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Developing a Resource Allocation Approach for Resource-Constrained Construction Operation under Multi-Objective Operation

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Abstract: In the construction industry, it is of great importance for project managers (PM) to consider the resource allocation arrangement problem based on different perspectives. In this situation, the management of resources in construction becomes a challenge. Generally speaking, there are many objectives that need to be optimized in construction that are in conflict with each other, including time, cost, and energy consumption (EC). This paper proposed a multi-objective optimization framework based on the quantum genetic algorithm (QGA) to obtain the best trade-off relationship among these goals. The construction resources allocated in each construction activity would eventually determine its execution time, cost, and EC, and a complexed time-cost-energy consumption trade-off framework of the project is finally generated due to correlations between construction activities. QGA was performed to find the best combination among time, cost, and EC and the optimal scheme of resource arrangement under this state. The construction process is simulated in BIM to check the rationality of this resource allocation mode. An industrial plant office building in China is presented as an example to illustrate the implementation of the proposed model. The results show that the presented method could effectively reduce 7% of cost, 17% of time, and 21% of energy consumption. This developed model is expected to help PMs to solve the problem of multi-objective optimization with limited resource allocation.

Keywords: construction; resource-constrained scheduling; multi-objective trade-off; time-cost-energy consumption overruns; resource allocation

1. Introduction

The construction industry has led to a huge consumption of resources [1]. It is of great importance for PMs to draw up a resource allocation arrangement in planning the process of a construction project [2] to avoid an uneven allocation and waste of resources. However, the construction sector has been known for its low productivity for several years [3], and inefficient construction resource allocation may lead to delays, cost overruns, and resource waste in the construction process [2,4].

Construction management is the work of allocating time and resources to each activity under the requirements of construction objectives [5]. Generally speaking, the allocation of project resources has a direct impact on the project’s progress. A reasonable project schedule also could help shorten the construction time and improve the resource utilization efficiency [6]. Much scientific research has developed different models to solve the resource allocation problem. At first, scholars took the goals of optimizing resource allocation, minimizing the time limit, and complying with all project precedence relationships to establish models [7–10]. Afterwards, the connection between resource allocation and cost management was taken into consideration. Feng and Chung suggested using the genetic algorithm (GA) for cost-time optimization in resource management [11]. Elazouni and Metwally developed a finance-based scheduling method that considered cost, time, and
resources [12]. Sonmez et al. performed a critical sequence crashing heuristic to solve the problem of time-cost trade-off optimization under resource constraints [13].

In general, each of the resource allocation alternatives determines specific combinations of the project, which includes time and cost [14]. However, the construction EC problem has been prominent in recent years [15,16], which has attracted close attention in previous research [17–19]. According to statistics, the current EC of the construction industry accounts for about one third of the whole global energy consumption [20]. In high-density cities, this proportion will be even higher. In Hong Kong, for example, the construction industry accounts for more than 60% of the total EC [21]. Therefore, since there are a large number of construction projects throughout the world each year, the problem of EC in the construction stage cannot be ignored [17]. It is of great importance for PMs to take the EC problem into consideration in decision making.

This is a topic of pivotal importance in designing a new resource allocation framework under the constraints of time, cost, and EC, where achieving the shortest construction time, the lowest cost, and the least EC is the goal. As a consequence, a faster approach to determine the optimal combination of project time, cost, and EC and the best resource allocation scheme for the project is desired to provide reference help for PMs in decision making. This could have the significance of allocating resources wisely and avoiding resource waste in construction management.

Compared with previous studies, the main contribution of this study to the body of engineering management knowledge includes three aspects. First, through the multi-objective optimization model proposed in this manuscript, we analyzed the relationship of resource allocation with time, cost, and EC. Secondly, we took labor and machines as renewable resources in this study and established the variable fitting functions as the basis of multi-objective optimization. The project could be decomposed into multiple construction activities through the work breakdown structure (WBS), and then the resources could be allocated. Third, this approach could provide the PM not only with the optimal time, cost, and EC compound mode but also with the specific resource allocation scheme of the activities under each situation. Finally, one of the novelties proposed in this model is to bring the resource allocation scheme and the schedule, which is obtained from the model, into BIM to the virtual construction process and check the rationality of resource allocation. The model presented in this study could help the PM find the optimal combination of time, cost, and EC and the resource allocation arrangement of each activity.

In this paper, Section 2 provides a summary of the previous studies on resource allocation and the multi-objective optimization problem in construction. Section 3 presents a framework to analyze the relationship of resource allocation with time, cost, and EC. This framework could arrange the resource of each activity under the constraint of the preference of the PM. Section 4 discusses the resulting analysis of a case study. Finally, Section 5 presents the conclusions.

2. Literature Review

2.1. Resource Allocation Problem in Construction Project

The decision of resource optimization aims to allocate and manage resources rationally within the budget [6]. The PM has to optimize the resource plan of the project under the limit to achieve the project goals [22]. In each activity, its resource allocation alternatives determine the specific time and cost in the construction process. If the required resources cannot be available on time, the construction activities will not be accomplished, which lead to economic damage to project participants [23]. Therefore, an effective technique is necessary to analyze the resources and project performance to avoid such issues [24]. Yeoh and Chua presented a four-dimensional scheduling model to arrange the resource allocation [25]. Kim and KJ evaluated the equipment scheduling through a multiagent system [26]. Tao et al. have investigated the project schedule and resource flow allocation which took site location and workspace congestion into consideration in their model [27].
In actual construction practice, the required resources, including manpower and equipment, have features such that the price of the resource often fluctuates [6], which will increase the degree of difficulty for the PM to take cost management into account when making resource allocation plans. Nabipoor et al. presented the adjusted fuzzy dominance genetic algorithm to conduct the problem of discrete time-cost trade-off with multimode resource constraints in construction [28]. Chen and Weng adopted GA to settle the time-cost trade-off problem by considering the resource-constrained scheduling question [29]. Hegazy and Menesi proposed a heuristic method to resolve any resource overallocation issues of the construction activity [30].

