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Research Article

Model and Algorithm for Human Resource-Constrained R&D Program Scheduling Optimization

Junjie Chen[1], **Shurong Tong**[1], **Hongmei Xie**[2], **Yafei Nie**[1], **and Jingwen Zhang**[1]

[1]*School of Management, Northwestern Polytechnical University, Xi'an 710072, China*
[2]*School of Electronics and Information, Northwestern Polytechnical University, Xi'an 710072, China*

Correspondence should be addressed to Junjie Chen; junjiechen75@nwpu.edu.cn

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In resource-constrained project scheduling problems, renewable resources can be expanded into human resources with competency differences. A flexible resource-constrained project scheduling problem with competency differences is proposed, which is a practical extension close to Research and Development (R&D) program management, from the traditional multimode resource-constrained project scheduling problem. A parameter and estimation formula to measure staff competency is presented, and a mixed-integer programming model is established for the problem. The single-objective optimization problems of optimal duration and optimal cost are solved sequentially according to the biobjective importance. To solve the model, according to the assumptions and constraints of the model, the initial network diagram of multiple projects is determined, the enumeration algorithm satisfying constraint conditions provides the feasible solution sets, and the algorithm based on dynamic programming is designed for phased optimization. Experimental results show that the proposed optimization model considering competence differences can solve the problem effectively.

1. Introduction

With the rapid development of high-tech enterprises, the number of similar projects is increasing, and the long-term development of enterprises requires the formulation of strategic plans; an effective multiproject management method, namely, program management, emerges at the historic moment. Traditional project management focuses too much on individual project performance. Program management is a collaborative management of multiple interconnected projects. Program management ability for a R&D program enterprise is the embodiment of its core competitiveness. Program management can meet the project needs within the program and achieve the strategic objectives of R&D enterprise and can improve the utilization of resources and organizational project management ability.

In the environment of program management, high-tech enterprises are faced with more technical transformation projects at the same time, the scale of the program is huger, and the management is more complex and more difficult, so that resource allocation management is facing greater challenges. Due to the unreasonable resource structure, unbalanced resource assignment, and lack of coordination capacity, there will be a surplus of resources or a shortage of resources. Elonen and Artto investigated the existing problems from the perspective of program management and concluded the importance of various factors affecting program management. The factors of shortage of resources and unreasonable assignment accounted for a quarter, ranking in the second place [1]. Therefore, how to optimize the assignment of resources among multiple projects to ensure the successful completion of the program is an urgent problem for enterprises to solve.

Enterprise R&D program is mainly committed to the research on new technologies to achieve the goals of reducing product costs, improving production capacity, improving the quality, and shortening the duration of R&D program. The implementation of R&D program is often a risky and dynamic innovation process. Its success depends on R&D staff, which is an important resource completing a lot of complex mental work. Therefore, the research on the optimal assignment of scarce R&D staff has been a core issue to be solved.

The optimal assignment of R&D program staff in enterprise is a resource-constrained project scheduling problem, which is the focus of current research on project management. Most of the existing researches consider resources such as materials and equipment in the project scheduling problem, while few consider the flexible nature of human resources in the project scheduling problem. The human resource-constrained project scheduling problem, in fact, belongs to the multiskill project scheduling problem [2, 3] or the flexible resource-constrained project scheduling problem [4, 5].

In view of the fact that the flexible resource-constrained project scheduling problem and the multiskill project scheduling problem play an important role in the application of enterprise R&D program, many scholars at home and abroad have begun to pay attention to and study these problems. Yu et al. proposed a flexible resource-constrained resource leveling project scheduling problem, designed a flexible resource model based on a two-level mapped network to express the relationship among activities, capability, and resources, and established a mathematical model of the problem [6]. Wang et al. proposed a two-stage algorithm for project scheduling problems with multiskilled workforce constraint [7]. Fu and Zhou studied the column generation method to solve the multiproject and multimode scheduling problem with human resource constraints and constructed a mathematical model. According to the column generation process, a heuristic algorithm and an immune genetic algorithm were used to solve the problem [8]. Ren et al. aimed to minimize the makespan of the project. Considering that the duration of the activity changes according to the skill level of the key resource used, a hybrid algorithm consisting of a two-level decision scheme and a local search optimization scheme was developed [9]. Wang and Zheng proposed a knowledge-guided multiobjective Drosophila optimization algorithm to solve a multiskill project scheduling problem [10]. Considering resource constraints such as operating table and knife-holder, Deng et al. constructed a fuzzy scheduling mathematical model of a multiobjective function and proposed an improved nondominated sorting genetic algorithm (NSGA-II) [11]. Chen and Zhang studied an ant colony algorithm based on event scheduling for software project scheduling and staffing [12]. Zheng et al. proposed a teaching-learning-based optimization algorithm (TLBO) to solve the resource-constrained project scheduling problem with the goal of minimizing the time limit [13]. Most of the above research projects are optimized in terms of total duration or total cost and few studied multiobjective scheduling optimization problems.

