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Research on the Multi-Factor Assignment Model of Engineering Support Mission

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Abstract

For solving assignment problems of staff, equipment and task in engineering support action, a 3-Dimensional assignment model is established, which contains staff skill level, equipment technique condition and collaboration efficiency factor. The task preparedness requires multi-skilled staff and multi-purposed equipment, and mission principle requires equipment no halt but staff halt. All these above are abstracted and viewed as constraint conditions in the assignment model. Based on form of objective function and constraint conditions, a fast solution algorithm is designed, in which multi-function equipment is decomposed into a combination of single-function equipment, here, called virtual equipment method. Finally, an introduction to the application of the assignment model in a certain example is presented in detail, and practicability of the assignment model and the fast solution algorithm is verified as well. The results of this paper are aimed at helping the field commander during making operational plans.

Keywords

Engineering Support Mission, Multi-Factor, Assignment Model, Global Optimum

1. Introduction

In the era of information, the ability to swiftly achieve the mobility, transfer, and deployment of support forces is paramount for seizing the advantage in the ever-evolving battlefield dynamics. This places elevated demands on engineering support units tasked with mobile support, and a spectrum of engineering support missions. When confronted with specific engineering support missions, commanders must formulate precise and efficient decisions pertaining to the allocation of tasks, including determining which staff should operate specific equipment for designated missions. Typically, when crafting these decisions, several key aspects necessitate consideration.

1) Generally, staff do not manually complete tasks; instead, they operate equipment. Furthermore, within engineering support units, staff are often trained as multi-skilled operators. Assigning tasks to staff requires consideration of both the impact of a staff proficiency on equipment operational efficiency and the variability in equipment performance due to its technical condition. For instance, it is evident that a highly skilled operator can handle a piece of equipment more efficiently and in less time than an operator with average skills. Similarly, the same staff operating fully functional equipment can complete the task more quickly and efficiently than if they were operating equipment of the same type but with suboptimal performance.

2) Under the condition of information, engineering support tasks are becoming more and more complicated, which requires the staff of engineering support troops to have multi-skills and can operate various equipment. In addition, engineering equipment is also gradually developing in the direction of multi-function, can perform a variety of tasks. Although the staff has a number of skills, considering the fatigue caused by long-term mission, which leads to reduced efficiency and safety risks, the engineering equipment is allowed to perform multiple tasks continuously, but the staff who operates the equipment can only perform one task, which is often said that “people do not rest and vehicles do not rest”. For example, a certain type of multi-purpose engineering vehicle can carry out both excavation and loading missions, so that the equipment can continuously perform two tasks of excavation and loading, and try not to let the staff operating the equipment continue to fatigue to perform two tasks.

3) In the context of real-world tasks, the superiors have an urgent need for the completion time of engineering support tasks, and usually need as much equipment as possible to work together to complete the task as quickly as possible. However, when multiple equipment works together in the same area to complete a task, too much equipment may even get in the way of each other due to site limitations or coordination effects. For example, two or even three excavators cooperate to dig large flat pits, and it is impossible to completely independently and synchronously carry out the cooperation process, and there is bound to be a certain degree of interference with each other, and the total operating efficiency is obviously smaller than the simple addition of the operating efficiency of several pieces of equipment.

To sum up, the completion of engineering support missions is not only related to the staff operating the equipment, but also related to the equipment operated by the staff, but also related to the “people and vehicles do not rest” and the efficiency of collaborative work. In essence, it is a multi-constrained and multi-dimensional assignment problem, which belongs to the non-deterministic polynomial-hard problem.