### 2.2. Construction Multi-Objective Performances and Optimization

Project time and cost are the two critical elements related to construction project success that have received intensive attention in recent years [31–35]. Gülçağ Albayrak proposed a novel hybrid algorithm to search the time-cost trade-off solution space and presented more economical alternatives for PMs [36]. Huang et al. developed a framework to find the minimal cost in a given time by searching for the best activity modes, start time, and work sequence [37]. Zou et al. adopted the mixed inter programming approach to find the least cost combination mode without exceeding a given deadline [38]. As the problem of EC has become more and more prominent in the construction process in recent years, PMs must take EC as one of the construction goals in decision making. Therefore, establishing a balance among the different aspects of the construction performance problem is increasingly important for PMs [39]. Marzouk et al. presented a GA method to perform the multi-objective optimization problem of project time, cost, and pollution and analyzed the relationship among them [40]. Ozcan et al. used correlational analysis to examine the time-cost-environment impact (TCEI) in a highway construction project and found that time and cost were positively correlated, cost and greenhouse gas (GHG) emissions were moderately positively correlated, and time and GHG emissions were weakly positively correlated [18]. Cheng et al. designed the OMODE method to optimize the three construction objectives of time limit, cost, and environmental impact and compared the method with other algorithms. It was found that the OMODE algorithm had better diversity characteristics and could obtain better compromise solutions and satisfaction [41]. However, there is not yet a systematic method to simultaneously identify the relationship optimization framework of project time, cost, and EC under the constraints of resource allocation.

The multi-objective optimization problem belongs to the nondeterministic polynomial-time hard (NP-hard) category, which is characterized by computational complexity [42,43]. At first, many methodologies were proposed to solve this question by searching for the best combination for construction activities [44,45]. Furthermore, this problem could also be solved through an analytical approach including linear and dynamic programming methods [46–48]. With the deepening of the research on this issue, the meta-heuristic algorithm shows better performance with the ability of producing relatively good solutions for large-scale projects [49], including priority rule-based scheduling heuristics [50], genetic algorithms [51–54], simulated annealing [55,56], and particle swarm optimization [57,58]. However, such solutions have the disadvantage of it being difficult to guarantee a global optimal solution [59]. In view of this, we adopt the quantum genetic algorithm (QGA) to solve the multi-objective trade-off problem of the time-cost-energy consumption problem (TCECP). Based on the genetic algorithm, this combines the parallelism of quantum computation, which can effectively improve the search efficiency on the basis of global search. Furthermore, this also has the advantages of reducing the application error of the Pareto solution and providing a better performance ratio than the traditional genetic algorithm.

### 2.3. BIM Application in Construction

Building information modeling (BIM) is an efficient engineering construction management tool which has accelerated informatization in the construction, engineering, architecture, and operation of buildings [60]. Generally speaking, BIM has evident advantages in...
project management, especially providing better coordination in information management for project managers in decision making [61]. The rise of BIM is an innovative development in the current construction industry, which has greatly improved construction productivity and decreased the waste of resources [62].

The conception of BIM was first presented in the 1970s, and its study progressed in the 1980s in Europe [63]. In recent years, its application has become widespread all over the world [61]. In fact, BIM is an operation paradigm in n-dimensional the construction models to visualize and administrate what will be built and what will occur in construction and operation process [64]. The BIM 4D technology can combine a three-dimensional (3D) model of a building with the time of construction activities, which can be visualized in a virtual view to simulate the construction process [65]. It could greatly increase the constructability and activity-scheduling alternatives and reduce unreasonable arrangements in the construction process [66,67]. With the BIM 5D technology applied in construction projects, the level of meticulous management in the construction stage is improved immensely, the resource waste of projects is reduced, and the construction progress is ensured in advance [68]. The development of BIM provides practical guidance value for achieving the goal of green sustainable development in the construction industry, which has practical guiding significance and can be widely applied in architecture. The advantages of BIM are that it could simulate the construction site and show the virtual construction process in advance. It could help PMs avoid unnecessary conflicts, rework problems during construction, reduce the waste of resources, save costs, and improve economic benefits. Hence, resource allocation schemes and schedules obtained from the model could be taken into BIM to the virtual construction process and check the rationality of resource allocation.

3. Materials and Method

The objective of this study is to design a new multi-objective optimization model that is also capable of simultaneously optimizing resource allocation in construction projects. This section develops the modeling approach of the multi-objective optimization and employs the real case of an industrial plant office building with a concrete structure to verify the validity of the proposed method.

3.1. Modeling Approach

The purpose of the multi-objective optimization model proposed in this study is to provide the PM with the optimal combination of time, cost, and EC and to arrange the resource allocation in the construction process. The flow diagram of the optimization modeling approach is shown in Figure 1. The process of the framework mainly comprises three essential stages: raw data management, parameter variable fitting analysis, and multi-objective optimization based on QGA. The raw data of the project is inputted into the model, and the PM can obtain the resource allocation arrangement that will eventually meet the constraint conditions. The following are the steps of the modeling approach.

Firstly, raw data need to be determined for every project. These data include the construction activities decomposed through a work breakdown structure (WBS); the original time, cost, and EC of each activity; and the resource allocation needed to perform the construction activity.