Naber and Kolisch, the proponents of FRCPSP, put forward a new term, flexible resource profile, and studied the effect of flexible resource allocation on activity duration [5]. The traditional multimode resource-constrained project scheduling problem (MRCPSP) does not fully consider the flexible attributes of human resources with multiple capabilities and only studies the impact of the amount of flexible resources allocation on activity time but also does not adequately study the impact of the specific allocation scheme of flexible resources on activity execution time or activity cost. For example, most scholars consider an activity that takes 30 days to complete if two people are assigned or 20 days to complete if three people are assigned. It is seldom considered that it may take 20 days to assign two persons to A and B, or 40 days to assign two persons to C and D. In particular, for knowledge workers in R&D projects, the staffing scheme will significantly affect the execution time and cost of activities.

Previous studies have shown that the performance of R&D staff mainly depends on the ability and skills of staff, so scholars mainly study the impact of human resource skill level or work efficiency on the actual execution time of activities. Heimerl and Kolisch established a mathematical model in a multiproject environment and solved it with optimization software, considering the effect of internal human resource efficiency on activity time. However, the exact workload of each staff was not estimated in the model [14]. Chen et al. studied the relationship between work efficiency and activity time, and quantified activity workload by using time rating [15]. Lv et al. studied the project scheduling problem considering the difference of flexible resource capability and proposed a particle swarm optimization algorithm based on activity sequence representation [16]. Wang et al. assumed that resources have or do not possess certain skills at all [7]. Some research works [5, 16–19] describe the capability differences of resources by skill levels and model the differences of resource capabilities. In recent years, it has been found that the skills of R&D staff have no direct predictive effect on the improvement of individual performance. The competence of R&D staff is a decisive factor in determining performance differences [20–22]; R&D staff with high competency has shorter activity execution time, lower material cost, and higher quality.

In this paper, considering the fact that human resource competence has a significant impact on the duration of activities and material costs of R&D expenditure in enterprise R&D program, a parameter to measure human resource competence is proposed, and the mathematical optimization model of the problem is established. The research problem is a new problem that combines human resource allocation with the project scheduling problem. It is an extension of the traditional MRCPSP, and its problem scale and solving difficulty are even greater. Dynamic programming is an important decision-making method for discrete resource allocation and scheduling problems, and the main objective is to minimize the program makespan. Therefore, this paper uses dynamic programming to transform the multistage decision-making problem into a series of interconnected single-stage problems.

The remainder of this paper is organized as follows: The formulation of the special MRCPSP is presented in Section 2. The details of the proposed algorithm for the special MRCPSP are described in Section 3. In Section 4, numerical results and comparisons are provided. Finally in Section 5, we end the paper with some conclusions and future work.

2. Formulation of the Special MRCPSP

2.1. Problem Description. This paper mainly studies how to determine the program schedule and assign the human resources to meet the multiobjective for completing multiple parallel projects in the most economical and time-saving way. The specific problem is defined as follows: there are parallel R&D projects within the enterprise, and priority projects have been designated. Staff in the human resource pool needs to be assigned activities. The predecessors and successors of each activity in each project are known, the material limit and the assignment quantity of human resources of each activity are known, the time rating of each activity is known, and the material consumption rate of the staff is known. The problem is to determine the execution mode and start time of activities in each project to achieve the goal of minimizing the total makespan and total cost of R&D program.

To simplify the problem, the following six hypotheses are made: (1) the combination of staff starts at the same time and ends at the same time when performing a certain activity, and the staff who do not complete the activity are not allowed to evacuate on the way; (2) the types of materials consumed by all activities (except human resources) are the same; (3) the staff consume the same material with the fixed material consumption rate in different activities; (4) the total cost of R&D program only considers the cost of materials consumed; (5) there are obvious differences in the duration and cost of activities performed by different staff; (6) there is no significant difference in the quality of activities performed by different staff, which can meet the quality requirements of the enterprise.

2.2. Staff-Time Coefficient. The study found that under the complex background of R&D program, R&D staff's work performance not only depends on their ability and professional skills, but also is influenced by implicit factors such as work motivation, self-cognition, work attitude, and values [20–23]. Ability is not an independent factor determining the performance. To play a role in the performance, ability must be combined with motivation. Therefore, the main way to improve staff performance is to enhance their competency. Competency is a kind of measurable explicit behavior, which can reflect the knowledge and work skills, work motivation and self-cognition, work attitude, and values of staff and can be used to distinguish the behaviors between staff with high performance and staff with general performance [24].

In this section, we will discuss how to define the staff-time coefficient to measure the competency level of staff. Staff-time coefficient will be used to build the model for special MRCPSP.

The traditional time coefficient is measured as the ratio between the actual working time and the standard working time. The standard working time refers to the time required to complete a single product or a certain work under certain technology, organization, and conditions. According to the calculation formula, if the time coefficient is greater than 1, it indicates the existence of backward management methods or technology; if it is equal to 1, it is standard; if it is less than 1, it indicates the existence of advanced management methods or advanced technology. In order to reflect the impact of different competency levels on activity performance, this paper extends the traditional concept of time coefficient and puts forward the concept and estimation formula of staff-time coefficient.

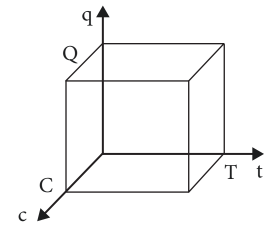

FIGURE 1: The planned value of activity k of project j.

