A Multi-objective Model for Multi-skill Project Scheduling Problem considering Perform Efficiency

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***Abstract*—The growing need of responsiveness for enterprises facing market volatility raises a strong demand for flexibility in their human resource management. This paper presents a multi-objective model for Multi-skill Project Scheduling Problem. We propose a new wage distribution method in which different perform efficiencies of human resources are taken into account. The model aims at minimizing project duration and project costs concurrently. An improved NSGA-II algorithm is designed to solve the model. The algorithm introduces a multi-dimensional chromosome coding scheme to identify the priorities and staff allocation of each activity. Special chromosome crossover and mutation operation are employed to address resource conflicts and constraint violations. Eventually, A case study is presented to verify the efficiency of the proposed approach.**

***Keywords*—Multi-skill Project Scheduling Problem; multi-objective model; human resource management; perform efficiency; improved NSGA-II algorithm**

I. INTRODUCTION

Along with the rapid world economic and social development, global competition is spreading daily and enterprises need to make best use of limited resources urgently in order to gain durative development and kernel capacity for figuring themselves effectively. It's generally known that the shortage of funds, technology and talents have been the main obstacles which blocked the development of enterprises[1]. Talents are the core competitiveness of the organizational structures. Hence, a reasonable allocation of human resources is crucial to performance in many industries. Meanwhile, several past studies[2-4] have indicated that the traditional single-skilled labor leads to unnecessary costs and substantial increase of the project duration, which no longer meets the time demanding.

Multi-skilled labor, however, is becoming more and more popular in modern enterprises. Field studies[5-7] have shown that there're a bundle of benefits brought from multi-skill strategy such as relief of human resource shortage, longer employment duration, increased job satisfaction and better employability. How to allocate the multi-skilled labor scientifically is going to be one of the most important issues needing to be resolved currently. This problem is an extension of Resource Constrained Project Scheduling Problem (RCPSP) called Multi-skill Project Scheduling Problem (MSPSP), which was presented by Néron[8]. The definition of resources and requirement of tasks in the MSPSP to each resource is different from that in the RCPSP. Briefly, the resources of the MSPSP are the human resources with different skills, and each task of a project network requires different skills with different numbers of staffs[9].

In addition, the results of tasks hinge on the effectiveness of the resources assigned to them[10]. Only with high effectiveness can project be completed as soon as possible. It's essential to find out the effectiveness of the available human resources in relation to different project tasks[11]. In this paper, human resources with different levels of effectiveness have been taken into account. The effectiveness of a human resource allocated to a given activity belonging to a certain task is based on the efficiency of the resource performing the skill required for that activity. Overall, the problem is how to schedule each activity and how to assign proper work for staffs under different perform efficiencies so that various requirements are met and the project duration as well as the costs are minimized.

The remainder of this paper is as follows. In section II, we will give a survey of the related work and compare the differences and similarities. In section III, the problem is defined and the model established on the problem is described. Afterwards, the improved NSGA-II algorithm designed to address the problem is proposed in section Ⅳ. Then, the computational results and validation of the model and algorithm are presented in section Ⅴ. Finally, a short summary and some suggestions for future work are provided in section Ⅵ.

II. RELATED WORK

Although a lot of efforts[12-14] have been made for solving the RCPSP, studies on the MSPSP are limited. Classical models for RCPSP usually assumed the single-skill case. For example, Brucker(1999) deemed that each staff has one specific skill and for each skill and each period the capacity of all resources can be aggregated to an overall capacity[15]. Nevertheless, those studies didn't consider that staffs are

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capable of mastering multiple skills and undertaking different types of work.

Heimerl (2009) considered the problem of simultaneously scheduling IT-projects. The problem is modeled as a mixed-integer linear program(MIP) with a tight LP-bound and solved by CPLEX[10]. This method is the most applicable to small or medium-sized problems. However, since the resource-constrained scheduling is a NP-hard problem in general, this exact algorithm usually yields large computational time and could be trapped in "combinatorial explosion" situation[7], a metaheuristic method such as the genetical algorithm (GA) and simulated annealing algorithm (SA) seems to be more effective and practical.