Second, the calculation function of time, cost, and EC needs to be determined as the mathematical basis. Additionally, the relationship models between time and resource allocation, cost and resource allocation, and EC and resource allocation are established, respectively. The aim of this section is to determine the optimal resource allocation plan along with satisfying the time, cost, and EC constraints.

Third, the variable parameter model established by Step 2 is substituted into the QGA. The Pareto solution set satisfying the constraint conditions in this project is found after the calculation, with the goals of the lowest cost, shortest time, and least EC.

The final output is the optimal combination of time, cost, and EC satisfying the constraint function and the resource allocation arrangements under each portfolio approach.
The PM can arrange the construction schedule and resource allocation plan according to the calculation results.

**Figure 1.** Optimization modeling approach.

### 3.1.1. Raw Data Management

In the model framework of this study, the raw data management includes (1) constraint construction objectives definition, (2) the WBS and activities break down of the project, and (3) resource allocation of each construction activity. A construction project must be divided into certain management elements, and the construction process is controlled through these elements. The project time, cost, and EC are essentially determined from each construction activity’s time, cost, and EC, respectively. Additionally, each construction activity performed depends on the resource allocation arrangement scheme. The overall and breakdown of activity time, cost, and EC relationship with resource allocation framework are shown in Figure 2. The WBS is an approach to decompose a project into numerous activities and to further arrange construction resources of each activity, including labor and machines, whose utilization will determine the time, cost, and EC of each construction activity and further make up the whole project’s time, cost, and EC.
The following notation is used:

(I) Index
- $i$ index of activity in a project, where $i = 1, 2, \ldots, I$;
- $k$ index of activity execution mode, where $k = 1, 2, \ldots, K$;
- $p$ index of the construction paths of the network, where $p = 1, 2, 3, \ldots, n$;
- $g$ index of the type of machine used in the construction activity.

(II) Certain Parameters
- $c_{ik}$ the direct cost of the $i$th activity;
- $c_0$ the indirect cost rates;
- $C_i$ the cost of the $i$th activity;
- $s_i$ the last time of the $i$th activity;
- $C_{ie}$ the minimum cost under the $e$th execution mode of the $i$th construction activity;
- $C_{in}$ the maximum cost under the $n$th execution mode of the $i$th construction activity;
- $d_{ik}$ the duration of the $i$th activity under the $k$th execution mode;
- $L_p$ the activity sequence should follow the $p$th path;
- $m_{ip}$ the sequence number of the $i$th activity on the $p$th path;
- $L$ the set of all paths of a network, where $L = \{L_p, p = 1, 2, 3, \ldots, n\}$;
- $D_{ie}^t$ the shortest time of the $e$th execution mode of activity;
- $D_{in}^t$ the longest time of the $n$th execution mode of activity;
- $E_i$ the energy consumption of the $i$th activity;
- $E_{mi}$ the machine energy consumption of the $i$th activity;
- $E_{li}$ the labor energy consumption of the $i$th activity;
- $P_{bi}$ the artificial energy consumption of the $i$th work each work shift;
- $E_o$ the other energy consumption;
- $E_{ie}$ the largest EC of the $e$th execution mode of the $i$th activity;
- $E_{in}$ the least EC of the $n$th execution mode of the $i$th activity.

(III) Uncertain Parameters
- $s_i$ the start time of the $i$th activity;
- $s_j(k)$ the start time of the $j$th activity;
- $C_i(k)$ the possible cost of the $i$th activity;
Decision variables

\( M_i \): the machine resource arrangement of the \( i \)th activity;

\( L_i \): the labor resource arrangement of the \( i \)th activity;

\( G_{ig} \): the mechanical grades of the \( g \)th machine used in the \( i \)th activity;

\( P_{ig} \): the mechanical work power of the \( g \)th machine used in the \( i \)th activity;

\( MT_{ig} \): the work shift of the \( g \)th machine used in the \( i \)th activity;

\( N_i \): the number of the labor in the \( i \)th activity;

\( MT_i \): the labor resource work shift of the \( i \)th activity.

Functions

\( C \): the total cost of the project construction;

\( T \): the total time of the project construction;

\( E \): the total energy consumption of the project construction.

(1) Construction cost

The objective is to minimize the construction cost, which consists of the direct cost and indirect cost of project [69]. Each construction activity has various execution modes, and each execution mode has a different cost. Equation (1) defines the execution mode of construction activities, and \((0,1)\) is used to determine if the current execution mode is selected for each construction activity [70]:

\[
m_{ik} = \begin{cases} 
1, & \text{activity } i \text{ is executed in mode } k \\
0, & \text{otherwise} 
\end{cases} \quad k = 1, 2, \ldots, M_i
\]  

(1)

where \( M_i \) is the number of the activities’ execution mode; if the execution mode is chosen, \( m_{ik} = 1 \). If the execution mode is not chosen, then \( m_{ik} = 0 \).