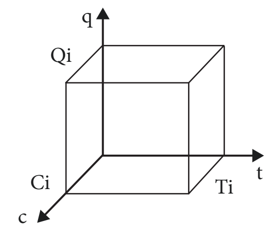

FIGURE 2: The value of staff i performing activity k of project j.

To estimate the staff-time coefficient of a staff in different activities, this paper improves the cube model [25] from the perspective of resource allocation. The staff-time coefficient is expressed by the ratio between the value of the activity performed by a staff and the planned value of the activity. The ratio reflects the competence of a staff performing an activity and sets the staff-time coefficient of the standard staff to be 1. Evaluating the size of the coefficient can assist decision-makers in making staff assignment decisions for the project.

Chen et al. [15] addressed the specific process of deducing the estimation formula of the staff-time coefficient as follows: First of all, establish a coordinate system with time (t), quality (q), and cost (c). The cuboid in Figure 1 established according Table 1 is on behalf of the activity k of the project j. In Table 1, ${j^k}_T$, ${j^k}_Q$, and ${j^k}_C$ denote estimated time, estimated quality, and estimated cost, respectively. In Figure 1, the values of point T in axis t, point C in axis c, and point Q in axis q can be calculated from (1) to (3). The value of T obtained from formula (1) reflects the fact that the execution time of activity k of project j is the same as the estimated value, which means that this activity is performed by a standard staff. It can be seen that the value of point T must be 1; similarly, the value of point Q on the axis of the quality condition and the point C of the cost condition axis must also be 1. The integral of time T, quality Q, and cost C is the volume j^k of the cuboid, which represents the planned value of the activity k of the project j, and the value can be obtained by (4). When the project is executed strictly by plan, the standard staff whose staff-time coefficient is 1 executes the project; the integral of volume j^k will be 1.

Then establish a coordinate system with the restrictive conditions t, q, and c. The cuboid in Figure 2 established

Table 1: The planned value of the activity.

	Time (T)	Quality (Q)	Cost (C)
Activity *1* of project j	${j^1}_T$	${j^1}_Q$	${j^1}_C$
...	...	...	...
Activity k of project j	${j^k}_T$	${j^k}_Q$	${j^k}_C$

Table 2: The predictive value of the activity by a staff.

	Time (T)	Quality (Q)	Cost (C)
staff a	${j^k}_{Ta}$	${j^k}_{Qa}$	${j^k}_{Ca}$
...	...	...	...
staff i	${j^k}_{Ti}$	${j^k}_{Qi}$	${j^k}_{Ci}$

according Table 2, which is determined by expert evaluation method, is on behalf of the activity k of the project j performed by staff i. In Table 2, ${j^k}_{Ti}$, ${j^k}_{Qi}$, and ${j^k}_{Ci}$ denote predictive time, quality, and cost of staff i performing activity k of project j, respectively. The values of point T_i in axis t and point C_i in axis c can be calculated by formulas (5) and (6). It is noteworthy that time and cost belong to cost indexes, the smaller the better, while the quality is benefit index, the bigger the better. So, the value of point Q_i in axis q is calculated by formula (7). The integral of time T_i, quality Q_i, and cost C_i is the volume ${j^k}_i$ of the cuboid, which represents the predictive value of staff i performing activity k of project j, and the value can be obtained by formula (8).

$$T = \frac{{j^k}_{\mathrm{T}}}{{j^k}_{\mathrm{T}}} \tag{1}$$

$$C = \frac{j^k_{\mathrm{C}}}{j^k_{\mathrm{C}}} \tag{2}$$

$$Q = \frac{j^k_{\mathrm{Q}}}{j^k_{\mathrm{Q}}} \tag{3}$$

$$j^k = \int_0^T dt \int_0^Q dq \int_0^C dc \tag{4}$$

$$T_i = \frac{{j^k}_{\mathrm{T}}}{{j^k}_{\mathrm{Ti}}} \tag{5}$$

$$C_i = \frac{j^k_{\mathrm{C}}}{j^k_{\mathrm{Ci}}} \tag{6}$$

$$Q_i = \frac{j^k_{\mathrm{Qi}}}{j^k_{\mathrm{Q}}} \tag{7}$$

$${j^k}_i = \int_0^{T_i} dt \int_0^{Q_i} dq \int_0^{C_i} dc \tag{8}$$

$$K_{ijk} = \frac{{j^k}_i}{j^k} \tag{9}$$

Equations (1)~(3) show the ratio of time, quality, and cost of the standard staff completing the activity k of project j to the time, quality, and cost of the activity plan. Equation (4) represents the planned value of activity k of project j. Equations (5)~(7) show the ratio of the time, quality, and cost of staff i to the time, quality, and cost of executing the activity k of project j. Equation (8) represents the execution value of the activity k of project j executed by staff i. Finally, staff-time coefficient of staff i executing the activity k of project j is derived from (9).

Staff-time coefficient will be used to build the following model.

2.3. Problem Formulation. In this section, a mixed-integer linear programming model for the above problem will be constructed. The symbols used in the paper are shown in Notations.

(1) Method for Solving the Value of Model Parameters

(a) K_{ijk}:

$K_{ijk} = {j^k}_i / j^k$. The specific meaning of the formula is specified in [15].

