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Original Article

Some Assignment Problems and its Applications in Hydraulic Engineering

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Abstract:
The problem of allocating human resources efficiently in hydraulic engineering is one of the key factors to improve the overall efficiency of the project. This study proposes an optimization approach of human resources in hydraulic engineering based on time-limited task assignment model. Under the conditions of time constraints, the minimal cost and the maximal satisfaction are taken as the objective functions, and the Hungarian algorithm and MATLAB program are used to solve the model, so as to obtain the optimal staffing scheme. For different types of time-limited task assignment models, the corresponding solution is also proposed. The calculation results of cases show that the model can reasonably allocate the limited human resources in the hydraulic engineering project, realize the cost minimization and work satisfaction maximization, save the cost, improve the work efficiency, shorten the construction period, and provide sufficient guidance for the smooth implementation of the project.

1. Introduction

Human resource is the key factor of enterprise development, therefore the reasonable and effective allocation of human resources is the premise of improving the overall efficiency of enterprise organization. The rational allocation of human resources is not only realizing the project schedule, cost, and quality goals, but also achieving enterprise strategic goals crucially [1]. With the development of hydraulic engineering construction and reform in China, the traditional method of determining posts and staff has lost the flexibility to respond to changes under the system and environment of complex hydraulic engineering management in recent years. How to efficiently allocate the limited human resources in hydraulic engineering projects has become an urgent practical problem for researchers to solve. At present, some researchers have made some research results in this aspect, but all have their own shortcomings.

Fang et al. put forward research on the flexible staffing model of hydraulic engineering, which improves the utilization rate of human resources based on labor-workload balance [2]. Peng pointed out that the linear programming assignment model was an effective resource optimal allocation model, and it could maximize the role of resources [3]. Sun showed that the linear programming assignment model could calculate the solution accurately and objectively when the optimal effect was reached, which had strong promotion and used the value for the optimal source allocation of human resources in related fields [4]. In the mathematical model of dual-criteria resource allocation problem, Shen allocated M employees to n different projects to maximize profits and minimize costs under resource constraints and extended the dual-criteria integer programming model into a new mathematical model of multi-objective optimization [5]. In the dual-criterion resource allocation problem, n different tasks are assigned to M employees to maximize profits and minimize costs under resource constraints. Liu and Xu used the assignment model to solve the job assignment scheme by establishing the individual ability matrix of employees and the fuzzy set of job satisfaction degree, which was based on the work allocation algorithm with fuzzy relations [6]. Feng et al. proposed the assignment model based on constraint conditions, but did not give the corresponding algorithm [7]. Liu et al. combined the assignment model and grey situation decision method to the optimal allocation of enterprise human resources and analyzed the assignment model and grey situation decision method [8]. Chen and Fan proposed an assignment method based on research field matching degree to solve the assignment problem in scientific research project evaluation [9]. Cheng et al. established an uncertain multi-factor assignment model based on interval number and verified it with relevant examples under the condition of the uncertainty of multi-factor resource optimal allocation problem [10]. Zheng et al. studied the optimal allocation of human resources through the use of a linear assignment model [11]. But the existing assignment model only considered the cost factor and completely ignored the influence of time factor on resource allocation. Arikan and Sozen presented a hierarchical solution approach for occupational health and safety (OHS) inspectors' task assignment problem [12]. This approach was expected to offer fruitful inspiration in the area of safety management and policy, and it provided a better guidance for social policy and organizational aspects in the field of OHS inspectors' task assignment. Wang et al. proposed a time-triggered dimension reduction algorithm for the task assignment problem. Optimality and computational efficiency are verified via numerical simulations on benchmark examples [13]. Poudel and Moh put forward task assignment algorithms for unmanned aerial vehicle networks [14]. Zeng et al. presented the main idea of Hungarian method and put up three implementations for Hungarian method [15]. The three implementations were DFS (Depth-First Search) single-augmented method, BFS (Bread-First Search) single-augmented method and Multi-augmented method. Elsisy et al. used interval operations in the Hungarian method to solve the fuzzy assignment problem and applied them in the rehabilitation problem of valuable buildings [16]. Quazzafi et al. proposed a modified Hungarian method for solving unbalanced assignment problems, which gave the optimal policy of assignment of jobs to machines [17]. Huang et al. presented a practical resilience assessment framework for tunnels subjected to earthquakes and the resilience quantifications were examined and assessed [18]. Aye et al. presented multi-fidelity multi-objective infill-sampling surrogate-assisted optimization for airfoil shape optimization [19]. Panagant et al. investigated many-objective truss structure problems from small to large-scale problems with low to high design variables [20]. Kumar et al. proposed the multi-objective multi-verse optimizer for dealing with multi-objective structure optimization problems [21]. Nonut et al. proposed a novel method for system identification of small-scale fixed-wing Unmanned Aerial Vehicles (UAVs) using a metaheuristics (MHs) approach [22]. Singh et al. presented an improved version of follow the leader (iFTL) algorithm that imitated the behavioral movement of a sheep within the flock [23]. These literatures were all about the multi-objective optimization, but they didn't analyse the optimization of different objects for different tasks