Meanwhile, many past studies[16, 17] only considered single objective in the MSPSP. Actually, enterprises have to achieve multiple objectives at the same time. There were also different keystones in the specific study of multi-objective. shahnazari-shahrezaei (2012) set the first objective to minimize the sum of positive deviations from the minimum penalty and the second objective to minimize the sum of positive deviations from the minimum number of employees considered to work at senior skill level[18]. Yannibelli (2013) held that one objective is the most effective set of employees be assigned each project activity. The other objective is to minimize the project duration[11]. Chen (2017) targeted at skill efficiency gain, product development cycle time and costs[19]. Our research has many similarities with the studies of Yannibelli (2013) and Chen (2017). The remarkable difference between their research and our paper is that we focus on minimizing project duration and project costs. A new wage distribution method where the wage is determined by effectiveness rather than time is proposed for that it's unfair to allocate less wage to the staff who get the work done faster. The high performers should be rewarded. Furthermore, we are able to provide a series of implementation plans for the project manager to choose in accordance with the actual situation of enterprises.

III. MODEL DESCRIPTION

To specify the MSPSP, we give a mathematical description of the problem and establish a multi-objective model as follows.

A. *Problem Description*

A project has n tasks to be processed, each task contains a variety of activities. Each activity requires several staffs with a certain skill to complete by cooperation. The total number of skills required for the project is r, and there are m staffs available for scheduling. Each staff masters multiple skills and each skill is held by various staffs. The effectiveness levels of staffs using a certain skill are different. We define efficiency β to describe the effectiveness level of skills. With high efficiency, staffs can complete activities fast. It is assumed that efficiency only affects the speed of work but doesn't affect the quality of work. The wages are composed of base wage and commissions. The base wage is fixed while the commission is determined by the activity-performing efficiency. During the construction period, the number of staffs is constant, regardless of the resignation. A scientific staff scheduling plan need to be drawn up under the logical constraints and resource constraints.

B. *Symbolic Representation*

1) *Sets*

I - The set of task $i, I = \{1, 2, \cdots, n\}$.
D - The set of tasks on the critical path $D = \{1, 2, \cdots, c\}, c \in [1, n]$.
K - The set of skill $k, K = \{1, 2, \cdots, r\}$.
P - The set of staff p, $P = \{1, 2, \cdots m\}$.

2) *Parameters*

J_{ki} - The activity belonging to task i which is performed with skill k.

b_{ki} - The number of required staffs for performing skill k in task i.

$T_{ki}^{\min}$ - The time that activity J_{ki} take when skill k is performed by staff at maximum efficiency.

$T_i^{\min}$ - The time that the task i take when skill k is performed by staff at maximum efficiency.

$$T_i^{\min} = \sum_{k=1}^{r} T_{ki}^{\min}$$

β_{pk} - The efficiency of staff p performing skill k.

$$\beta_{pk} \in [0, 1]$$

$\overline{\beta}_i$ - The average performing efficiency of task i.
B_i - The beginning time of task i.
F_i - The immediate predecessor task set of task i.
B_{ki} - The beginning time of activity J_{ki}.
φ_{ki} - The priority of activity J_{ki}.
T_{ki} - The duration that spend in activity J_{ki}
$v_{ki}^{\max}$ - The commission for the staff who performs skill k at maximum efficiency in task i
w - The base wage;

3) *Decision variables*

x_{pki} - If staff p doesn't master skill k, then $x_{pki} = -1$, else if staff p is allocated to activity J_{ki}, then $x_{pki} = 1$, or else $x_{pki} = 0$.

y_{pkit} - If staff p is allocated to activity J_{ki} at period t, then $y_{pkit} = 1$, or else $x_{pkit} = 0$.