(b) Φ_{jkmz}:

$$\Phi_{jkmz} = \sum_{i=1}^{NR} \Phi_{ijkz} S_{ijkm}, \quad \forall j = 1, \ldots, NP;\ k = 1, \ldots, Nj;\ z = 1, \ldots, Z \tag{10}$$

(c) d_{jkm}:

$$\sum_{i=1}^{NR} d_{jkm} K_{ijk} S_{ijkm} \geq N_{jk} T_{jk}, \quad \forall j = 1, \ldots, NP;\ k = 1, \ldots, Nj;\ m \in H(j,k) \tag{11}$$

$$d_{jkm} \Phi_{jkmz} \leq L_{jkz}, \quad \forall j = 1, \ldots, NP;\ k = 1, \ldots, Nj;\ z = 1, \ldots, Z;\ m \in H(j,k) \tag{12}$$

Equation (11) shows that the actual workload of an activity processed by the staff combination cannot be less than the activity planned workload. It should be noted that the actual activity duration is usually noninteger. In order to ensure the completion of the activity, it is generally round up to an integer. Equation (12) indicates that the material consumed by the staff cannot exceed the limited quantity of the material and is generally round down to an integer.

The value of d_{jkm} is the minimum integer that satisfies both (11) and (12).

(d) $H(j,k)$:

$$\sum_{i=1}^{NR}\sum_{m\in H(j,k)}\sum_{t'=t-d_{jkm}+1}^{t} y_{jkmt}S_{ijkm} = N_{jk}, \quad \forall j = 1,\ldots,NP;\ k = 1,\ldots,Nj \tag{13}$$

Equation (13) specifies the number of staff assigned to the kth activity of the jth project.

$H(j,k)$, the feasible modes set, is obtained by the following steps: first, using (13) to obtain the execution modes of each activity that only satisfy the number of staff; second, selecting the feasible execution modes satisfying both (11) and (12) from the execution modes obtained by the first step.

(2) Objective Function

$$\text{Minimize } D$$

$$\sum_{t=0}^{T}\sum_{m\in H(j,k)}\left(t + d_{jkm}\right) y_{jkmt} \leq D, \quad \forall j = 1,\ldots,NP;\ k = 1,\ldots,Nj. \tag{14}$$

$$\min\sum_{z=1}^{Z}\sum_{t=0}^{T}\sum_{j=1}^{NP}\sum_{k=1}^{Nj}\sum_{m\in H(j,k)} d_{jkm}y_{jkmt}\phi_{jkmz}p_z \tag{15}$$

(3) Constraints

$$\sum_{j=1}^{NP}\sum_{k=1}^{N_j}\sum_{m\in H(j,k)}\sum_{t'=t-d_{jkm}+1}^{t} y_{jkmt}S_{ijkm} \leq 1, \quad \forall i = 1,\ldots,NR;\ t = 0,\ldots,T. \tag{16}$$

$$\sum_{t=0}^{T}\sum_{m\in H(j,k)} y_{jkmt} = 1, \quad \forall j = 1,\ldots,NP;\ k = 1,\ldots,Nj \tag{17}$$

$$\sum_{i=1}^{NR}\sum_{j=1}^{NP}\sum_{k=1}^{N_j}\sum_{m\in H(j,k)}\sum_{t'=t-d_{jkm}+1}^{t} y_{jkmt}S_{ijkm} \leq N_t, \quad \forall t = 0,\ldots,T. \tag{18}$$

$$\sum_{t=0}^{T}\sum_{m\in H(j,k)} t y_{jkmt} \geq \sum_{t'=0}^{T}\sum_{m\in H(j,k)} y_{j'k'mt'}\left(t + d_{j'k'm}\right), \quad \forall a_{j'k'} \in P_{jk} \tag{19}$$

$$y_{jkmt} \in \{0,1\}, \quad \forall j = 1,\ldots,NP;\ k = 1,\ldots,Nj;\ t = 0,\ldots,T;\ m \in H(j,k) \tag{20}$$

Equation (14) is the primary objective to minimize the total makespan of multiple projects. The total makespan of multiproject refers to the duration of the program, the time from the start of the earliest activity to the completion of the last activity in multiple projects. Equation (15) is the secondary objective to minimize the total cost of the multi-project. Equation (16) ensures that each staff can be assigned to only one activity at a time. Equation (17) ensures that each activity can choose only one mode, and the execution mode could not be changed or interrupted. Equation (18) ensures the maximum number of staff who can be assigned to activities at a time. Equation (19) guarantees the order of the activities; the beginning time of an activity is not less than the ending time of all its immediate predecessor activities. Equation (20) restricts the range of the y_{jkmt}, which is 0~1 decision variable.

3. Algorithm for Special MRCPSP

3.1. Problem Complexity Analysis. In this paper, the introduction of human resources with different competencies increases the number of decision factors and constraints in the traditional resource-constrained project scheduling problem and leads to a more complex problem model and feasible solution distribution and a sharp increase in the number of feasible solutions as well.

The execution time of each activity is variable in this paper, and the activity has "multiple execution modes", so people are likely to interpret this issue as a traditional MRCPSP. The main differences between the special MRCPSP in this paper and the traditional MRCPSP are as follows.

Firstly, in MRCPSP, the allocation of resources over the duration of each activity is given and usually constant. The "multiple execution modes" studied in this paper are determined according to the constraints of the model, such as the workload of the activity, the limited quantity of the material, and the number of staff that are assigned to the activity.