Considering the influence of time, cost, task, labor amount, work satisfaction factors, and the relationship of these related factors on the progress of the project and the completion of the work, all above studies use the assignment model or regression model for analysis on engineering project. In the present study, a new time-limited task assignment model is established. The objective functions are cost minimization and work satisfaction maximization. Taking into account the difference of task cost and work satisfaction caused by different working techniques in "Yin Jiang Ji Huai" canal project in China, the human resource allocation models are set up under the constraint condition of completing the task with the minimum cost in the specified time, and the Hungarian algorithm is used to solve the models.

2. Materials and Methods

The Task Assignment Problem (TAP) is proposed that there are a number of resources and a number of tasks, how to optimize and allocate the resource scientifically and reasonably, to maximize the economic and social benefits, or to minimize the cost of completing these tasks, so that the overall effect of the assignment scheme is best. For the assignment problem in its standard form, it means to determine the optimal assignment scheme for individuals to complete the work given the efficiency matrix, to assign the "task" to the "person" in the best way according to the one-to-one principle [24]. The mathematical model resulting from this problem is also known as the assignment model, which is essentially a 0-1 programming problem [25]. The TAP problems can be divided into the following categories (see Fig. 1).

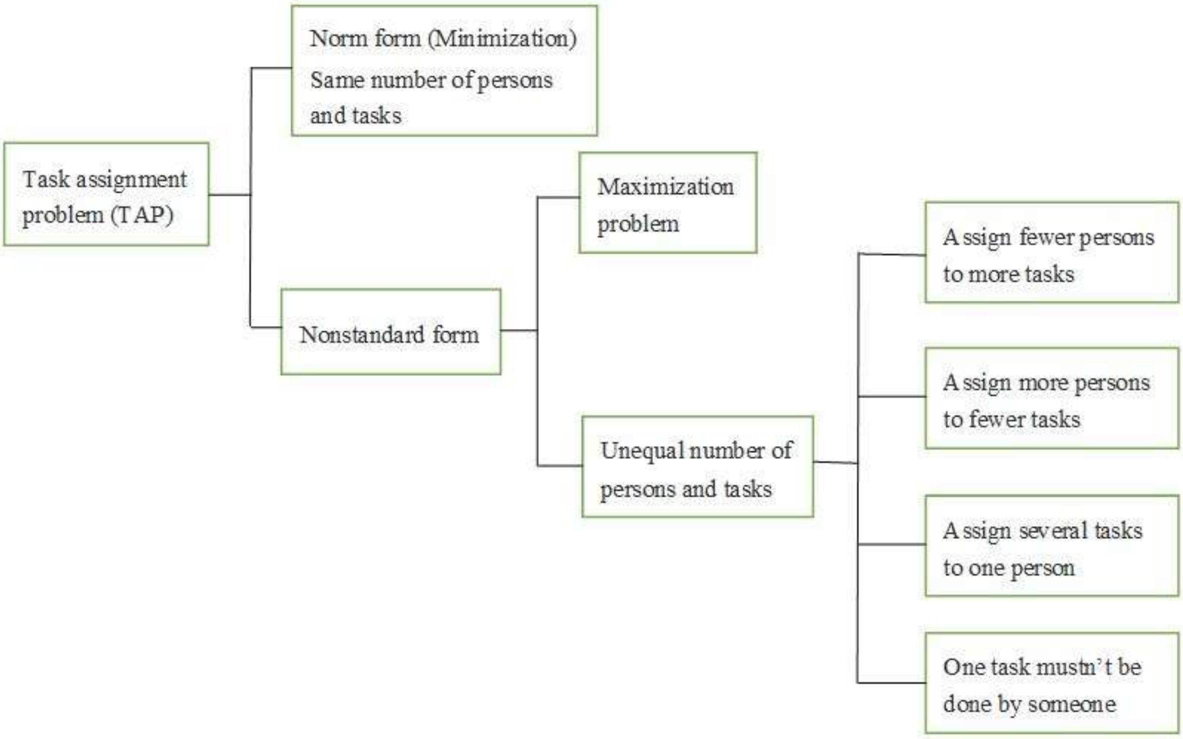

Figure 1: Classification of TAP problems

2.1. Normal form of Assignment Model

Denote X_{ij} the personnel A_i to complete the task B_j, and let:

$$X_{ij} = \begin{cases} 1, & assigning\ A_i\ to\ do\ B_j\ work \\ 0, & not\ assigning\ A_i\ to\ do\ B_j\ work \end{cases} \quad i = 1,2,\dots,n; j = 1,2,\dots,n$$

Given that A_i accomplishes B_j with C_{ij} efficiency, the formulation of the generalized assignment problem is as follows:

$$minZ = \sum_{i=1}^{n} \sum_{j=1}^{n} C_{ij} X_{ij} \qquad (1)$$

$$s.t. \begin{cases} \sum_{i=1}^{n} X_{ij} = 1, \quad j = 1,2,\dots,n \\ \sum_{j=1}^{n} X_{ij} = 1, \quad i = 1,2,\dots,n \\ X_{ij} \in \{0,1\}, \quad i,j = 1,2,\dots,n \end{cases}$$

2.2. Nonstandard form of Assignment Model

In practical applications, we often encounter various nonstandard forms of assignment problems, which are also called generalized assignment problems. The processing method is to convert them into a standard form firstly and then solve them by the Hungarian algorithm.

2.2.1. Maximization Assignment Problem

The objective function of the maximization assignment problem is as follows:

$$maxZ = \sum_{i=1}^{n}\sum_{j=1}^{n} C_{ij}X_{ij} \tag{2}$$

For the above assignment problem, let $M = \max\{C_{ij}\}$, A new efficiency matrix can be constructed $\left(M - C_{ij}\right)_{n\times n}$, apparently $\left(M - C_{ij}\right)_{n\times n} \geq 0$.

$$\sum_{i=1}^{n}\sum_{j=1}^{n}\left(M - C_{ij}\right)X_{ij} = \sum_{i=1}^{n}\sum_{j=1}^{n} MX_{ij} - \sum_{i=1}^{n}\sum_{j=1}^{n} C_{ij}X_{ij} = nM - \sum_{\mathrm{i=1}}^{\mathrm{n}}\sum_{\mathrm{j=1}}^{\mathrm{n}} \mathrm{C_{ij}X_{ij}} \tag{3}$$

Making an optimal solution to $min\sum_{i=1}^{n}\sum_{j=1}^{n}\left(M - C_{ij}\right)X_{ij}$ is making an optimal solution to $maxZ = \sum_{i=1}^{n}\sum_{j=1}^{n} C_{ij}X_{ij}$, so as to

$$maxZ = \sum_{i=1}^{n}\sum_{j=1}^{n} C_{ij}X_{ij} = nM - min\sum_{i=1}^{n}\sum_{j=1}^{n}\left(M - C_{ij}\right)X_{ij} \tag{4}$$