At present, there are few research literatures on personnel assignment in engineering support missions, but there are still some research results in other fields which have certain reference value to solve the above-mentioned problems. The classical assignment model only studies the assignment of one person, one thing, one thing, and one person, which does not involve the difference of equipment performance or the situation of collaborative work, so it cannot be directly used to solve the above problems [1]. In [2], Addressing varying skill proficiencies among multi-skilled workers in flexible production systems, a model for allocating multi-skilled workers is proposed, considering no influence from tools on workers' work efficiency. In [3] [4], considering the skill classification and rest time of maintenance personnel, a task assignment model suitable for multi-skill maintenance personnel is established. In [5], considering the influence of fatigue accumulation of maintenance personnel on maintenance ability, a task assignment model suitable for maintenance unit is established. Taking into account the impact of accumulated fatigue on the maintenance capacity of maintenance personnel, a task assignment model suitable for maintenance units has been established [6]. When addressing tasks with parallel operational phases, an improved Hungarian algorithm has been developed to address assignment problems that involve these concurrent phases. Nevertheless, within concurrent operational phases, personnel operate independently, and collaborative work is not considered [7]. The assignment model of ice and snow equipment group-work area is established for the situation of multi-equipment snow removal on airport road surface, but only the solution process of two-dimensional cooperation to complete a certain task is given. In [3]-[7], these are two-dimensional assignment problems, which only consider the assignment relationship between people and tasks, and do not involve other intermediate links. For issues related to human resources management, multi-sensor multi-target tracking, data fusion, and related fields, separate three-dimensional assignment models have been established. While their model structures differ significantly from the problem described in this paper, their modeling processes are worth drawing lessons from. Furthermore, the aforementioned research also highlights from another perspective that the assignment problem under investigation in this paper is not an isolated theoretical issue but a highly practical problem with significant real-world applications [8]-[10].

2. Model Construction

Assuming that a certain engineering support mission can be divided into l sequential phase tasks, the commander needs to assign n staff to operate m pieces of equipment sequentially to complete l phase tasks, where $n > m$. To address this assignment problem, a mathematical model is formulated through the following steps:

1) The decision variables is

$$x_{ijk} = 1 \text{ or } 0 \tag{1}$$

where $x_{ijk} = 1$ that the i-th staff is assigned to operate the j-th equipment to complete the k-th task, while $x_{ijk} = 0$ signifies that the i-th staff is not designated to operate the j-th equipment or is not assigned to carry out the k-th task.

2) In accordance with the "staff rest, equipment does not" principle, each staff is limited to being assigned to perform a single task, thus necessitating the fulfillment of the following constraint conditions.

$$\sum_{k=1}^{l}\sum_{j=1}^{m} x_{ijk} \le 1, i = 1, 2, \cdots, n \tag{2}$$

3) In accordance with the "staff rest, equipment does not" principle, each piece of equipment should ideally be involved in as many tasks across different stages as possible. However, it should also be ensured that the equipment's involvement does not lead to a decrease in the overall operational efficiency. This means that a specific piece of equipment may participate in multiple stage tasks or may not be involved in any stage task at all. Therefore, the following constraint conditions must be satisfied.

$$\sum_{i=1}^{n}\sum_{k=1}^{l} x_{ijk} \ge 0, j = 1, 2, \cdots, m \tag{3}$$

4) Each phase task requires at least one piece of equipment for completion, and the number of participating equipment should not exceed the total number of equipment with the capability to complete that specific task, denoted as m_k. Therefore, the following constraint conditions must be satisfied.

$$1 \le \sum_{i=1}^{n}\sum_{j=1}^{m} x_{ijk} \le m_k, k = 1, 2, \cdots, l \tag{4}$$

5) The introduction of t_{ijk} signifies the time coefficient matrix, which denotes the time required for the i-th staff to autonomously complete the k-th task using the j-th equipment. This matrix can be computed using the following formula.

$$t_{ijk} = t_{jk} / c_j e_{ij} \tag{5}$$

where t_{jk} represents the time required for each piece of equipment to independently complete the k-th phase task under ideal conditions (with the best staff proficiency and equipment technical status). c_j represents the technical status influence coefficient of the j-th equipment, with values ranging from [0, 1]. A higher value indicates higher operational efficiency. e_{ij} represents the coefficient of the proficiency level effect of the i-th operator on the j-th equipment, with values ranging from [0, 1]. A higher value indicates a higher level of proficiency.