Secondly, the number of modes is quite different. There is a great possibility that the number of modes in special MRCPSP is far larger than in traditional MRCPSP. As for the traditional multiproject human resource-constrained scheduling problem, the number of the activity modes is generally less. For example, supposing there are 6 persons in the human resource pool that can be used and the time is required to be rounded, there are only 4 modes for activity a_{11}, {(6 days,1 person), (3 days, 2 persons), (2 days, 3 persons), and (1 day, 6 persons)}. However, in the problem of this paper, since the staff-efficiency coefficient varies from person to person, there are 6 (C_6^1) different modes if activity a_{11} is allocated with one person. These modes are {(5.8 days, A), (5.5 days, B), (5.7 days, C), (6.1 days, D), (6.3 days, E), (6.6 days, F)}. In the same way, for activity a_{11}, there are 15 (C_6^2) different modes if it is allocated with two persons, 20 (C_6^3) different modes if it is allocated with three people, and 1 (C_6^6) mode if it is allocated with 6 people. Thus, it can be seen that the number of activity modes increases sharply with the increase of the resources required. The expansion of the number of mode combinations among activities in the whole project brings a great challenge to the traditional optimization scheduling method.

Thirdly, the actual makespan of an activity can only be determined after allocating human resources. This is also the difference between this study and the general multimode project scheduling problem. For example, for activity a_{11}, the makespan is 7 days according to the traditional multimode scheduling method. However, if the person with high level of competency or high efficiency is assigned, the actual makespan of the activity can be shortened to 4 days.

The traditional scheduling method of MRCPSP and the mode search solving method [26–28] may lead to misjudgment of the start-up execution time of the activity when the activity scheduling order and the actual duration of the activity are obtained by decoding, thus resulting in poor decoding quality. Therefore, aimed at the special "multimode" problem, an effective algorithm for optimization needs to be designed.

3.2. General Idea of the Algorithm. First, the initial Gantt chart of the program is determined according to the priority start-up project specified by the enterprise, the limit of staff allocation in each period, and the activity sequence relationships of each project. Then the hierarchical sequence method of multiobjective decision-making is used to optimize the objective functions ranked from high to low by importance, then the single-objective optimization is carried out one by one according to this order, and the final solution is regarded as the optimal solution of multiobjective optimization. Subsequently, the feasible solution of the staff combination of each activity is obtained by using the enumeration algorithm; thus the "multiple execution modes" of each activity are obtained. Then the multiproject is divided into several stages according to the critical activities of the multiproject based on the dynamic programming idea. According to the time sequence, the stages are optimized and the staff allocation and the start time of each activity are determined. Finally, the optimal scheduling plan for multiple projects is determined.

3.3. Procedure of the Algorithm. The procedure and flow of algorithm for special MRCPSP are shown in Figure 3.

Step 1 (obtain the feasible solution set of staff combinations for each activity of multiproject). According to the mathematical model established in Section 2.3, firstly the enumeration algorithm is used to enumerate solutions of each *activity*, which form set I. The solutions of set I only meet the requirement of staff quantity. Secondly we pick out the feasible solutions of each *activity* from set I. The feasible solutions form set I_0. These feasible solutions satisfy the following two conditions: first the workload done by staffs of each *activity* cannot be less than rated workload of each *activity*; second the materials consumed by staffs cannot exceed the limited materials quantities of each *activity*.

Step 2 (draw the initial Gantt chart of multiproject and divide it into several stages). The initial Gantt chart of the multiproject can be drawn according to the immediate predecessor and successor relationships among the *activities* in each project; the time rating of each *activity*; priority project to start specified by the enterprise and everyday limited quantity of available assigned staff; and so on. Then the critical routes can be identified, followed by the division of stages according to a series of critical *activities*. After processing the *activities* of a certain stage in the multiproject, the staffs need to return to the human resource pool and wait for being reassigned to *activities* in the next stage.

Step 3 (obtain the optimal staff assignment scheme of the multiproject based on dynamic programming).

Step 3(a) (obtain the solution of staff combinations with the minimum makespan and the lowest cost for each stage in the multiproject). The general idea of solving the optimal solution of each stage is as follows. Firstly for each stage, the primary goal is to minimize the makespan of each stage; from solutions of set I_0, picking out the solutions of staff combinations to form set I_1, the selected solutions can satisfy the shortest makespan of each stage; and then from solutions of set I_1, picking out the solutions of staff combinations to form set I_2, the selected solutions can satisfy the lowest cost of each stage. The detailed steps for solving the optimal solution of each stage are as follows. Firstly, for the first stage in multiproject, the staff combinations, which can satisfy the shortest makespan of the critical activity, should be selected; secondly, noncritical activities in this stage, whose makespans are shorter than the shortest makespan of the critical activities, will be selected, and ensure each staff processes one activity at a time, so all the feasible solutions with the shortest makespan of this stage are solved; finally, the staff combinations with the lowest cost of this stage can be selected, from the feasible solutions with the shortest makespan of this stage, and so on until all the stages in multiproject are solved.