The following formula restricts each activity to only one execution mode:

\[
\sum_{k=1}^{M_i} m_{ik} = 1, \ i = 1, 2, \ldots, I
\]  

(2)

Each activity execution mode has a different cost, and the cost of the construction activity includes direct cost and indirect cost. Furthermore, the direct cost equals total direct cost of each construction activity, and the indirect cost is proportional to the time of the construction project. Equation (3) represents the calculation method of the cost of the \( i \)th activity. Equation (4) represents the total construction cost of the construction project [69]. Additionally, the execution mode of each activity should not exceed the maximum cost or fall below the minimum cost. In this case, the constraint is shown as Equation (5):

\[
C_i = c_0 s_i + \sum_{k=1}^{M_i} c_{ik} m_{ik}
\]  

(3)

\[
C = \sum_{i=1}^{n} c_0 s_i + \sum_{i=1}^{n} \sum_{k=1}^{M_i} c_{ik} m_{ik}
\]  

(4)

\[
s.t.
\]

\[
C_i^m \leq C_i^{(k)} \leq C_i^n
\]  

(5)

(2) Construction time

The objective is to minimize the construction time. There are priority constraints with activities, which are on the critical path in the construction process and embedded between the start time and finish time. Additionally, the start of an activity must take the finish of the prior activity as a prerequisite in the critical path. The total construction time equals
the construction period of the critical path. The relationship is expressed in the following inequation of Equation (6) [70]:

$$s_i + \sum_{k=1}^{M_i} m_{ik} d_{ik} \leq s_j$$

(6)

$T$ is the total time of the project construction, parameter $L_p$ indicates that the activity sequence should follow on the $p$th path, and $L_p = [m_{1,p}, m_{2,p}, \cdots, m_{i,p}]$, where $m_{i,p}$ represents the sequence number of the $i$th activity in the $p$th path. Parameter $L$ stands for the set of all paths of a construction network, and $L = \{L_p, p = 1, 2, 3, \cdots, n\}$, where $n$ indicates the number of all paths of the network [69]. Equation (7) indicates the total time of the project construction process. Equations (8) and (9) present the restricted conditions of the construction time of the $i$th activity in the calculation process:

$$T = \max_{L_p \in L} \left[ \sum_{i \in L_p} m_{ik} d_{ik} \right]$$

(7)

s.t.

$$T \leq T_{\text{max}}$$

(8)

$$D_{ei}^c \leq D_{ei}^{(k)} \leq D_{ei}^n$$

(9)

(3) Construction energy consumption

The objective is to minimize the EC of building construction, and the construction process analysis method for statistics in this part is adopted. The total EC of the project is equal to the sum of EC of each subitem as shown in Equation (10). The energy consumption of the $i$th task is equal to the sum of artificial energy consumption ($E_{li}$), mechanical energy consumption ($E_{mi}$), and other energy consumption ($E_o$) (including living energy consumption and working energy consumption in construction), which is shown in Equation (11). Equations (12) and (13) indicate the computational method of artificial energy consumption ($E_{li}$) and mechanical energy consumption ($E_{mi}$). The construction activities are decomposed according to WBS, the EC of each construction activity is calculated during normal construction and emergency construction situations, and the constraint relationship is shown in Equation (14).

$$E = \sum_{i=1}^{n} E_i$$

(10)

$$E_i = E_{mi} + E_{li} + E_o$$

(11)

$$E_{li} = P_i N_i MT_i$$

(12)

$$E_{mi} = \sum_{g=1}^{M_i} P_{ig} MT_{ig}$$

(13)

s.t.

$$E_{li}^c \leq E_{li}^{(k)} \leq E_{li}^n$$

(14)

(4) Labor resource arrangement

The labor resource arrangement in construction will affect the time, cost, and EC of each activity. The labor resources for each construction activity can be calculated by the following Equation:

$$L_i = N_i \times MT_i$$

(15)

$$L = \sum_{i=1}^{n} L_i$$

(16)
The total labor resource of the project is equal to the sum of each activity as shown in Equation (16).

(5) Machine resource arrangement

The types of machinery used in the construction activity are different and vary in type and quantity. In order to facilitate the calculation of this model, a unified machinery designation standard is adopted in this model as shown in Table 1. For example, according to the power of the machinery, if the mechanical value is between [0,100), the machine grade will be 1, and if the mechanical value is between [100,200), the machine grade will be 2, from which the other machines can be deduced. The unit of machine is KW. The machinery grade is designated, and the machinery used onsite is classified, as shown in Table 1.

The machine resource arrangement in construction will affect the time, cost, and EC of each activity. Since there are multitudinous mechanical resources, it is necessary to have a unified method to quantify the mechanical resource. In this model, the mechanical resources used in each construction activity are equal to the sum of the various mechanical grades multiplied by the working class. The machine resource of each activity can be calculated by the following equation:

\[
M_i = \sum_{g=1}^{G_i} (G_{ig} \times MT_{ig})
\]  

\[
M = \sum_{i=1}^{n} M_i
\]

The total machine resource of the project is equal to the sum of each activity.

| Name of Mechanical Equipment (M)                                | Machine Class (G_{ig}) |
|---------------------------------------------------------------|------------------------|
| Drilling machine                                             | 5                      |
| Truck-mounted crane                                          | 3                      |
| Lift pump (100 m)                                            | 2                      |
| Excavator                                                    | 1                      |
| Muck truck                                                   | 1                      |
| Motor pump                                                    | 2                      |
| Reinforcing steel cutter (GQL40)                             | 1                      |
| Reinforcement bar straightening machine                      | 1                      |
| Steel bar bender (GJ40)                                      | 1                      |
| Electroslag pressure welder (630)                            | 1                      |
| Electric welding machine                                     | 1                      |
| Tower crane (QTZ79)                                          | 1                      |
| Mortar mixer                                                 | 1                      |
| Construction elevator (SC200/200)                            | 1                      |
| Forklift truck (CPCD30C)                                     | 1                      |
| Floodlight                                                   | 1                      |
| Water suction pump (QY-15)                                   | 1                      |
| Mist cannon truck (100 m)                                    | 2                      |
| Concrete seam cutting machine (handheld)                     | 1                      |
| Portable pneumatic agitator                                  | 1                      |
| Concrete delivery pump truck                                 | 3                      |
| Water torch                                                  | 1                      |
| Cleaning machine                                             | 1                      |
| Portable pneumatic agitator                                  | 1                      |
| Electric bucket car                                          | 1                      |
| Electric hand drill                                          | 1                      |