C. *Multi-objective Model*

$$\min T = \sum_{i \in D} \frac{T_i^{\min}}{\overline{\beta}_i} \tag{1}$$

$$\min C = \sum_{i=1}^{n} \sum_{k=1}^{r} \sum_{p=1}^{m} \left[w + x_{pki} \cdot \frac{T_{ki}^{\min}}{T_{ki}} \cdot v_{ki}^{\max} \right] \tag{2}$$

s.t.

$$\overline{\beta}_i = \frac{\sum_{k=1}^{r} \sum_{p=1}^{m} \beta_{pk} \cdot x_{pki}}{\sum_{k=1}^{r} b_{ki}} \tag{3}$$

$$B_i - B_j \geqslant \frac{T_j}{\overline{\beta}_j}, \forall i \in I, \forall j \in F_i \tag{4}$$

$$B_{ki} - B_{kj} \geqslant T_{kj}, \varphi_{kj} \geqslant \varphi_{ki} \tag{5}$$

$$\sum_{p=1}^{m} x_{pki} = b_{ki}, x_{pki} \neq -1 \tag{6}$$

$$\sum_{i=1}^{n} \sum_{k=1}^{r} y_{pkit} \leqslant 1 \tag{7}$$

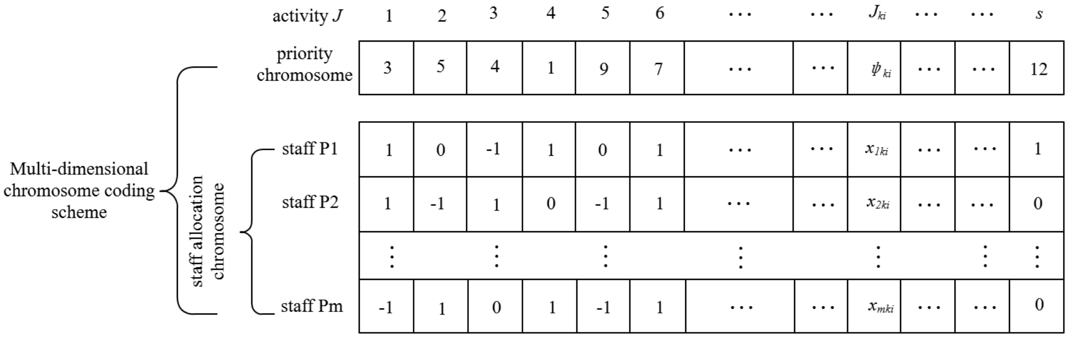

Fig. 1 Multi-dimensional chromosome coding scheme

$$x_{pki} \in \{0, 1, -1\}, y_{pkit} \in \{0, 1\}; \forall p, k, i, t \tag{8}$$

$$x_{pki} = \begin{cases} 1 \ \forall t, y_{pkit} \geq 1 \\ 0 \ \forall t, y_{pkit} < 1 \end{cases} ; \forall p, k, i \tag{9}$$

The objective (1) minimizes the project duration, which is equal to the time when the tasks on the critical path are all finished while the objective (2) minimizes the projects costs, which is composed of base wage and commissions; (3) describes the computational method of the average performing efficiency of task i; (4) is the task logic precedence constraint, which ensures immediate predecessor task j of task i have to be finished before the beginning of task i; (5) denotes that when human resources conflicts occur, high-priority activities take priority occupy of resources; (6) ensures that the required amount of staff in a certain activity is equal to the amount of staff allocated to that activity; (7) represents that once a staff has been allocated to a certain activity, he can't be assigned to another activity at the same time; (8) defines the values of decision variables; (9) denotes the link between the two decision variables.

IV. IMPROVED NSGA- II ALGORITHM

Details of different components in the algorithm are presented in the next sections. The main components of the algorithm are the coding scheme, the fitness function, and crossover, mutation and selection operations.

A. *Coding scheme*

To solve the MSPSP, many previous coding schemes[11, 19] were based on staff, which have led to many illegal coding situations in the process of calculating the objective function. For example, a staff who doesn't master a certain skill may be allocated to the activity that requires that skill. In order to handle that problem, it was common practice to reduce the fitness of unfeasible solutions by penalty, so that it will naturally be eliminated from the future iterations, however, this method will narrow the feasible domain of the solutions. Therefore, we propose a new multi-dimensional activity-based coding scheme in which most of the infeasible solutions will be ruled out without narrowing the search space of the algorithm.