2.2.2. Assignment problems with unequal number of persons and tasks

(1) The problem of assigning fewer persons to more tasks

Denote X_{ij} the personnel A_i to complete the task B_j, $i = 1,2,\dots,m; j = 1,2,\dots,n$, in $m < n$, C_{ij} is for work efficiency. For the assignment problem with fewer people and more tasks, the mathematical model can be written as follows:

$$minZ = \sum_{i=1}^{m}\sum_{j=1}^{n} C_{ij}X_{ij} \tag{5}$$

$$s.t.\begin{cases}\sum_{i=1}^{m} X_{ij} \leq 1, & j = 1,2,\dots,n\\ \sum_{j=1}^{n} X_{ij} = 1, & i = 1,2,\dots,m\\ X_{ij} \in \{0,1\}, & i = 1,2,\dots,m; j = 1,2,\dots,n\end{cases}$$

Since the efficiency matrix of the Hungarian algorithm is required to be a square matrix, some virtual people can be added in the actual solution, so that the number of people is the same as the number of tasks, and the efficiency of these virtual people in each task is zero.

(2) The problem of assigning more persons to fewer tasks

Denote X_{ij} the personnel A_i to complete the task B_j, $i = 1,2,\dots,m; j = 1,2,\dots,n$, in $m > n$, C_{ij} is for work efficiency. For the assignment problem with more people and fewer tasks, the mathematical model can be written as follows:

$$minZ = \sum_{i=1}^{m}\sum_{j=1}^{n} C_{ij}X_{ij} \tag{6}$$

$$s.t.\begin{cases}\sum_{i=1}^{m} X_{ij} = 1, & j = 1,2,\dots,n\\ \sum_{j=1}^{n} X_{ij} \leq 1, & i = 1,2,\dots,m\\ X_{ij} \in \{0,1\}, & i = 1,2,\dots,m; j = 1,2,\dots,n\end{cases}$$

Similar to the above assignment problems with fewer people and more tasks, in the specific solution, the dummy task can be added which are completed with an efficiency of zero.

(3) The problem of assigning several tasks to one person

If a person can complete several tasks, he can be considered as the same several people to accept the assignment, who complete the same task is equally effective.

(4) The problem of assignment work that must not be done by someone

If a task must not be completed by a single person, the corresponding efficiency value can be set to a large enough number when solving the minimum problem. When solving the maximum problem, the corresponding efficiency value can be set to zero, and then the model is assigned to solve according to the maximization of the objective function.

2.3 The Hungarian Method for the Assignment Problem

In addition to 0-1 programming, there is also a special method to solve the assignment problem using the Hungarian algorithm. This approach is a kind of graph-theoretic algorithm for assigning problems proposed by the famous Hungarian mathematician (D. Konig) and improved and developed by the American mathematician (H.W. Kuhn), therefore the Hungarian method of assignment is established.

2.3.1 Basic Principles of the Hungarian Algorithm

The Hungarian algorithm for solving assignment models has the following two properties:

Property 1: If a constant k (which can be positive or negative) is subtracted from each element of any row/column of the efficiency matrix C to obtain a new matrix F, then the assignment problem with F as the efficiency matrix has the same solution as the original problem, but its optimal value is less than k of the original problem's optimal value.

Property 2: If some elements in a square matrix are aero and some elements are nonzero, then the minimum number of lines covering all zero elements in the square matrix is exactly equal to the maximum number of zero elements located in different rows and different columns, i.e., the maximum number of independent zero elements in the matrix is equal to the minimum number of lines covering all zero elements.

2.3.2, The Main Steps of the Hungarian Algorithm

The main calculation steps of Hungarian algorithm are as follows:

Step 1. Transform the efficiency matrix C of the assignment problem so that zero elements appear in each row and column, and a new efficiency matrix F is obtained. The specific implementation method is following:

(1) Subtract the smallest element of each row from the coefficient matrix;

(2) Subtract the smallest element from each column of the resulting coefficient matrix.

