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Abstract: Human resource is a key factor for IT new product development. Considering multi-skilled employees in IT Project Portfolio Scheduling, a mixed integer nonlinear programming model with three optimization objectives is proposed from the view of project or product managers. The three objectives are to maximize the increments of skill efficiency values for all multi-skilled employees, to minimize R&D cycle and to minimize R&D costs for the IT product respectively. We develop an improved ant colony optimization algorithm combining with the advantages of genetic algorithm to acquire the Pareto solution set of the multi-objective optimization problem and get the optimal solution by a weighted ideal point method. Finally, empirical analysis is done through a new IT product portfolio scheduling and staff assignment problem of the distribution network automation monitoring terminal from an electrical device company. The empirical results show our model accords with the business's practice and the proposed algorithm is effective.

Keywords: portfolio scheduling, staff assignment, multi-skill, ant colony optimization, IT project

1. INTRODUCTION

IT product development is one of the main businesses for IT companies. With the development of technology and the promotion customer requirements, IT product development becomes more and more complex and results in that a new IT product development integrates a set of projects which is called project portfolio. From that, IT New product research and development (R&D) project portfolio refers to a set of projects which need to be managed concentratedly to achieve the new IT product development targets, which usually contains both software projects and hardware projects. Therefore, the general project management methods and tools can't meet the demand of IT Project portfolio management. Cooper et al. made systematic research for general portfolio management theory and method [1-5]. They pointed out that portfolio management is the basis of new product development for a company, and is about resources distribution, that is how a company allocates capital and human resource and how to select the proper investment projects.

There has been lots of works on portfolio selection and capital allocation [6-10], but papers on portfolio scheduling, especially on staff scheduling has seldom been seen. This problem belongs to the Resource-Constrained Multi-Project Scheduling Problem (RCMPSP), but it has a more complicated relationship under the environment of portfolio. When refer to R&D activities for IT product development, the critical resource is human resource. In an IT product R&D project portfolio, staff scheduling become complicated because employees are usually multi-skilled. For example, a programmer may master several computer languages such as C, C++, java, C#, etc. A system designer may master some development language and/or algorithm designing. What's more, a hardware designer may hold skills of software design. In general, this kind of the problem which is called multi-skilled can be expressed as an employee holds more than one skill, a skill may be mastered by more than one person, and a project needs several skills to perform the tasks. It forms the

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many-many relationships between skills and employees. From the practice, a multi-skilled employee has different skill efficiency level on different skill. That is to say, skill efficiencies of multi-skilled employees are usually heterogeneous. Some papers haves made efforts on the research of multi-skilled allocation in project scheduling and even in a multiple projects environment. Bellenguez-Morineau and Néron[11] researched multi-skill scheduling problem with a single objective of makespan in a single project and proposed a branch-and- bound method to solve the linear programming. Correia and Saldanha-da-Gama[12] present a linear programming model for multi-skill project scheduling with single objective of costs in a single project and solve it with CPLEX. Heimerl and Kolisch[13] researched multi-skilled workforce scheduling problem with single objective of costs in multiple projects for IT product development and solve it with CPLEX. All of the above papers assumed that skill levels are homogeneous and considered a single objective model. Yannibelli and Amandi [14] researched a multi-objective model for multi-skill scheduling problem in a single project and solve it with a multi-objective evolutionary algorithm. They assumed skill efficiency was determined by four factors: activity, skill, set of employees and attributes of employees.

Wu and Sun[15] established a nonlinear multi-skill scheduling model considering skill efficiency increasing due to learning effect with a single objective of costs in multiple projects of software and solve it with a GA algorithm. They only considered one kind of skill. Gutjahr, Katzensteiner et al[16] put forward a multi-objective model for project portfolio selection which contain a sub problem of multi-skill employee scheduling and solve the problem with two meta-heuristic algorithms. Their main innovation point was through multi-skilled employee scheduling to solve the problem of in-house “production” of competencies, thus the company attain and sustain strategic positions in market competition. But the model only considered two objectives of economic benefits and competency benefits, and aimed to portfolio selection in nature. They didn’t consider the relationship between subprojects. The key objective of time for scheduling problem has not been thought over. Time target shouldn’t be ignored in new product R&D portfolio, because the low innovation efficiency may lead to a loss of market opportunities. The lag of time gives competitors a chance to push new product one step ahead, and results in the failure of company’s new product strategy or a heavy discount of new product profitability.