What's more, when human resource conflicts occur, in other words, when two parallel activities request the same staff, the parallel activities need to be converted to serial activities. However, which activity should be executed first hasn't been determined yet between the serial activities. Thus, we introduce a priority coding scheme to the original coding scheme for identifying the priority of each activity, then the order for execution can firm up. Each complete chromosome consists of a priority chromosome and a staff allocation chromosome, as shown in Fig. 1.

- Priority chromosome. A gene of a priority chromosome represents a priority variable φ_{ki} . A row of priority φ form a chromosome, φ is a random natural number ranging from 1 to s (s is the number of activities), when human resources conflicts occur, high-priority activities take priority occupy of resources.
- Staff allocation chromosome. A gene of a Staff allocation chromosome represents a decision variable x_{pki} . Each staff corresponds to a certain row of the chromosome. If the staff doesn't master the skill required for a given activity, then give the gene a value of -1, which means it do not participate in the following operations. If the staff who master the skill is allocated to the activity, the value is 1, otherwise the value is 0.

B. *Fitness function*

Th fitness function evaluates a given solution in relation to Equation (1) and (2). The strategies to calculate the two objectives are summarized as follows.

when a feasible coding scheme is formed, the commissions allocated to each staff can be calculated. The sum of all staffs' wages is equal to the project costs.

Based on the semaphore mechanism in the operating system[20], we abstract one-time activity scheduling as one-time process scheduling on operating systems. The human resources required for activities are abstracted as the shared resources for processes. Firstly, an execution queue and a blocking queue are set separately. The execution queue allows concurrent execution of activities without human resource conflicts. When an activity requests to occupy a resource, if the resource is idle, then it will be transferred to the execution queue for execution, and the resource will be converted to busy; when the activity is completed, the resource will be released.

On the basis of topological sorting algorithm[21], we abstract each activity as a node in topology graph. At first, we set the activity with zero indegree as the initial activity, then add it into the execution queue. Once the activity is completed, it will be removed from the graph, and the indegree of its subsequent activity will subtract one. Next, the following activity is to judged, and so it goes on. When human resource conflicts occur, the activity execution order will be determined by the priorities, the activity with higher priority will be transferred to the execution queue while the activity with lower priority will be transferred to the blocking queue for waiting. The time it takes to complete all activities is equal to the project duration.

C. *Crossover and mutation operation*

To eliminate illegal coding situations and ensure large search space, we design special crossover and mutation operation as follows .

- Priority chromosome. We adopt the SEC crossover strategy[22]: select one group of genes on one parent，find the position of these genes on another parent and fix the position of the unselected genes, then exchange the corresponding genes in two parents according to the order of the appearance position of the selected genes. In addition, we adopt a random mutation strategy[23] for priority chromosomes: randomly generate a mutation point, and replace the corresponding gene value on the mutation point with another randomly generated priority.

- Staff allocation chromosome. a new multi-column merged crossover strategy is proposed: two points are randomly selected as the crossover start point and the crossover end point, then the multi-column gene values between the two cross-sections of the parent chromosome are merged to exchange for generating new feasible offspring chromosomes, as shown in Fig. 2. In order to ensure that the offspring chromosome is still a viable chromosome after mutation, the corresponding amount of staffs must be removed from that activity when a certain amount of staffs are allocated to a activity. Hence, we adopt a reverse mutation strategy: randomly select two gene positions with a gene value of 1 and 0 in one column of a chromosome, then exchange the gene value, as shown in Fig. 3.