Step 2. Make a trial assignment:

(1) Check every row and column of F, determine the row/column with the least zero elements, and circle zero element. If there are more than one zero element in the row, circle any one, and then cross out the row and column where the zero element is. Repeating the above process in the remaining submatrix until there is no zero element in the remaining submatrix, and the resulting matrix is denoted as D. Assign one to the circled position in D, and zero to the remaining position to get the 0-1 matrix E;

(2) If the number of elements one in E is the same as the dimension of the efficiency matrix, i.e., they must be neither in the same row nor in the same column, then the matrix E is the optimal solution matrix of the original assignment problem, and the algorithm stops; otherwise, go to Step 3.

Step 3. Make a set of lines that can at least cover all zero elements and operate on matrix D as follows:

(1) Check the row lines that are not circled;

(2) Check the column in which all zero elements in the ticked row are located;

(3) Check the circled row lines on the ticked columns;

(4) Repeat (2) and (3), until no new checkmarked rows and columns can be found.

Drawing horizontal lines for the unchecked rows and vertical lines for all checked columns and the smallest set of lines that cover all zero elements are got.

Step 4. Adjust the efficiency matrix:

Find the smallest element in the part of the element that is not covered by a line and subtract it from every element in the row that is not covered by a line; add this minimum element to each element of the column with the line drawn, and the new efficiency matrix is still denoted as F. Go to step 2.

2.3.3 The program flow chart of Hungarian algorithm

According to the calculation steps of the above algorithm, the following program flow chart can be obtained (see Fig. 2).