The general principle of staff assignment for each *activity* is introduced below. In order to achieve the primary objective to minimize the total makespan of the multiproject, first of all, it is critical to minimize the makespan of the critical *activity* through assigning staff with the highest staff-time coefficient. The next is to assign staff to the noncritical *activities*. If a noncritical *activity* has a unique solution or finite solutions, this *activity* needs to be allocated first.

Step 3(b) (obtain the optimal staff assignment scheme of each activity in multiproject). Based on the staff assignment scheme with the shortest makespan and the lowest cost of each stage in multiproject obtained by the previous step 3(a), we can obtain the optimal staff assignment scheme of each activity in multiproject.

Step 4 (obtain the start time of each activity in multiproject). On the basis of the optimal staff assignment scheme obtained by the previous step 3(b) and according to the constraints

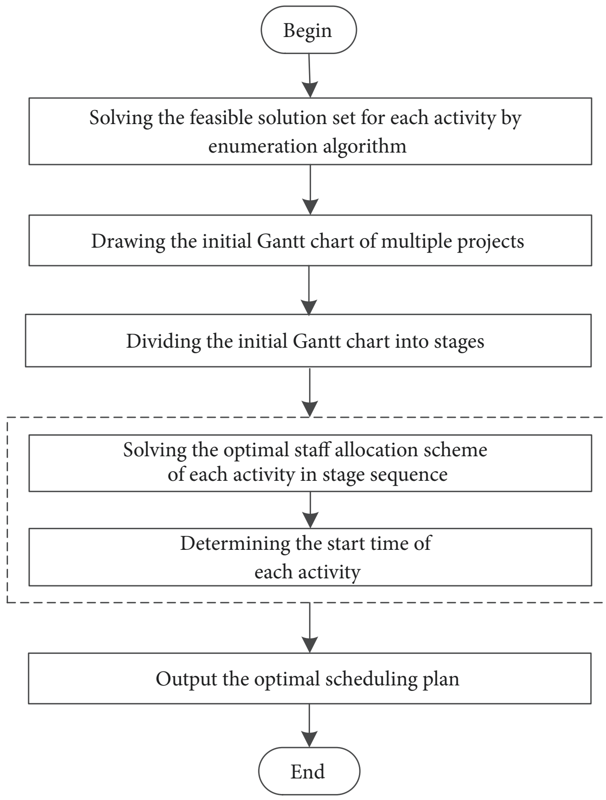

Figure 3: The flowchart of algorithm for special MRCPSP.

such as the maximum supply quantity of staff allocation every day and the allocation of each person to just one *activity* at a time, we can obtain the start time of each *activity* in sequence.

Step 5 (obtain the optimal scheduling scheme of the multiproject). According to the results of Steps 2 and 3, the optimal scheduling scheme of the multiproject, the optimal staff assignment scheme, and the start time of each *activity* in multiproject can be obtained.

4. Numerical Results and Comparisons

4.1. Random Test Instances. Project Scheduling Problem Library (i.e., PSPLIB), is an acknowledged problem library in the field of project scheduling. Kolisch and Sprecher [29] present a set of benchmark instances for the evaluation of solution procedures (i.e., PSPLIB) for classical single-mode and classical multimode resource-constrained project scheduling problems. The instances have been systematically generated by the standard project generator (ProGen). They are characterized by the input-parameters of ProGen. The entire benchmark set including its detailed characterization and the best solutions known so-far are available on a public ftp-site. Hence, researchers can download the benchmark sets they need for the evaluation of their algorithms.

Because special MRCPSP studied in this paper is the nonclassical MRCPSP problem, it is impossible to directly use the benchmark instances in PSPLIB. It is necessary to appropriately adjust ProGen and generate a set of new instances suitable for special MRCPSP. Through setting parameters in the EXPL.BAS file in ProGen, six groups of random test instances are generated; each group contains five instances. Each instance contains two or three randomly generated projects. The total number of real activities of multiple projects J values is 13, 15, 17, 19, 21, and 23, respectively. In the random instances, the activity sequence relationship is consistent with the PROGEN.

Each execution mode requires one renewable resource i and two kinds of nonrenewable resources z_1 and z_2. The limited quantities of renewable resource and nonrenewable resources are given in the instance.

Since the problem studied in this paper originates from FRCPSP, multiple feasible modes are generated for each activity. Table 7 shows the set of feasible modes of each activity obtained by referring to Step 1 of the algorithm. The instances generated through the PROGEN will give the number of resources required for the activity. The FRCPSP model needs to set some additional parameters, which are generated randomly in a given range, as shown in Table 3.

It can be seen from Table 4 that, with the increase of projects scale, the number of feasible solutions of the model will increase. For example, the S-MRCPSP studied in this paper has at least 2.78E+13 feasible solutions and at most 1.09E+19 feasible solutions when the real activity J=13. It is quite time-consuming to search so many feasible solutions. Compared with traditional MRCPSP, S-MRCPSP shortens

Table 3: Rules for parameters generation.