3.1.2. Variable Parameter Fitting Analysis

In this section, the kernel establishes the relationship function between the labor, machine resource, and optimization target time, cost, and EC, in order to establish the multiobjective optimization model under the constraints. The input variables of the model
are the artificial and mechanical resources of each activity, and the output variables are the overall project time, cost, and EC. The labor and machine resource are inputted into each activity whose time, cost, and EC are influenced through a certain weight combination, respectively. Through variable parameter fitting analysis, the labor, machine, and time formula is established through this framework, and the labor and machine with cost and the labor and machine with EC are also established, respectively. Equation (19) is the total time of construction activities which are performed in a critical path. Equation (20) represents the sum of construction cost of the project, and Equation (21) represents the EC of the construction project.

\[ T = \sum_{i=1}^{n} f_1(M_i, L_i) + \theta_1 \]  

\[ C = \sum_{i=1}^{n} f_2(M_i, L_i) + \theta_2 \]  

\[ E = \sum_{i=1}^{n} f_3(M_i, L_i) + \theta_3 \]  

\( M_i \) and \( L_i \) are the machine and labor resources allocated in the \( i \)th activity. \( \theta_1, \theta_2, \) and \( \theta_3 \) are the error correction factors of Equations (19)–(21). With the state of normal construction as upper limit and emergency construction as lower limit for model optimization, Formulas (19)–(21) are performed as optimization functions to find the optimal resource combination scheme under constraint conditions of the goals of the shortest time, the lowest cost, and the least EC.

3.1.3. Multi-Objective Optimization Based on QGA

QGA is an evolutionary optimization algorithm that integrates quantum computation into the genetic algorithm. Compared with GA, QGA has the advantages of less iterations, high search efficiency, and wide adaptability, etc. In this study, a construction project consists of set of building elements and construction operations, each of which has different execution modes. The chromosome structure of the QGA for multi-objective optimization is shown in Figure 3. The length of every chromosome is \( N \), among which one cell corresponds to one construction activity. \( A_{ki} \) represents the execution mode selected for the \( j \)th solution of the \( i \)th activity.

**The length of chromosome N**

Solution 1

|  A_{11} | A_{21} | A_{31} | A_{41} | ... | A_{N1} |
|--------|--------|--------|--------|-----|--------|

...  

Solution K

|  A_{1K} | A_{2K} | A_{3K} | A_{4K} | ... | A_{NK} |
|--------|--------|--------|--------|-----|--------|

Figure 3. Chromosome structure diagram.

In the optimization process of QGA, the virtue or defect degree of the individual in the population is judged by the adaption degree. Generally speaking, the greater fitness of the individual is easier to be retained, and the fitness evaluation function is consistent with the objective function. Since the optimization objective function is to seek the minimum value of the objective function, the change of the objective function is

\[ Value1 = 1/C \]  

(22)
\[ Value_2 = \frac{1}{T} \]
\[ Value_3 = \frac{1}{E} \]

For this case, the optimal value of this model is as shown Equation (25). The fitness evaluation function is an important part of QGA, which will affect the search rate of the algorithm as well. The simpler the fitness evaluation function is, the shorter the search time of the program will take. In general, the search efficiency is faster when the fitness function evaluation is used to solve the maximum value. Therefore, considering that this calculation is the combination of the minimum value of time, cost, and EC, the objective function needs to be transformed to seek a simple fitness evaluation function in this design as Equation (25).

\[ OF = \text{Max}(\text{Value}_1, \text{Value}_2, \text{Value}_3) \] (25)

The flow chart of multi-objective optimization of QGA is shown in Figure 4. The first step is to collect the data of the construction project. The accuracy of the data of time, cost, and EC obtained according to the project contract and construction project schedule will significantly increase the performance of this study. The second step is to obtain the fitting objective of time, cost, and EC with resource allocation. This is the foundation of the multi-objective optimization problem. Additionally, the third step is to set up the multi-objective optimization function. The fourth step is to use the QGA to find the Pareto frontier, which could help the PM obtain the optimal resource allocation plan. In QGA process, the operational process of QGA is introduced, which includes population initialization, set population parameters, and chromosomal coding. The QGA increases the diversity of the solution set by means of updating the revolving door. A new population represents a new solution set and is judged by fitness evaluation to ascertain whether the current solution is superior to the previous solution.

Figure 4. Optimization flow chart of QGA.
3.2. Object of Case Study

The object case of this study is an industrial plant office building whose upper floor is 7 layers, with a construction area of 3493 m$^2$. The structure form is shear wall structure, and the total height of the building is 32.3 m. The time, cost, and EC in construction are selected as constraint targets, and the labor arrangement and mechanical resources are used as renewable resources to be allocated to construction activities. The optimal combination of resource allocation for construction activities is obtained with the goals of the shortest time, the lowest cost, and the least EC.