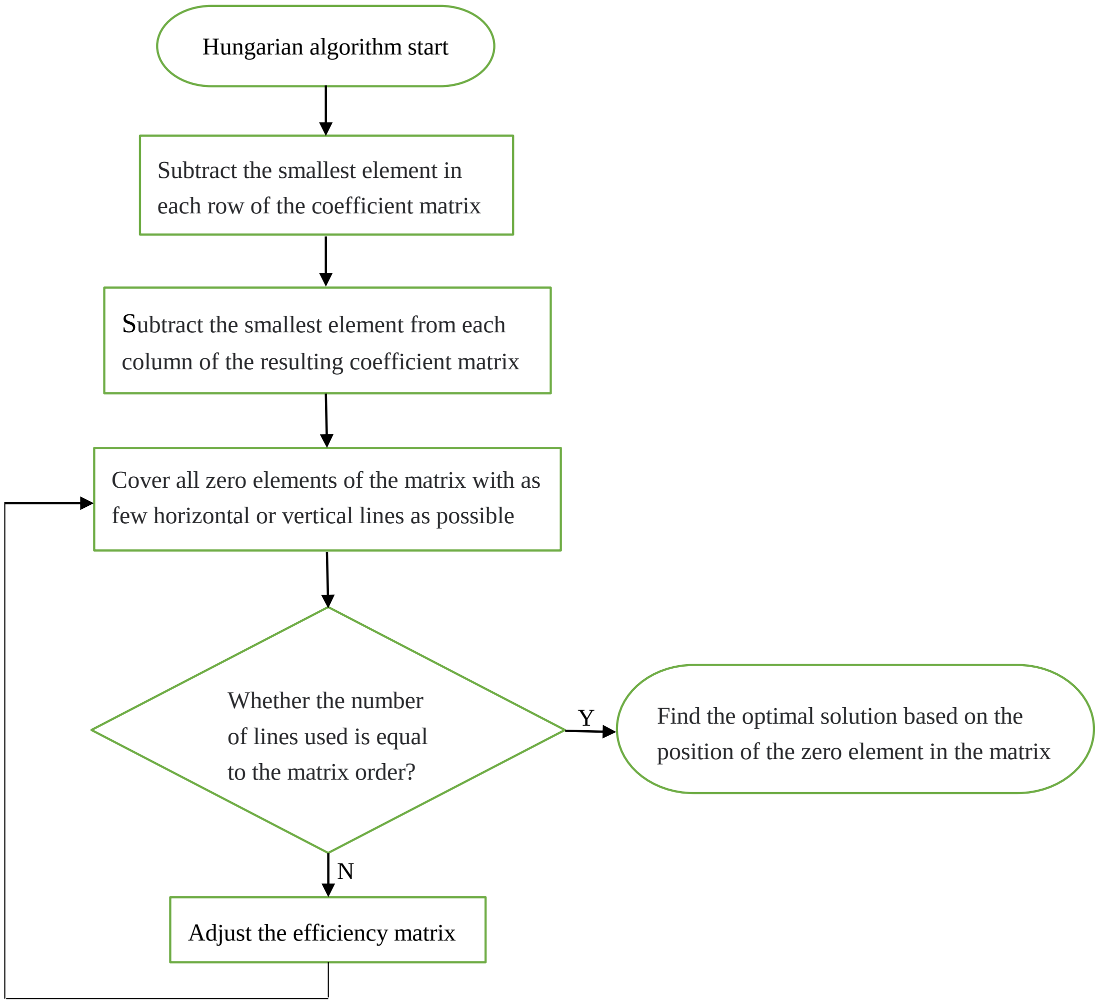

Figure 2: The program flow chart of Hungarian algorithm

3. Cases Analysis and Discussion

In Anhui segment of "Yin Jiang Ji Huai" canal project in China, in order to ensure the engineering quality, it distributed a range of testing tasks for the third part testing unit that should arrange personnel to complete the corresponding detection. Each test can only arrange one person to complete, the person can't do other testing tasks at the same time, and all testing tasks are completed in one day. Tasks (B row) are represented at the top-right of all tables and the left column in all tables is the person (A column). The middle numbers are either cost or satisfaction.

3.1. The Problem of the Same Number of Persons and Tasks

There are six detection tasks in total, which are completed by six different people. In the prescribed time of one day, the cost of each person to complete each detection task is shown in

Table 1 below. What assignment minimizes the total cost for six people to complete six tasks?

Table 1: Cost of each person to complete each detection task (Unit: Thousand Yuan).

	B_1	B_2	B_3	B_4	B_5	B_6
A_1	2	13	1	3	6	14
A_2	7	3	1	15	9	4
A_3	11	12	10	7	2	2
A_4	13	14	3	5	1	13
A_5	4	3	13	5	7	4
A_6	4	4	3	5	13	10

The assignment model can be established in the standard form as shown in Equation (1), which used the Hungarian algorithm to calculate the minimal total cost 14 thousand yuan required for six people to complete six tasks by MATLAB program. The optimal solution shown in the red box in Table 1 is $X_{11}=1$, $X_{23}=1$, $X_{36}=1$, $X_{45}=1$, $X_{52}=1$, $X_{64}=1$, the other variables are all zero. The total cost required is the lowest (minimal cost $Z=C_{11}+C_{23}+C_{36}+C_{45}+C_{52}+C_{64}=14$ thousand yuan). The best assignment scheme is to assign A_1 to complete the B_1 task, A_2 to complete B_3 task, A_3 to complete B_6 task, A_4 to complete B_5 task, A_5 to complete B_2 task, and A_6 to complete B_4 task.

3.2. Satisfaction Maximization Task Problem

The satisfaction of the above hydraulic engineering testing task is investigated. If the testing cost is understood as satisfaction, the satisfaction results as shown in Table 2 can be acquired. How to schedule the tests so that the overall satisfaction is the highest?

Table 2: Testing of task satisfaction.