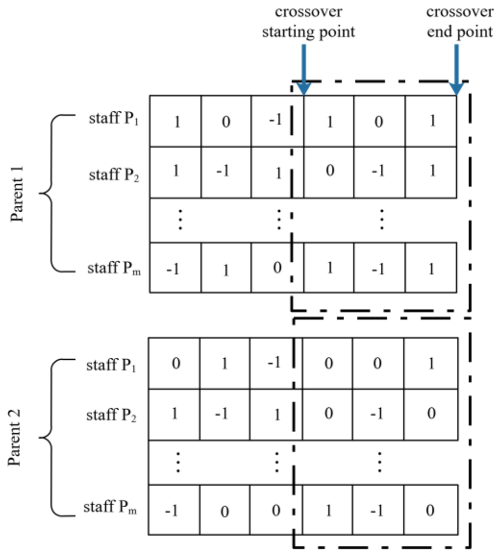

Fig. 2 Staff allocation chromosome crossover operation

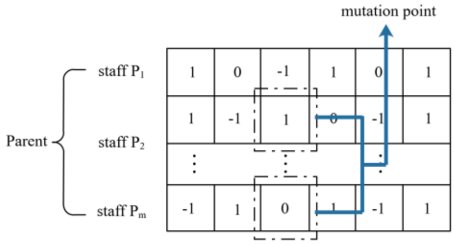

Fig. 3 Staff allocation chromosome mutation operation

D. *Selection operation*

To maintain the diversity of the population，we make use of the fast nondominated sorting approach and adopt the elitist strategy and a crowded-comparison approach in selection operation of NSGA-II[24]. The non-dominated level r and crowding distance d of each individual are calculated. If $r_a < r_b \ or \ r_a = r_b \ and \ d_a > d_b$, the solution a is better than the solution b. The individuals with low non-dominated level and large crowding distance have greater probability of entering the offspring. Based on this method, the non-dominated solutions generated during the algorithm running time are stored in the elite retention pool.

V. CASE STUDY

In this section, the computational experiments developed to test the validity of the our model and evaluate the performance of the improved NSGA-II algorithm are presented. A project of a decoration company is exemplified here.

A. *case specification*

DY is one of the decoration companies in china which contract a construction project for VK residential area. The project contains 16 tasks and requires 3 skills. Each task includes several activities in which staffs need to use a specific skill and the activities total 29. K1 represents the skill mastered by electrician, K2 represents the skill mastered by plumber and K3 represents the skill mastered by mason. The distribution of staff skills and the skill efficiency values are shown in Tab. I. The logic constraints of each task, the required amount of staff, the minimum time and the maximum commission for each activity in relation to a certain skill are shown in Tab. II. We define the base wage 2000 CNY for each staff.

B. *computational experiments and analysis of results*

The improved NSGA-II algorithm proposed for solving the case described above was implemented in MATLAB 9.1.0 (R2016b) and executed on a PC (Intel (R) Core (TM) i5-8250U CPU @ 1.80 GHz). The parameters of algorithm are set as follows: population size $N_p = 400$, crossover probability $P_c = 0.9$, mutation probability $P_m = 0.4$, maximum iterations $G_{\max} = 3000$. Human resource allocation under three different plans are presented respectively in Tab. III. Plan 1 consumes the least time while Plan 3 costs the least. The project duration and project costs under the three plans are 68.2, 83.3, 133.1 days and 63482, 59042, 56910 CNY. The project manager can choose one of the plausible plans and implement it depending on the actual conditions. The assignment and scheduling of each staff under Plan 1 is shown in Fig. 5. The numbers in the figure denote activity ID. Fig. 4 shows the evolutionary processes for the two objective values. From that figure, we can see that both of the objective values are convergent, proving the effectiveness of the algorithm.

TABLE I. THE LOGIC CONSTRAINTS OF EACH TASK, THE REQUIRED AMOUNT OF STAFF, THE MINIMUM TIME AND THE MAXIMUM COMMISSION FOR EACH ACTIVITY IN RELATION TO A CERTAIN SKILL