Table 2 shows the time, cost, and EC of each construction activity in construction of the building. According to the sequence of construction, the project is divided into 17 construction activity items, which indicates that $I = 17$. The cost of each construction activity is determined according to the contract and financial report signed by the project, the time required for each construction activity comes from the project schedule, and the EC data of the construction is calculated with the construction process analysis method. The data used in this case are shown in Table 2.

| No. | Activity                        | Time/Day | Cost/1 KY ($) | EC/GJ |
|-----|---------------------------------|----------|---------------|-------|
|     |                                 | Normal $D_i^n$ | Emergency $D_i^e$ | Normal $C_i^n$ | Emergency $C_i^e$ | Normal $E_i^n$ | Emergency $E_i^e$ |
| 1   | Construction preparation         | 1        | 0.5           | 0.1    | 0.3    | 0.74          | 0.75          |
| 2   | Supporting the precipitation     | 2        | 1             | 0.3    | 0.5    | 17.31         | 47.07         |
| 3   | Earth excavation                 | 8        | 6             | 6.2    | 8.5    | 8.42          | 19.1          |
| 4   | Foundation construction          | 25       | 17            | 3.1    | 5.4    | 45.06         | 66.71         |
| 5   | Structure of the first layer     | 10       | 7             | 52.35  | 59.37  | 37            | 68.49         |
| 6   | Structure of the 2nd layer       | 10       | 7             | 52.35  | 59.37  | 34.48         | 52.81         |
| 7   | Structure of the 3rd layer       | 10       | 7             | 52.35  | 59.37  | 26.68         | 50.81         |
| 8   | Structure of the 4th layer       | 9        | 6             | 49.8   | 57.69  | 26.39         | 48.45         |
| 9   | Structure of the 5th layer       | 9        | 6             | 51.8   | 57.69  | 26.893        | 48.45         |
| 10  | Structure of the 6th layer       | 9        | 6             | 51.8   | 57.69  | 26.89         | 48.45         |
| 11  | Structure of the 7th layer       | 9        | 6             | 51.8   | 57.69  | 28.31         | 50            |
| 12  | Rendering engineering            | 26       | 20            | 14.7   | 16.6   | 8.72          | 18.37         |
| 13  | Roofing engineering              | 6        | 5             | 15.1   | 17.5   | 4.79          | 6.25          |
| 14  | Floor engineering                | 8        | 6             | 30.2   | 33.6   | 5.78          | 9.12          |
| 15  | Insulation works                 | 8        | 6             | 7.4    | 9.2    | 4.44          | 8.12          |
| 16  | Waterproofing project            | 6        | 4             | 4.2    | 5.6    | 5.88          | 8.01          |
| 17  | Doors and windows project        | 10       | 8             | 90     | 98     | 36            | 45.26         |
Table 3. Resource allocation of each activity.

| No. | Activity                  | Labor ($L_i$)/MT | Machine ($M_i$)/MT |
|-----|---------------------------|------------------|--------------------|
|     |                           | Normal | Emergency | Normal | Emergency |
| 1   | Construction preparation  | 3      | 6        | 1      | 2         |
| 2   | Supporting the precipitation | 2      | 5        | 22     | 30        |
| 3   | Earth excavation          | 10     | 16       | 20     | 32        |
| 4   | Foundation construction   | 60     | 89       | 39     | 52        |
| 5   | Structure of the first layer | 56     | 84       | 34     | 48        |
| 6   | Structure of the 2nd layer | 56     | 84       | 34     | 48        |
| 7   | Structure of the 3rd layer | 56     | 84       | 34     | 48        |
| 8   | Structure of the 4th layer | 56     | 84       | 34     | 48        |
| 9   | Structure of the 5th layer | 56     | 84       | 34     | 48        |
| 10  | Structure of the 6th layer | 56     | 84       | 34     | 48        |
| 11  | Structure of the 7th layer | 56     | 84       | 34     | 48        |
| 12  | Rendering engineering     | 12     | 20       | 3.5    | 5         |
| 13  | Roofing engineering       | 15     | 25       | 4.5    | 7         |
| 14  | Floor engineering         | 8      | 15       | 3      | 6         |
| 15  | Insulation works          | 8      | 15       | 1      | 2         |
| 16  | Waterproofing project     | 6      | 10       | 2      | 4         |
| 17  | Doors and windows project | 10     | 15       | 9      | 15        |

4. Results and Discussion

The validity of the suggested model was shown in the construction of an industrial plant office building to represent the modeling process and the model’s abilities. The relationship models of time, cost, and energy consumption with resource allocation of various activities are first established. The constraint function includes (1) the model of resource allocation with time, (2) the model of resource allocation with cost, and (3) the model of resource allocation with EC. The project generates numerous construction activities through WBS decomposition, and the resource allocation of each activity will affect its time, cost, and energy consumption required for the construction completion, which then affects the whole project. According to the variable parameters of the project obtained in Section 3.2, the functional relationship model is as follows:

$$\begin{bmatrix}
T \\
C \\
E
\end{bmatrix} = \begin{bmatrix}
A & B & C \\
\end{bmatrix} \times X$$ (26)

where $A$ represents the time coefficient of the activity in the critical path, $B$ is the cost coefficient of each activity, and the construction activity’s coefficient of EC is $C$. $X$ denotes the combination of labor and machine resources. The constraint function is the basis of multi-objective optimization. The constraint function is brought into QGA to search for the optimal combination of time, cost, and energy consumption. Taking the shortest construction time, the lowest cost, and the least EC as the goals, the optimal combination of time, cost, and energy consumption and the optimal resource allocation scheme of each construction activity are sought for this project. Table 4 shows the parameter settings for the proposed QGA in this study which are defined through a contrast experiment. The quantum genetic algorithm is easily affected by the parameter design. If the parameter design is not reasonable, the advantage of the algorithm will be significantly reduced. The calculation time will greatly increase as well. Thus, the QGA parameter settings are generated through a contrast test and shown in Table 4. The process is realized by MATLAB2019b. The completion of the selected industrial plant project needs 166 days, the cost is CNY 5.3355 million, and the total energy consumption of the construction activities is 343,783 MJ according to the normal construction plan of the project.
Table 4. QGA parameter settings.

| Input Parameters        | Notation | Setting |
|-------------------------|----------|---------|
| Initial Angle           | IA       | 0.01π   |
| Population size         | NP       | 1000    |
| Variable dimension      | D        | 34      |
| Maximum generation      | G<sub>max</sub> | 400     |

This section analyzes the results of the experiment undertaken: Figure 5 records the evolution iteration process of time/cost/EC, respectively. All three targets are on a downward trend in the optimization process, which proves that the QGA proposed in this framework is an effective approach. Additionally, as the iteration increases, the curve remains horizontal in the end. This indicates that the algorithm is convergent and can reach the optimal value in the process of local evolution. As shown in Figure 5, when the number of iterations is about 160, the cost tends to be stable with the increase of iteration times. When the number of iterations is about 190, the time tends to be steady and does not decline. When the number of iterations is 170, the energy consumption tends to be stationary. This indicates that the optimal results of the construction time, cost, and energy consumption are convergent.