	B_1	B_2	B_3	B_4	B_5	B_6
A_1	2	13	1	3	6	14
A_2	7	3	1	15	9	4
A_3	11	12	10	7	2	2
A_4	13	14	3	5	1	13
A_5	4	3	13	5	7	4
A_6	4	4	3	5	13	10

From the discussion of the maximization assignment problem above, the maximum number 15 among the satisfaction parameters is selected, and each satisfaction parameter in the satisfaction table is subtracted by the maximum number, and the new table is shown in Table 3 below. Where M is equal to $\max\{C_{ij}\}$ (M=15). Therefore, only the minimal problem corresponding to Table 3 needs to be solved to obtain the maximally resolved solution of the original problem. According to the calculation results of Equation (4), the Hungarian algorithm is still used to solve the problem. The optimal solution shown in the red box in Table 3 can be obtained from the program running results as $X_{16}=1$, $X_{24}=1$, $X_{31}=1$,

X_{42}=1, X_{53}=1, X_{65}=1, and the other variables are zero, and the optimal solution of this minimization problem is 10 (the minimal value $Z=C_{16}+C_{24}+C_{31}+C_{42}+C_{53}+C_{65}=10$). It can be seen that the optimal solution of the corresponding maximization problem shown in the blue box in Table 2 is also X_{16}=1, X_{24}=1, X_{31}=1, X_{42}=1, X_{53}=1, X_{65}=1, the other variables are zero, and the maximal satisfaction is 80 (the maximal satisfaction $Z=C_{16}+C_{24}+C_{31}+C_{42}+C_{53}+C_{65}=80$). Therefore, the best scheme of assigning A_1 to complete B_6 task, A_2 to complete B_4 task, A_3 to complete B_1 task, A_4 to complete B_2 task, A_5 to complete B_3 task, and A_6 to complete B_5 task can achieve maximum satisfaction.

Table 3: values of $M - C_{ij}$ (M=15).

	B_1	B_2	B_3	B_4	B_5	B_6
A_1	13	2	14	12	9	1
A_2	8	12	14	0	6	11
A_3	4	3	5	8	13	13
A_4	2	1	12	10	14	2
A_5	11	12	2	10	7	11
A_6	11	11	12	10	2	5

3.3. The Problem of Assigning Fewer Persons to More Tasks

For the above hydraulic engineering detection task problem, there are still six tasks, but only four persons, and each detection task can be completed by at most one person, each person must and only needs to complete one detection task, and the required detection cost is shown in Table 4. Try to determine the assignment scheme that minimizes the total test cost.

Table 4: Testing cost of each person to complete the corresponding task (Unit: Thousand Yuan).

	B_1	B_2	B_3	B_4	B_5	B_6
A_1	13	10	5	2	7	5
A_2	8	6	3	10	13	4
A_3	3	12	3	6	12	5
A_4	10	8	11	13	5	9

In accordance with the corresponding discussion in the second part of this paper, its mathematical model can be established according to Equation (5), and Table 4 can be rewritten into Table 5 as follows, where A5 and A6 displayed in red font are the new virtual person, and their corresponding detection costs are zero. The running results of the Hungarian algorithm program are that the optimal solution shown in the red box in Table 5 is X_{14}=1, X_{23}=1, X_{31}=1, X_{45}=1, X_{52}=1, X_{66}=1, and the other variables are all zero. The best scheme is to assign A_1 to complete task B_4, A_2 to complete task B_3, A_3 to complete task B_1, and A_4 to complete task B_5. At this time, the total testing cost required is the lowest (minimal cost $Z=C_{14}+C_{23}+C_{31}+C_{45}$=13 thousand yuan).

Table 5: Detection cost after adding virtual person (Unit: Thousand Yuan).

	B_1	B_2	B_3	B_4	B_5	B_6
A_1	13	10	5	2	7	5
A_2	8	6	3	10	13	4
A_3	3	12	3	6	12	5
A_4	10	8	11	13	5	9
A_5	0	0	0	0	0	0
A_6	0	0	0	0	0	0

3.4. The Problem of Assigning More Persons to Fewer Tasks

Similarly, for the detection task problem in the hydraulic engineering, there are six people, but there are only 4 detection tasks, and each detection task can only be completed by one person at most, and each person can only do one job at most. The required testing cost is shown in Table 6. Try to find the assignment scheme that minimizes the total detection cost.