6) The sum of the time required for each phase task is the total duration of the entire engineering support mission. The optimization objective is to find a set of decision variables that minimize the total duration of the engineering support mission. In other words, the objective function can be expressed as.

$$\min \sum_{k=1}^{l} \left(\left(\frac{1}{\sum_{i=1}^{n}\sum_{j=1}^{m} \frac{x_{ijk}}{t_{ijk}}} \right) \left(\frac{1}{1 - C\left(k, N_k\right) \times sign\left(N_k - 1\right)} \right) \right) \tag{6}$$

where $N_k = \sum_{i=1}^{n}\sum_{j=1}^{m} x_{ijk}$ represents the number of equipment units involved in the k-th task. $C(k, N_k)$ represents the coefficient of interference when N_k equipment units collaborate on the k-th task, with values ranging from [0, 1], where a higher value indicates more interference between the equipment units.

In summary, Equation (6) describes the objective function of the assignment model, and Equations (2), (3), (4) together constitute the constraint conditions of the assignment model. It is not difficult to see that the model described in this paper not only takes into account the staff's operational proficiency but also considers the equipment's technical condition and the impact factors of collaborative missions. With the increase in the number of equipment m_k involved in collaborative missions, this model turns into an m_k times integer programming problem, essentially belonging to a large-scale nonlinear integer programming problem.

3. Algorithm Design

For large-scale nonlinear integer programming problem, the assignment model can be transformed into integer linear programming problem by transformation in very special cases, and then solved by integer linear programming method. In most cases, the exact solution cannot be obtained, and the approximate solution is usually obtained by the extended cut plane method [11], the generalized Benders decomposition [12], the branch-and-bound algorithm [13], and the external approximation algorithm [14]. These methods are all solved by solving the relaxation problem or linear subproblem of the original nonlinear integer programming problem [15] [16]. These methods all involve solving the relaxation problems or linear subproblems of the original nonlinear integer programming problem to obtain solutions. However, unlike most existing nonlinear integer programming problems, the objective function of the assignment model described in this paper is complex and high-order nonlinear. It cannot be transformed into an integer linear programming problem, and it is challenging to find corresponding relaxation problems or linear subproblems. As a result, many excellent algorithms for fast solving of nonlinear integer programming problems cannot be directly applied to solve the model presented in this paper. In the absence of fast solving algorithms, the typical approach is as follows: firstly, construct a relatively large feasible space composed of 2^{1*m*n} solutions; then, assess each one for compliance with the constraints provided in Equations (2) and (4) to narrow down the feasible space; finally, find the optimal decision variables within the narrowed feasible space through Equation (6). Following this approach, the solution process is considerably time-consuming and cannot meet the requirements of rapid decision-making in information scenarios.

Through Equation (3), it is not difficult to observe that x_{ijk} is 0 - 1 variables. Therefore, the constraint conditions described by this equation are actually invalid, making it impossible to construct a smaller feasible region for the model's solution. Furthermore, if we treat all multi-function equipment as virtual collections of multiple single-function equipment, the constraint conditions described by Equation (3) can be transformed into.

$$\sum_{i=1}^{n}\sum_{k=1}^{l} x_{ijk} \le 1,\ j = 1,2,\cdots,m_v \tag{7}$$

where m_v is represents the sum of actual equipment and virtual equipment quantities after splitting the multi-function equipment into virtual equipment, thus $m_v \geq m$.

The reason this method is referred to as the "virtual equipment approach" is that, after decomposition, physically, equipment with single functions does not exist; they are virtual sets. Through the enhanced constraints resulting from the virtual equipment approach in Equation (3), the feasibility region of the assignment model is significantly reduced. Furthermore, after modifying the constraints of the assignment model based on the virtual equipment approach, we have designed a rapid solving algorithm. The following are the specific implementation steps.

Step 1 I_{k,m_k} is introduced to represent all the possible equipment combination schemes capable of cooperatively completing the k-th phase task. The number of equipment combination schemes that can be allocated to the k-th phase task is

$$n_k = \sum_{i=1}^{m_k} C_{m_k}^{i} \tag{8}$$

where m_k represents the total number of equipment that can be assigned to the k-th phase task.