Figure 5. Time, cost, and EC iterative curve of QGA.

Figure 6 shows a typical Pareto optimal front obtained through QGA. This model performs well within a reasonably wide range of considering the time-cost-energy consumption of the project. It can be seen from the 3D scatter diagram that the Pareto solutions are relatively dispersed, and 83 optimal combinations are found among 400,000 possible combinations. The results indicating the Pareto solution of the optimal combination are shown graphically in Figure 6, which demonstrates that each point represents the optimal combination of construction activities under the constraints of time-cost-EC. This three-dimensional visualization of the trade-off could help the PM obtain the optimized process combination with elastic activities and evaluate the impact on the project performance of the various potential resource utilization plans.

Figure 6. Time-cost-energy consumption trade-off Pareto front using QGA.
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Figure 6. Time-cost-energy consumption trade-off Pareto front using QGA.

Table 5 lists the first 12 nondominated solutions in descending order of time, cost, and EC of the project, respectively, along with the optimal resource allocation of each activity. Solution 1 indicates the smallest project time, solution 4 generates the least cost of the project, and the minimum EC is demonstrated in solution 9. Other solutions strike a balance between the three targets. The PM could select the construction plan according to their preference. For example, if the PM want to accomplish the project in the shortest time, they could select solution 1. If the project is located in an area where environmental concerns are required, the PM could select solution 7. The project manager can arrange the construction and decide on the resource allocation according to the current activity combination, which is the optimal combination scheme satisfying the target condition constraints. The optimal results could help the PM shorten the construction time, decrease the cost, and reduce the EC of the project. The PM could be guided to a certain optimal resource arrangement according to their preferences. The optimal results indicate that this framework can effectively solve the problem of resource waste and idle resource problems on the construction site.

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Table 6 shows the optimal results of GA and QGA; it can be seen that the result from the QGA has slightly better performance compared with GA. Meanwhile, the QGA is superior in population renewal, the initial population size that is set to meet the population diversity is smaller, and the number of iterations required for evolution is also greatly reduced. However, when the parameter design is unreasonable, the advantage of the algorithm will be significantly reduced, and the calculation time of the algorithm will be greatly increased. Therefore, it is of great importance to determine the optimal parameters of the QGA. Table 6 shows the comparison of the experimental results between the GA and QGA.

The nondominated solutions may also be analyzed between any two objectives on a two-dimensional plane. Figures 7–9 show the relationship between time-cost, cost-EC, and EC-time, respectively. As shown in the time-cost curve example (Figure 7), the time and cost are negatively correlated, compressing time will lead the cost to gradually increase, and the rate of increase will slow down as the construction time continues to be compressed. This conclusion is consistent with previous studies [41,42,71–73]. As shown in the time-EC curve example (Figure 8), the time and EC are negatively correlated. The cost-EC curve demonstrated in Figure 9 shows that the EC has a positive correlation with cost, which is consistent with Cheng [74]. This demonstrates the reliability of the variable parameter fitting formula and QGA optimization results in this framework. The PM could also refer to this relationship when making decisions in project management.
### Table 5. The best nondominated solutions obtained by QGA.

| Solution | Partial Set | Activity | Project Performance |
|----------|-------------|----------|---------------------|
|          |             |          | Time | Cost | EC |
| 1        | Sorted by Time | 3 1 2 13 10 28 79 52 57 44 73 40 58 38 63 39 57 45 56 47 56 42 18 5 21 6 9 | 14 2 | 9 2 | 14 12 | 138.14 | 525.51 | 355,662.70 |
| 2        | 5 1 4 10 14 31 62 52 80 41 56 47 56 44 57 39 72 43 56 34 63 42 18 5 19 6 8 5 8 2 | 9 2 | 14 12 | 139.11 | 525.42 | 347,228.47 |
| 3        | 5 1 4 11 12 29 70 51 56 43 56 42 65 45 78 44 56 43 56 45 73 42 18 5 15 5 8 5 11 2 | 9 2 | 11 14 | 139.41 | 526.01 | 345,932.44 |
| 4        | Sorted by Cost | 4 1 3 12 16 20 63 51 56 36 58 41 57 36 57 35 57 36 56 44 56 35 18 4 15 6 9 5 9 2 | 7 3 | 10 9 | 153.62 | 503.56 | 282,754.93 |
| 5        | 5 1 4 13 11 22 63 43 56 34 56 37 56 36 56 37 56 43 56 40 56 34 19 5 18 5 9 5 12 1 | 6 2 | 10 13 | 155.74 | 504.18 | 280,071.75 |
| 6        | 4 1 2 10 15 24 64 48 60 34 58 41 56 34 57 35 58 34 56 36 70 34 15 5 18 5 9 3 | 11 1 8 3 | 10 13 | 157.44 | 504.27 | 271,728.91 |
| 7        | Sorted by EC | 4 1 2 10 15 24 64 48 60 34 58 41 56 34 57 35 58 34 56 36 70 34 15 5 18 5 9 3 | 11 1 8 3 | 10 13 | 157.44 | 504.27 | 271,728.91 |
| 8        | 5 1 3 13 13 25 60 48 56 44 56 47 58 34 57 34 57 36 64 34 64 34 14 4 | 16 6 | 10 5 12 2 | 9 2 | 10 10 | 153.63 | 510.34 | 2792.48 |
| 9        | 4 1 2 11 13 20 68 40 58 47 61 43 56 35 65 34 56 36 57 38 58 39 20 4 | 16 5 8 5 13 2 | 8 2 | 10 14 | 156.93 | 510.43 | 272,281.17 |
| 10       | Compromised | 3 1 4 10 12 28 65 51 56 35 56 44 56 37 59 46 56 36 72 38 72 36 19 5 | 20 4 9 3 | 12 2 | 8 2 | 10 13 | 144.99 | 515.75 | 309,346.21 |
| 11       | 5 1 3 11 15 22 60 52 56 39 58 48 56 35 66 38 58 34 63 48 66 43 19 5 | 24 6 | 10 6 10 2 | 9 2 | 10 13 | 144.04 | 517.31 | 310,709.16 |
| 12       | 5 1 2 13 15 24 79 52 56 36 58 43 56 42 58 36 56 44 56 42 58 39 15 5 | 17 6 | 9 5 9 1 | 10 2 | 13 13 | 147.28 | 510.81 | 311,016.29 |
Table 6. The comparison of results between GA and QGA.