Parameters	Rules
p_z	The unit price of the z^{th} material obeys the discrete uniform distribution on 3~10
Φ_{ijkz}	The consumption rate of each person obeys the discrete uniform distribution of 6~15
T_{jk}	The time rating obeys the discrete uniform distribution of 5~15
L_{jkz}	The limited quantity of the material using in the activity obeys the discrete uniform distribution of 140~500
N_{jk}	The given number of staff assigned to the each activity obeys the discrete uniform distribution of 1~3
K_{ijk}	The staff-time coefficient for the staff to finish the activity obeys the discrete uniform distribution of 0.4~1.8
N_i	The maximum number of available assigned staff in each period is 80% of NR
NR	The total number of the available staff i obeys the discrete uniform distribution of 10~15

the total program duration by about 30% and reduces the total program cost by about 48%. This shows that, for enterprise R&D program, if the competency level of staff is taken into account and the staff is allocated reasonably, the optimal projects scheduling plan can be obtained.

4.2. Real-Life Instance. For the sake of brevity, a real-life instance is used to test models. The instance contains 9 actual activities. The relevant parameters of the multiproject are shown in Table 5, and the consumption rates of resources z_1 and z_2 of each staff are shown in Table 6. The unit prices of nonrenewable resources z_1 and z_2 are set as 3 and 5, respectively. The upper limit of available assigned staff in each period is 7, and the total number of available staff is 12. The calculation process of the algorithm is realized by MATLAB programming on the test platform with Intel Core i7 processor, 3.6 GHz main frequency, 4 GB memory, and Windows 7 operating system.

In this instance, the number of feasible modes of staff combination of a_{11} is 30, and the corresponding numbers of feasible modes of a_{12}, a_{13}, a_{14}, b_{11}, b_{12}, b_{13}, b_{14}, and b_{15} are 16, 20, 38, 7, 34, 2, 17, and 16, respectively. The feasible modes of staff combination of b_{11} are shown in Table 7. It is estimated that the number of feasible solutions in the feasible solution set has reached 10 billion.

Based on the traditional MRCPSP and the “multimode” scheduling problem studied in this paper, two scheduling methods are used to optimize the instance generated from the PROGEN. Table 8 shows the optimal scheduling scheme without considering the competence difference among staff. All the project activities are performed by standard staff. This belongs to the traditional multimode scheduling study. The optimal scheduling result is that the total makespan of the multiproject is 46 days and the cost is 19,360 Chinese Yuan. Table 9 is an optimal scheduling scheme that takes into account differences in competency level of staff, which is the special “multimode” scheduling researched in this paper. The total makespan is reduced to 40 days, and the cost is reduced to 16,335 Chinese Yuan.

Comparing the two optimal scheduling schemes, we find that the scheduling method proposed in this paper can shorten the total project’s makespan by 6 days, which accounts for almost 13% of the total makespan, and the total costs were reduced by 3,025 Chinese Yuan, which accounts for nearly 15.6% of the total costs (shown in Table 10). The results show that the multiproject human resource scheduling method based on staff-time coefficient and dynamic programming can shorten the total program makespan, reduce the total cost, and ease the staff conflicts in resource-constrained situation.

The real-life instance has been solved by GA in [30]. In Table 11, we compare genetic algorithm (GA) with dynamic programming (DP) algorithm proposed in this paper for solving the small size special MRCPSP. The results show that the proposed DP is superior to the GA in terms of program duration and program cost. DP can shorten the program duration by one day, which accounts for almost 2.4% of the total makespan, and the program cost was reduced by 949 Chinese Yuan, which accounts for nearly 5.5% of the total costs. The effectiveness of the proposed solution approach is verified for solving the small size special MRCPSP.

5. Conclusions

Based on the recent research results, staff competency is the critical factor affecting job performance. This paper extends the traditional MRCPSP and studies the special “multimode” project human resource scheduling problem, which is a new problem combining human resource allocation and project scheduling. A new parameter, staff-time coefficient, is proposed to measure staff competence. The total cost of the program only considers the material consumption of R&D activities. The objectives of the optimization are to minimize the total cost and the total makespan, and the constraints are human resource limitation and material resource limitation. After analyzing the complexity of the problem and the difficulty of solving the model, an algorithm based on dynamic programming is proposed, which divides the program into stages and gradually narrows the feasible solution range according to different constraints. Random test instances and a real-life numerical instance are given to compare the special “multimode” optimal scheduling model with the traditional MRCPSP model. The results show that the special “multimode” model which considers the difference of competency levels is not only shorter in program makespan but also lower in total cost than the traditional MRCPSP model which does not consider the difference of competency. Compared with the traditional MRCPSP model, the special “multimode” optimal scheduling model is more consistent with the practice of R&D program management. The research results of this paper are expected to provide a quantitative basis for the R&D program to make more

Table 4: Comparison of two models (random instances).

The number of actual activities	Traditional MRCPSP		Special MRCPSP			
	Average program duration	Average program cost	Average program duration	Program duration reduction%	Average program cost	Program cost reduction%
J=13	37	36730	26	29.7	19212	47.7
J=15	49	58984	34	30.6	30807	47.8
J=17	50	60631	34	32.0	30806	49.2
J=19	60	52661	40	33.3	26269	50.1
J=21	51	61870	37	27.5	32060	48.2
J=23	59	83762	41	30.5	43782	47.7

Table 5: The relevant parameters of the multiproject.