Step 2 Introduce I to represent the combination of equipment configurations throughout the entire engineering support mission. Since the entire engineering support mission is composed of a sequence of phase tasks, thus $I = I_{1,m_k} \cup I_{2,m_k} \cup \cdots \cup I_{l,m_k}$, the number of equipment combination schemes corresponding to the entire engineering support mission is

$$n_l = \prod_{k=1}^{l} n_k \tag{9}$$

Step 3 Following the principle of "staff rest while vehicles don't", it is required that each staff is assigned only one task. Therefore, the number of staff-assignment combinations within a particular equipment combination scheme is

$$n_{sw} = C_n^{m_w} A_{m_w}^{m_w} \tag{10}$$

where $m_w = \text{card}(I)$ represents the number of equipment assigned to a specific equipment scheme combination, as each piece of equipment is assigned one staff. In practice, this corresponds to the number of staff assigned to a particular equipment scheme.

Step 4 First, arrange the task numbers in ascending order to obtain a task number array. Second, choose a specific equipment combination scheme from all the equipment combination schemes corresponding to the task number array, and arrange the equipment numbers in ascending order to obtain an equipment number array. Finally, select a specific staff combination scheme from the staff combination schemes corresponding to this equipment number array and perform a complete sort based on staff numbers to obtain a staff number array.

Step 5 Since the coordinates of the decision variable matrix elements are defined based on staff numbers, equipment numbers, and task numbers, it is possible to determine the coordinates of staff, equipment, and tasks in the decision variables based on step 5. This will yield a set of decision variables, denoted as x.

Step 6 By iterating through the set of all equipment combination scenarios and subsequently through the set of staff combination scenarios corresponding to each equipment combination scenario, all decision variables can be obtained. These decision variables can then be successively substituted into equation (6) for computation, resulting in the optimal decision variables and their corresponding task duration.

4. Numerical Experiments

A certain unit is tasked with conducting a construction mission that mainly consists of three consecutive phase tasks: excavation, installation of support structures, and covering the soil. Each phase must be completed before moving on to the next one. The unit consists of a total of 8 staff and is equipped with 6 pieces of construction machinery from 5 different categories (2 excavators, 1 trencher, 1 crane, 1 bulldozer, and 1 loader). The combination of construction equipment deploying the most in each stage of the tasks can be determined based on the explicit functions of these equipment. This leads to a potential equipment combination scheme for the entire construction of the shelter construction project, known as the maximum equipment combination scheme, as shown in Figure 1. It can be observed that the loader can be involved in both excavation and soil covering operations.

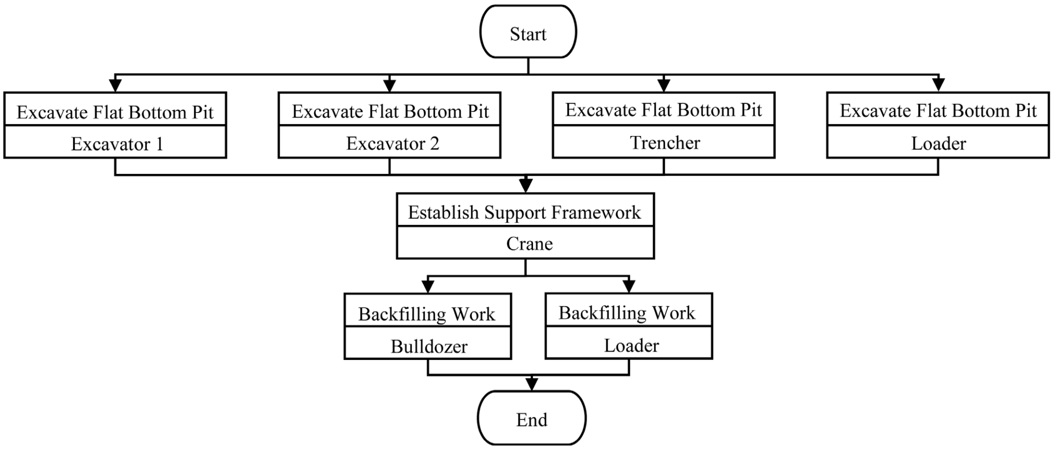

Figure 1. Maximum combination scheme of equipment.

