the stochastic search in the multi-mode space, precedence, and the resource space together without search's criteria is a very difficult and time-consuming process. The proposed approach in this paper deals with only the non-preemptive activities whereas the construction projects in the real world have some preemptive activities, so the preemptive activities should be taken into account in future studies.

References

[1] M. Kannimuthu, B. Raphael, E. Palaneeswaran, A. Kuppuswamy, “Optimizing time, cost and quality in multi-mode resource-constrained project scheduling”, *Built Environment Project and Asset Management* Vol. 9, No. 1, pp. 44-63, Mar. 2019.

[2] M. Kannimuthu, B. Raphael, P. Ekambaram, A. Kuppuswamy, “Comparing optimization modeling approaches for the multi-mode resource-constrained multi-project scheduling problem”, *Engineering, Construction and Architectural Management,* Vol. 27, No. 4, pp. 893-916, Nov. 2019.

[3] H. Wang, J. Lin, J. Zhang, “Work package-based information modeling for resource-constrained scheduling of construction projects”, *Automation in Construction,* Vol. 109, SP. 102958, Jan. 2020.

[4] A. E. Mae, W. K. Kwee, P. Y. Han, and L. S. Hoe, "Resource Allocation for Real-time Multimedia Applications in LTE's Two-level Scheduling Framework," *IAENG International Journal of Computer Science*, vol. 43, no.4, pp427-437, 2016.

[5] Q. Xu, T. Huang, J. Li and Y. Yang, "Solving Production Scheduling Problem of Automotive Parts Workshop Based on Improved Genetic Algorithm," *2020 IEEE 4th Information Technology, Networking, Electronic and Automation Control Conference (ITNEC)*, Chongqing, China, 2020, pp. 2231-2235.

[6] S. Liu and N. Wang, "Collaborative Optimization Scheduling of Cloud Service Resources Based on Improved Genetic Algorithm," *in IEEE Access*, vol. 8, pp. 150878-150890, 2020.

[7] J. Cao, M. Lin, and X. Ma, "A Survey of Big Data for IoT in Cloud Computing," *IAENG International Journal of Computer Science*, vol. 47, no.3, pp585-592, 2020.

[8] M. R. Afshara, V. Shahhosseini, M. H. Sebta, "A genetic algorithm with a new local search method for solving the multimode resource-constrained project scheduling problem", *International Journal of Construction Management*, pp. 1-9, 2019.

[9] F. Li, Z. Xu, "A multi-agent system for distributed multi-project scheduling with two-stage decomposition", *PLoS One*, Vol. 13, No. 10, pp 1-24, 2018.

[10] R. Kolisch, Description of the Problems. In: Project Scheduling under Resource Constraints. *Production and Logistics*. Physica, Heidelberg, 1995.

[11] T. R. Browning, A. A. Yassine, "Resource-Constrained Multi-Project Scheduling: Priority Rule Performance Revisited", *International Journal of Production Economics*, Vol. 126, No. 2, pp. 212-228. Aug. 2010.

[12] M. Kannimuthu, P. Ekambaram, B. Raph, A. Kuppuswamy, "Resource Unconstrained and Constrained Project Scheduling Problems and Practices in a Multiproject Environment", *Advances in Civil Engineering*, Vol. 2018, pp. 1-13, 2018.

[13] G. Maher, N. EL-Hefnawy, A. Kfafy, O. Abd-EL-Raouf, "Efficient Model with an Intelligent Approach for Powerful Construction Project Scheduling", *International Journal of Intelligent Engineering and Systems*, Vol. 13, No. 3, pp. 189-200, Jun 2020.

[14] J. A.S. Araujo, H. G. Santos, B. Gendron, S. D. Jena, S. S. Brito, D. S. Souza, "Strong bounds for resource constrained project scheduling: Preprocessing and cutting planes", *Computers and Operations Research*, Vol. 113, 104782, January 2020.

[15] E. N. Afruzi, A. Aghaie, A. A. Najafi, "Robust optimization for the resource-constrained multi-project scheduling problem with uncertain activity durations", *Scientia Iranica E*, Vol. 27, No. 1, pp. 361-376, 2020.

[16] F. Villafáñez, D. Poza, A. López-Paredes, J. Pajares, R. del Olmo, "A generic heuristic for multi-project scheduling problems with global and local resource constraints (RCMPSP)", *Soft Computing*, Vol. 23, pp. 3465–3479, 2019.

[17] G. Maher, O. Abd-El-Roaf, N. El-Hefnawy and A. Kfafy, "A Novel Approach for Multi-Resource Planning in Construction Engineering", *2019 IEEE Ninth International Conference on Intelligent Computing and Information Systems (ICICIS)*, Cairo, Egypt, pp. 278-284, 2019.