Task ID	Precedent Tasks	The required amount of staff			The minimum time(day)			The maximum commission (hundred CNY)		
		K1	K2	K3	K1	K2	K3	K1	K2	K3
I1		3	1	-	5	3	-	6	3	-
I2	I1	-	4	-	-	8	-	-	7	-
I3	I2	3	-	1	6	-	2	5	-	2
I4	I3	-	2	4	-	4	9	-	4	10
I5	I3	-	2	-	-	5	-	-	5	-
I6	I3	4	-	1	9	-	1	6	-	1
I7	I4	3	-	2	5	-	3	6	-	3
I8	I5	-	3	3	-	7	6	-	8	5
I9	I8	-	3	-	-	5	-	-	5	-
I10	I8, I9	1	3	2	2	6	4	3	6	4
I11	I9	-	3	1	-	7	4	-	9	3
I12	I9	-	4	-	-	10	-	-	7	-
I13	I10	2	-	5	5	-	13	5	-	10
I14	I12, I16	-	2	3	-	3	7	-	2	8
I15	I4	1	3	-	3	4	-	3	6	-
I16	I11	-	3	2	-	6	2	-	8	3

TABLE II. THE DISTRIBUTION OF STAFF SKILLS AND THE SKILL EFFICIENCY VALUES

Skill ID		K1	K2	K3
Staff ID	P1	1	0.8	-
	P2	1	-	0.6
	P3	1	0.8	0.6
	P4	0.8	1	0.6
	P5	0.8	1	-
	P6	-	1	0.7
	P7	0.6	0.8	1
	P8	-	0.9	1
	P9	0.7	-	1
	P10	1	0.6	-
	P11	-	1	0.5
	P12	0.8	-	1
	P13	0.5	-	1

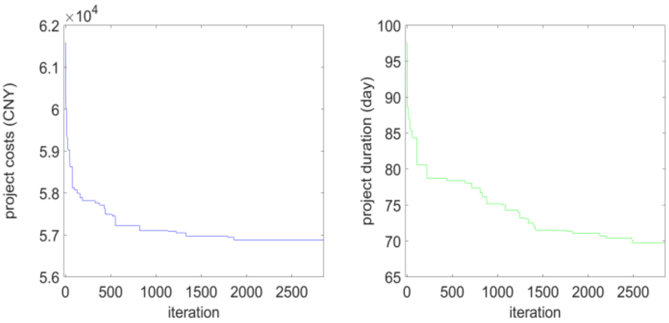

Fig. 4 Evolutionary processes of project duration and project costs

TABLE III. HUMAN RESOURCE ALLOCATION UNDER DIFFERENT PLANS

Activity ID	Skill ID	Typical Plan		
		Plan 1	*Plan 2*	*Plan 3*
1	K1	P1, P2, P3	P5, P7, P12	P7, P9,P12
2	K2	P10	P10	P10
3	K2	P1, P4, P5, P6	P1, P7, P8, P10	P1, P7, P10, P11
4	K1	P1, P2, P5	P9, P10, P12	P5, P7, P9
5	K3	P13	P2	P4
6	K2	P6, P11	P8, P11	P10, P11
7	K3	P8, P9, P12, P13	P2, P3, P4, P13	P2, P3, P4, P13
8	K2	P3, P4	P1, P10	P10, P11
9	K1	P1, P2, P7, P10	P5, P7, P9, P12	P4, P7, P9, P12
10	K3	P13	P2	P3
11	K1	P2, P3, P5	P5, P7, P9	P5, P7, P9
12	K3	P4, P13	P2, P6	P3, P13
13	K2	P3, P5, P6	P1, P10, P11	P3, P10, P11
14	K3	P7, P8, P12	P4, P8, P13	P2, P3, P4
15	K2	P3, P5, P11	P1, P3, P10	P1, P7, P10
16	K1	P12	P7	P7
17	K2	P1, P6, P8	P6, P8, P11	P3, P10, P11
18	K3	P4, P9	P2, P4	P2, P13
19	K2	P1, P5, P11	P1, P3, P10	P7, P10, P11
20	K3	P3	P2	P2
21	K2	P4, P7, P8, P10	P5, P7, P8, P11	P1, P7, P10, P11
22	K1	P4, P7	P7, P9	P7, P9
23	K3	P2, P6, P9, P12, P13	P4, P6, P9, P12, P13	P2, P3, P4, P6, P13
24	K2	P3, P10	P10, P11	P8, P10
25	K3	P7, P8, P12	P2, P3, P13	P2, P4, P13
26	K1	P9	P12	P7
27	K2	P1, P10, P11	P1, P3, P10	P1, P10, P11
28	K2	P1, P3, P5	P1, P3, P10	P7, P10, P11
29	K3	P9, P12	P2, P8	P2, P4