Each staff's identification number and proficiency in operating various types of construction equipment are presented in **Table 1**. In this table, the proficiency levels A, B, C, and D correspond to impact coefficients of 1.0, 0.8, 0.6, and 0.0, respectively.

Table 1. The number and operant level of staff.

ID	Excavator	Trencher	Crane	Bulldozer	Loader
S1	A	A	B	A	A
S2	A	B	B	A	B
S3	A	B	C	A	B
S4	A	B	B	B	A
S5	B	D	C	B	B
S6	B	C	D	B	C
S7	C	C	D	C	D
S8	C	D	C	C	C

Each piece of engineering machinery has a technical state as shown in **Table 2**, where technical states A, B, and C correspond to impact coefficients of 1.0, 0.8, and 0.6, respectively.

Table 2. Technique condition of engineering equipment.

Equipment	Technical status
Excavator 1	B
Excavator 2	C
Trencher	A
Crane	A
Bulldozer	B
Loader	A

Through measurements and experience, we can obtain the completion time for each stage task under ideal conditions (an operator with proficiency level A operating engineering equipment with technical state A). This is shown in **Table 3**.

Using the "virtual equipment approach," we treat the loader as two virtual loaders, one for excavation only and the other for backfilling. According to the maximum equipment combination scheme shown in **Figure 1**, the engineering equipment numbers are provided from left to right and from top to bottom, as shown in **Table 4**.

Table 3. Task time at all stages under the ideal case (unit: min).

Machinery	Excavation	Lifting	Backfilling
Excavator	120	∞	∞
Trencher	80	∞	∞
Crane	∞	40	∞
Bulldozer	∞	∞	80
Loader	160	∞	60

Table 4. Equipment number and task time based on virtual equipment method (unit: min).

ID	Equipment	Excavation	Lifting	Backfilling
E1	Excavator 1	120	∞	∞
E2	Excavator 2	120	∞	∞
E3	Trencher	80	∞	∞
E4	Loader v1	160	∞	∞
E5	Crane	∞	40	∞
E6	Bulldozer	∞	∞	80
E7	Loader v2	∞	∞	60

The task numbers for each stage and the coefficients representing the collaboration of multiple equipment in that stage are shown in **Table 5**. Larger values indicate a greater hindrance.

Table 5. Collaboration efficiency factor at all stages.

ID	Task	Number			
		1	2	3	4
T1	Excavation	0.0	0.1	0.2	0.3
T2	Support	0.0	0.0	0.1	0.2
T3	Backfilling	0.0	0.0	0.0	0.1

In practice, the units, personnel, and equipment within the engineering support units are each assigned unique identification codes in the respective software systems. Proficiency levels of staff operating equipment, the technical condition of equipment, and the impact coefficients of multiple equipment collaborating are typically obtained through routine training assessments, exercise evaluations, or equipment performance assessments and are subsequently entered into the system.

For the sake of calculation and analysis in this paper, the identification numbers for staff, equipment, and tasks are manually assigned, while the proficiency level impact coefficients, technical condition impact coefficients, and collaboration impact coefficients are assumed to be known conditions. Therefore, these various impact coefficients are used solely for the purpose of algorithm validation and serve no other purpose.

Finally, utilizing the fast-solving algorithm described in this paper, the optimal assignment scheme was implemented through programming on a Windows 7 64-bit platform equipped with MATLAB 2017a and an Intel Core i7 7th Gen processor (2.70GHz clock speed). The results are presented in **Table 6**, with the corresponding action duration for the optimal assignment scheme being 142.24 minutes.