[18] T. L. Saaty, "How to make a decision: The Analytic Hierarchy Process", *European Journal of Operational Research*, vol. 48, pp. 9-26, 1990.

[19] F. Renno, F. Barbato, G. Barbarino, F. Guarino, R. Guida, and S. Papa, "AHP and Multi-Voting Approaches for Conceptual Design of New Detectors: The Crystal Eye Case Study", *Engineering Letters*, vol. 28, no.2, pp470-476, 2020.

[20] J. Liu, Y. Liu, Y. Shi, J. Li, "Solving Resource-Constrained Project Scheduling Problem via Genetic Algorithm*", Journal of Computing in Civil Engineering*, Vol. 34. No. 2, 0000874 ,Mar. 2020.

[21] V. V. Peteghem, M. Vanhoucke, "A genetic algorithm for the preemptive and non-preemptive multi-mode resource-constrained project scheduling problem", *European Journal of Operational Research*, Vol. 201, No. 2, pp. 409-418, Mar. 2010.

[22] S. C. Vanucci, E. G. Carrano, R. Bicalho and R. H. C. Takahashi, "A modified NSGA-II for the Multiobjective Multi-Mode Resource-Constrained Project Scheduling Problem," *2012 IEEE Congress on Evolutionary Computation*, Brisbane, QLD, pp. 1-7, 2012.

[23] A. Singh, "Resource Constrained Multi-Project Scheduling with Priority Rules & Analytic Hierarchy Process", *Procedia Engineering*, Vol. 69, pp 725 – 734, 2014.

[24] J. Cheng, J. Fowler, K. Kempf, S. Mason, "Multi-mode resource-constrained project scheduling problems with non-preemptive activity splitting", *Computers & Operations Research*, Vol. 53, pp. 275-287, Jan. 2015.

[25] U. Beşikci, Ü. Bilge, G. Ulusoy, "Multi-mode resource constrained multi-project scheduling and resource portfolio problem", *European Journal of Operational Research*, Vol. 240, No. 1, pp. 22-31, Jan. 2015.

[26] A. H. Chen, Y. Liang, J. D. Padilla, "A Practical and Robust Execution Time-Frame Procedure for the Multi-Mode Resource-Constrained Project Scheduling Problem with Minimal and Maximal Time Lags", *Algorithms*, Vol. 9, No. 4, 63, pp. 1-19, 2016.

[27] P. I. Adamu, M. C. Agarana, and H. I. Okagbue, "Machine Learning Heuristic for Solving Multi-Mode Resource-Constrained Project Scheduling Problems, Proceedings of the International Multi Conference of Engineers and Computer Scientists 2018 Vol I IMECS 2018, March 14-16, 2018, Hong Kong.

[28] A. E. F. Muritiba, C. D. Rodrigues, F. A. da Costa, "A Path-Relinking algorithm for the multi-mode resource-constrained project scheduling problem", *Computers & Operations Research*, Vol. 92, pp. 145-154, Apr. 2018.

[29] B. Afshar-Nadjaf, "A solution procedure for preemptive multi-mode project scheduling problem with mode changeability to resumption", *Applied Computing and Informatics*, Vol. 14, No. 2, pp. 192-201, Jul. 2018.

[30] Z. T. Kosztyán, A. Pribojszki-Németh, I. Szalkai, "Hybrid multimode resource constrained maintenance project scheduling problem", *Operations Research Perspect*ives, Vol. 6, P. 100129, 2019.

[31] R. Nemati-Lafmejani, H. Davari-Ardakani, H. Najafzad, "Multi-mode resource constrained project scheduling and contractor selection: Mathematical formulation and metaheuristic algorithms", *Applied Soft* Computing, Vol. 81, 105533, Aug. 2019.

[32] R. K. Chakrabortty, A. Abbasi, M. J. Ryan, "Multi-mode resource-constrained project scheduling using modified variable neighborhood search heuristic", *Intl. Trans. in Op. Res*., Vol 27, No. 1, pp. 138–167, Jan. 2020.

[33] A. Cesta, A. Oddi, Policella N., S.F. Smith, "A Precedence Constraint Posting Approach, In: C. Schwindt, J. Zimmermann, (eds) Handbook on Project Management and Scheduling", Vol.1. *International Handbooks on Information Systems*. Springer, Cham, 2015.

[34] X. Yang, "Multi-Objective Optimization", In Nature-Inspired Optimization Algorithms, 1st Edition, Elsevier, PP 197-211, 2014.

[35] L. Zhang, Multi-attribute Decision Making. *In: Michalos A.C. (eds) Encyclopedia of Quality of Life and Well-Being Research*, Springer, 2014.

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