| Population Size | Iterative Convergence | Iterative Termination | Optimal Result |
|-----------------|-----------------------|-----------------------|----------------|
|                 | Iteration | Time    | Iteration | Time    | Cost   | Time   | EC    |
| GA              | 1200      | 2300    | 30.2 min | 4500    | 41.6 min | 536.67 | 138.14 | 356,541.2 |
| QGA             | 1000      | 160     | 21.1 min | 400     | 26.5 min | 525.51 | 138.14 | 355,662.7 |

Figure 7. Time-cost trade-off analysis.

Figure 8. Time-EC trade-off analysis.

Figure 9. Cost-EC trade-off analysis.
The optimization results obtained from the calculation could provide scientific guidance for the PM in the decision making of resource allocation and schedule management. However, as project construction activity has the characteristics of practicality and dynamism [75], a resource allocation plan made in advance may have conflicts or ill-considered problems in the actual construction process [76,77]. Therefore, this design introduces the BIM technology as a complement to the resource allocation plan and multi-objective optimization result in this framework. The advantages of BIM can simulate the construction site and show the virtual construction process in advance [78]. It could help PMs avoid unnecessary conflicts and rework problems during construction and reduce the waste of resources, save costs, and improve economic benefits [79–81]. Hence, the resource allocation scheme and the schedule obtained from the model are taken into BIM to the virtual construction process and checked for the rationality of resource allocation scheme.

Figure 10 is the industrial plant building model. Figure 11 is the resource scheduling data import page. According to the optimized time arrangement and resource arrangement, Timeliner is used to carry out a collision check on the scheme and virtual construction process. The construction schedule is simulated according to the current resource allocation plan, and the rationality of the resource allocation can also be tested.

![Figure 10. Interface diagram of industrial plant.](image1)

![Figure 11. Resource scheduling data import page.](image2)
The BIM virtual construction process can test the optimization results of the algorithm. The PM can simulate the resource arrangement and schedule the arrangement in advance, and the unreasonable optimization results obtained in this framework can be eliminated. Finally, the optimal result can guide the project manager to make scientific decisions effectively.

5. Conclusions

This paper presented a multi-objective optimization framework of time, cost, and EC and analyzed the relationship of the three targets with the resource allocation of a project. The building project was decomposed into construction activities through WBS. Each activity was distributed with different construction resource, respectively, and the combination of the construction resources determined the performance of the project, including time, cost, and EC. The contribution of this study is to establish a framework which could help PMs find the best resource allocation scheme with the goals of shortening the construction time, decreasing the cost, and reducing the EC of a project. PMs could be guided to a certain optimal resource arrangement according to their preferences. The framework proposed by this study can effectively solve the problem of resource waste and idle resource problems on the construction site.

The proposed framework of this study has the potential to elevate the state of project management in construction resource administration. It could help PMs develop resource arrangement plans and construction schedules according to construction time, cost, and energy consumption requirements. The framework provides contributions to saving costs, shortening construction time, and effectively reducing construction energy consumption in the case of meeting construction requirements. The QGA was adopted to find the Pareto solution set to demonstrate the optimal combination scheme of various construction activities. PMs could allocate the labor and machinery of each activity according to the optimal Pareto solution. This framework can effectively solve the resource waste problem in practical construction management.

The model was applied to a case study of an industrial factory office building. The application demonstrated model’s usefulness and facilitated its evaluation. Additionally, this could help PMs create the best combination scheme of project construction activities in practical engineering management. This framework could provide PMs with optimal resource allocation schemes, and the optimal construction process could be simulated in BIM to verify the effectiveness of the resource allocation scheme. The result of the case study shows that according to the optimized construction resource arrangement plan, PMs can effectively shorten the construction time, save costs, and reduce energy consumption. The performance of the case demonstrates that this framework has guiding significance for PMs in decision making in actual project management.

This study has limitations and offers directions for new research. In practical engineering management, construction resources include more than manual labor and machinery, and a more detailed resource allocation plan should be taken into consideration. In further works, a statistical survey which contains more comprehensive resource planning will solve this issue.

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