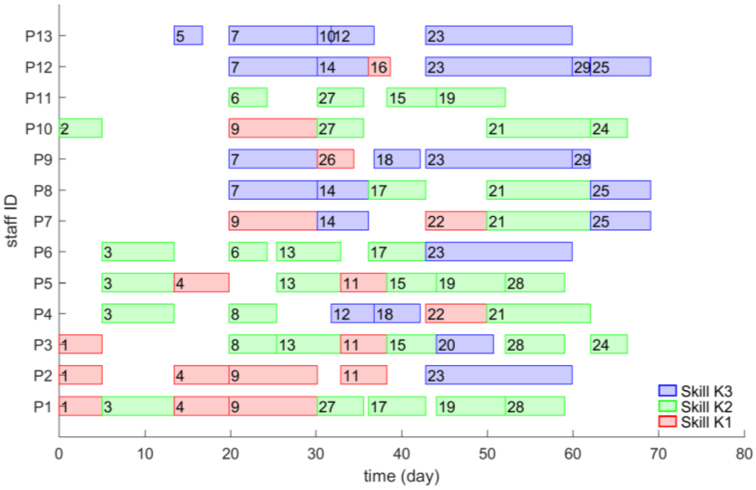

Fig. 5 The assignment and scheduling of each staff under minimum costs (Plan 1)

To evaluate the validity of the proposed multi-skill model, we use the single-skill model in which each staff can only perform one of their skills in the above project for comparison. Fig. 6 shows the pareto optimal solution sets from the above two models. The blue is from multi-skill model while the red is from single-skill model. It can be easily concluded that the multi-skill strategy can shorten the project duration and decrease the project costs to a great extent, which indicates that our proposed model is far more efficient.

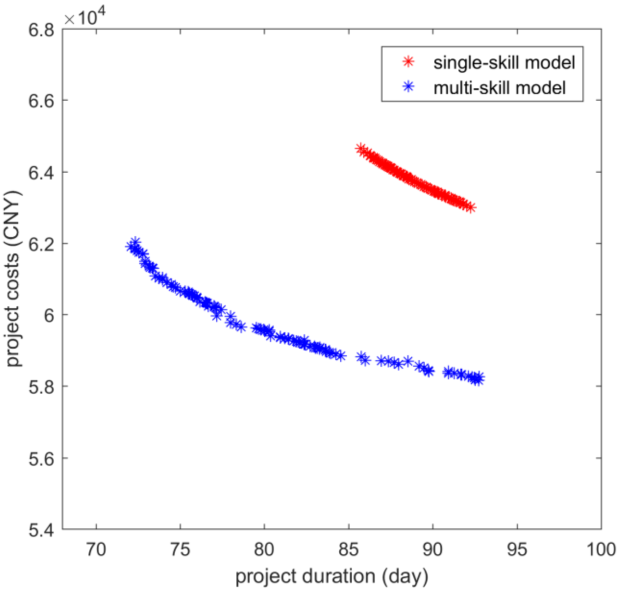

Fig. 6 The pareto optimal solution sets from the single-skill model and the multi-skill model

VI. CONCLUSION

This paper studies Multi-skill Project Scheduling Problem in construction projects from the perspective of multi-skilled labor allocation and multiple objectives in enterprises. We propose a new wage distribution method and establish a multi-objective model for that problem. An improved NSGA-II algorithm is designed to solve the model. The validity of the model and the performance of the algorithm are illustrated through a simulation case. The results indicate that our approach can provide a reasonable basis for the decision-making of talent allocation, construction period estimation and cost budgeting in industries. Further research, the realization of other objectives such as internal talent training, project quality value will be taken into consideration.

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