j	k	T_{jk}	L_{jk1}	L_{jk2}	N_{jk}	Successor Activities
1	a_{11}	7	170	140	2	a_{13}, b_{21}, b_{22}
	a_{12}	9	175	165	2	a_{13}, b_{21}, b_{22}
	a_{13}	12	355	410	3	a_{14}
	a_{14}	10	240	220	2	
2	b_{21}	19	380	340	2	b_{23}
	b_{22}	12	360	300	2	b_{24}
	b_{23}	12	260	220	2	b_{25}
	b_{24}	14	500	450	3	b_{25}
	b_{25}	13	280	240	2	

Table 6: The consumption rates of nonrenewable resources.

i	1	2	3	4	5	6	7
Φ_{il}	10	10	13	9	12	10	7
Φ_{i2}	11	8	10	10	13	9	14
i	8	9	10	11	12	Standard staff	
Φ_{il}	12	10	9	10	11	10	
Φ_{i2}	11	9	7	12	13	10	

Table 7: The feasible mode set of staff combinations of b_{11}.

Staff combination	Activity duration	Consumption of z_1	Consumption of z_2	Total cost of z_1 and z_2
1,2	17	340	323	2635
9,10	19	361	304	2603
8,10	17	357	306	2601
6,10	18	342	288	2466
4,10	18	324	306	2502
2,10	17	323	255	2244
1,10	16	304	288	2352

Table 8: The optimal scheduling scheme of traditional MRCPSP.

Activity	Staff combination	Activity duration	Cost	Earliest start time - Earliest finish time
a_{11}	2 Standard staff	7	560	0-7
a_{12}	2 Standard staff	9	720	0-9
a_{13}	3 Standard staff	12	960	9-21
a_{14}	2 Standard staff	10	800	21-31
b_{21}	2 Standard staff	19	1520	0-19
b_{22}	2 Standard staff	12	960	7-19
b_{23}	2 Standard staff	12	960	21-33
b_{24}	3 Standard staff	14	1120	19-33
b_{25}	2 Standard staff	13	1040	33-46

accurate project human resource allocation decisions and project group scheduling.

Since the number of activity modes increases significantly in the special MRCPSP, the NP-hard characteristics of the model cannot be avoided when the scale of the problem is large. Therefore, the dynamic programming algorithm still has its shortcomings. Future work could focus on more universal and effective algorithms to solve the model from the perspective of improving the traditional hyper-heuristic algorithm.

Table 9: The optimal scheduling scheme of special MRCPSP.

Activity	Staff combination	Activity duration	Cost	Earliest start time - Earliest finish time
a_{11}	8,9	4	664	0-4
a_{12}	1,6	6	960	0-6
a_{13}	1,6,7	11	2761	6-17
a_{14}	4,11	7	2004	32-39
b_{21}	2,10	17	2244	0-17
b_{22}	9,12	12	1730	4-16
b_{23}	1,3,10	10	3540	17-27
b_{24}	2,5	15	1368	17-32
b_{25}	10,11	8	1064	32-40

Table 10: Comparison of two models (real-life instance).

Parameter	Traditional MRCPSP	Special MRCPSP (DP)
Program duration /day	46	**40**
Program duration reduction ratio /%		13
Program cost /Chinese yuan	19360	**16335**
Program cost reduction ratio /%		15.6

Table 11: Comparison of the best results obtained by GA and DP for solving special MRCPSP (real-life instance).

Parameter	Special MRCPSP (GA)	Special MRCPSP (DP)
Program duration /day	41	**40**
Program duration reduction ratio /%		2.4
Program cost /Chinese yuan	17284	**16335**
Program cost reduction ratio /%		5.5

Notations

Parameters

a_{jk}: the k^{th} activity of the j^{th} project
P_{jk}: a set of immediate predecessor activities of the k^{th} activity of the j^{th} project
NP: the total number of the projects
Nj: the total number of the activities of the j^{th} project
NR: the total number of the available staff
T: upper limit of multiproject duration
T_{jk}: the time rating of the k^{th} activity of the j^{th} project
N_{jk}: the given quantity of staff that are assigned to the k^{th} activity of the j^{th} project
N_i: the limited quantity of available assigned staff in each period
$\boldsymbol{K_{ijk}}$: the staff-time coefficient for the i^{th} staff to finish the k^{th} activity of the j^{th} project
$H(j,k)$: a set of feasible execution modes for the k^{th} activity of the j^{th} project
Z: the number of species of the material
p_z: the unit price of the z^{th} material
L_{jkz}: the limited quantity of the z^{th} material used for the k^{th} activity of the j^{th} project
Φ_{ijkz}: in each period the consumption quantity of the z^{th} material used for the k^{th} activity of the j^{th} project by the i^{th} staff
Φ_{jkmz}: the sum of staff consumption quantity in each period of the z^{th} material used for the k^{th} activity of the j^{th} project by staff belonging to the m^{th} mode
d_{jkm}: the duration of the k^{th} activity of the j^{th} project under the m^{th} mode
S_{ijkm}: if the i^{th} staff belong to the m^{th} mode of the k^{th} activity of the j^{th} project, the value is 1; otherwise, the value is 0.

0 ~ 1 Decision Variables

y_{jkmt}: if the k^{th} activity of the j^{th} project selects the m^{th} mode and starts at time t, the value is 1; otherwise, the value is 0.

Other Variables

D: the duration of the program, the time from the start of the earliest activity to the completion of the last activity in multiple parallel projects.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

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

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