Table 6: The testing cost per person to complete the corresponding task (Unit: Thousand Yuan).

	B_1	B_2	B_3	B_4
A_1	13	10	3	2
A_2	6	9	15	8
A_3	6	12	4	13
A_4	11	14	4	3
A_5	8	6	13	7
A_6	7	13	11	10

In a similar way, according to Equation (6), Table 6 can be rewritten into Table 7 as follows, where B_5 and B_6 displayed in red font are the new virtual tasks, and the cost of each tester to complete these two tasks is zero. The optimal solution of the problem shown in the red box in Table 7 can be obtained as X_{13}=1, X_{25}=1, X_{31}=1, X_{44}=1, X_{52}=1, X_{66}=1 (or X_{14}=1, X_{25}=1, X_{31}=1, X_{43}=1, X_{52}=1, X_{66}=1, which is displayed in red dotted box, at the same time, the values of X_{13} and X_{44} are zero. or X_{14}=1, X_{21}=1, X_{36}=1, X_{43}=1, X_{52}=1, X_{65}=1, which is displayed in blue solid box, or X_{13}=1, X_{21}=1, X_{36}=1, X_{44}=1, X_{52}=1, X_{65}=1, which is displayed in blue dotted box, meanwhile, the values of X_{14} and X_{43} are zero.) by the Hungarian algorithm calculation program, and the other variables are all zero. The best scheme is to assign A_1 to complete B_3 task, A_3 to complete the B_1 task, A_4 to complete B_4 task, and A_5 to complete B_2 task, or to assign A_1 to complete B_4 task, A_3 to complete the B_1 task, A_4 to complete B_3 task, and A_5 to complete B_2 task, or to assign A_1 to complete B_4 task, A_2 to complete B_1 task, A_4 to complete B_3 task, and A_5 to complete B_2 task, or to assign A_1 to complete B_3 task, A_2 to complete B_1 task, A_4 to complete B_4 task, and A_5 to complete B_2 task. At this time, the total testing cost required is the lowest (the minimal cost $Z=C_{13}+C_{31}+C_{44}+C_{52}+C_{25}+C_{66}=C_{14}+C_{31}+C_{43}+C_{52}+C_{25}+C_{66}=C_{14}+C_{21}+C_{43}+C_{52}+C_{36}+C_{65}=C_{13}+C_{21}+C_{44}+C_{52}+C_{36}+C_{65}=18$ thousand yuan). There are four groups of optimal solutions, but the minimal cost of each group is the same.

Table 7: Testing cost after adding virtual tasks (Unit: Thousand Yuan).

	B_1	B_2	B_3	B_4	B_5	B_6
A_1	13	10	3	2	0	0
A_2	6	9	15	8	0	0
A_3	6	12	4	13	0	0
A_4	11	14	4	3	0	0
A_5	8	6	13	7	0	0
A_6	7	13	11	10	0	0

When one person can accomplish more than one task, this person can be increased to the same several people, and then the efficiency matrix is transformed into a square matrix structure, and the Hungarian algorithm is still used to solve the problem. If a task must not be done by someone, whose efficiency to complete this task will be taken to infinity (Inf) in MATLAB, when calculating the objective function minimization problem, but the efficiency of this person is zero when calculating the objective function maximization problem. The efficiency matrix is transformed into square matrix and the Hungarian algorithm is continued to solve the problem.

4. Conclusion

Aiming at the problem of optimal allocation of human resources in hydraulic engineering, an optimization approach of human resources is proposed in hydraulic engineering using time-limited task assignment model, and the optimal staffing scheme is obtained. The calculation results of different types of cases show that the approach can reasonably allocate the limited human resources in the hydraulic engineering project, achieve the minimal cost and maximal work satisfaction. It also proves the feasibility, correctness and rationality of the model, which can provide scientific guidance for the implementation of engineering projects and improve the overall work efficiency of the project. It is an effective and practical method.

Conflict of Interest Statement:

The authors declare no conflict of interest.

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