Table 6. Optimal staff & equipment & task assignment results.

task equipment warrior	T1	T2	T3
S1	E3		
S2		E5	
S3			E6
S4			E7
S5	E4		
S6	E1		
S7			
S8			

It can be observed that in the optimal assignment scheme, E4 and E7 were respectively assigned to tasks T1 and T3, meaning that the loader (E4) participated in both the excavation and backfilling stages. However, the excavator represented by E2 (Excavator 2) was not assigned to the excavation task. In fact, if we consider the maximum equipment combination scheme, Excavator 2 is also assigned to the excavation task. In this case, the action duration for the optimal assignment scheme is 142.80 minutes. This indicates that the involvement of Excavator 2 in the excavation task did not accelerate the excavation but rather slightly hindered it. In other words, the maximum equipment combination scheme is not necessarily the optimal equipment combination scheme. Further analysis reveals that Excavator 2 had a technical condition of C, indicating lower operational efficiency. Additionally, the impact coefficient of four engineering equipment collaborating in the excavation task was 0.3, which contributed to the counterproductive situation. It is not difficult to conclude that the decision scheme presented in **Table 6** better aligns with the actual circumstances, thereby confirming the practicality and effectiveness of the assignment model.

On the other hand, if an exhaustive search approach is employed, directly searching for solutions within the feasible domain formed by the $2^{\mathrm{l}*m*n}$ decision variables that satisfy the constraints (a total of 2^{8*6*3} decision variables, with each decision taking approximately 9.4×10^{-5} seconds), the estimated time required on the same computing platform would be around 2.1×10^{39} seconds, which is almost unacceptable. The simulated annealing algorithm was adopted, generating new decision variables through random perturbation and gradually converging to a local optimal solution based on the Metropolis criterion. A total of 352,401 decision variables were produced, taking approximately 3.5×10^{15} seconds, which was relatively time-consuming. The genetic algorithm was then used, directly encoding 2^{8*6*3} decision variables as real numbers, establishing the objective function based on the optimal assignment model identified by the previous algorithm, and ultimately converging to an optimal solution through multi-point crossover. It was estimated to take about 1.6×10^{12} seconds.

However, by using the fast-solving algorithm described in this paper, the feasible domain (consisting of a total of 284,928 decision variables) can be significantly reduced, and the time required is only 26.85 seconds. Therefore, the fast algorithm based on the concept of virtual equipment can substantially reduce computational costs and provides a highly effective solution for solving the assignment model mentioned above.

5. Summary

This article begins by analyzing the characteristics of engineering support tasks, highlighting that engineering support missions represent a multi-constraint, multi-dimensional assignment problem. Subsequently, based on considerations of staff proficiency, equipment technical status, and collaborative task impact, a three-dimensional assignment model for staff, equipment, and tasks is established. Furthermore, addressing the inability of existing intelligent algorithms to directly solve the model, a rapid solution algorithm is designed based on the concept of virtual equipment. The primary distinction between this assignment model and all other "assigning staff to tasks" models lie in its ability to assist commanders in the assignment of tasks to staff while concurrently considering the impact of equipment technical status and collaborative factors.

The practicality and effectiveness of this model and solution method are then demonstrated through practical examples. It is worth noting that, regarding the scheduling of rest for staff and equipment, there exist four possible scenarios: "staff rest while equipment doesn't", "staff rest and equipment rests", "staff don't rest while equipment rests", and "neither staff nor equipment rest". However, this article specifically focuses on the "staff rest while equipment doesn't" scenario. In actual missions, if the engineering equipment possesses the capability to complete a certain stage of a task and its technical status is normal, there is generally no situation of "equipment rest" unless computations reveal that the equipment's participation in collaboration would lead to an overall decrease in operational efficiency. On the contrary, in highly urgent situations, the scenario of "neither staff nor equipment rest" is likely to occur. The solution for the "neither staff nor equipment rest" scenario can be tackled by breaking down the engineering support missions into stage-specific tasks, making it relatively simpler. Readers interested in solving the latter case may conduct further research. In the actual mission process, there are often situations where multiple tasks need to be carried out collaboratively by several staff. The approach of virtual equipment in the text can be borrowed. By creating virtual personnel and constructing their operational capabilities, a "personnel-equipment" combination plan can be formed in step 3. In step 6, the optimal decision variable can be obtained by traversing all the plans. This calculation will not be repeated here.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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