Different from their researches, we present a mixed integer nonlinear programming model with multi-objectives for IT product R&D project portfolio multi-skill scheduling. From the view of R&D manager, three objectives of skill increments, R&D cycle and costs are considered simultaneous in the model. The last two objectives are mostly used by many optimization models, but the first objective is seldom considered. Actually cultivate the R&D team is a main duty for R&D manager, but a skillful employee can’t be easy recruited in time from job market when encountering the problem of shortage of qualified personnel. Therefore an effective way to solve the problem is internal training during routine project developing process. Thus, the objective of the skill earnings is a practical goal for R&D manager which should be taken into account. We solve the multi-objective optimization model with an improved ant colony optimization (ACO) algorithm.

The remainder of this paper is organized as follows. Section 2 describes the model of R&D portfolio scheduling and multi-skilled staff assignment. Section 3 proposes the algorithm for the proposed model. Section 4 adopts an instance to illustrate the proposed model and algorithm presented in section 2 and 3. The last section gives the conclusion.

2. MODEL FORMULATION

2.1 Problem description

Suppose an IT product R&D portfolio PP has m subprojects to be performed and subprojects precedence has been given. Each subproject needs several skills to finish all tasks. Assume each task in a project need one skill, so we can use the certain skill to replace the task in rest of this paper. s is the total number of skills required by the whole portfolio and n is the total number of staff. A project contains several tasks and each task needs one certain skill. A skill is held by more than one employee and an employee possesses more than one skill. The scheduling decision is to assign i with skill j to project p ($i=1,2,\cdots,n$, $j=1,2,\cdots,s$, $p=1,2,\cdots,m$) and determine final scheduling scheme by the tradeoff of skill efficiency profits, R&D cycle and costs. Assume that employee skill level complies with learning curve[17], that is to say, an employee's efficiency will promote by more practice. We deal with the expression of skill efficiency value like Wu and Sun[15]. Calculation of employees' skill efficiencies will be done at the end of each project, without considering the changes at each period within a single project. The increment of employee's skill efficiency accords with the so-called plateau effect. That is to say, the most skilled employee can't enhance the skill efficiency or increases efficiency so little that it can be neglected by doing more.

2.2 Notation

2.2.1 Parameters

I_j set of employees who master skill j.

S_p set of skills which is needed by project p.

R_p^j binary variable that indicates whether skill j is required by project p.

C_i salary of employee i for each period.

$T_{jp}^{\min}$ time of the skill j required by project p when the skill j is performed by the most skilled employee which represents the topmost level of R&D in the company.

PS_p precedence project set of project p.

PE project set which includes all projects completed before project p.

E_{ij}^s initial efficiency value of skill j of employee i, $E_{ij}^s \in [0,1]$. E_{ij}^s is given at the beginning of portfolio by expert panel which includes R&D manager, project manager, industry expert and personnel assessment specialist, according to an employee's skill, knowledge, experience and performance etc. If employee i doesn't master skill j, E_{ij}^s is equal to 0. If employee i is the most skilled person in skill j in the company, E_{ij}^s is set to 1.

E_{ijp}^s efficiency value of skill j of employee i at the beginning of project p.

E_{ij}^f final efficiency value of skill j of employee i when the portfolio is completed.

a_{ij} learning factor of staff i in skill j, $a_{ij} = -\ln(l_{ij}) / \ln 2$ and $0 < l_{ij} \le 1$. l_{ij} is the learning percentage. The smaller is the value of l_{ij}, the larger is the value of a_{ij}, and the greater is the learning effect.

T_{ijp} time of the skill j of employee i spent in project p.

T_p duration of project p.

t_p^s start time of project p.

t_p^f end time of project p.

ΔE_{ij} the skill increment of employee i on skill j.

2.2.2 Decision Variables

x_{ijp} binary variable that takes the value of 1 if employee i is allocated to project p with skill j.

y_{ijpt} binary variable that takes the value of 1 if employ i is allocated to project p with skill j at period t.

2.3 Mathematical model

The proposed mathematical model is as follows, which contains three objective functions and multiple constraints.

$$\max \Delta E = \sum_{i=1}^{n} \sum_{j=1}^{s} \Delta E_{ij} \tag{1}$$

$$\min T = \max_{1 \le p \le m} t_p^f \quad (2)$$

$$\min C = \sum_{i=1}^{n}\sum_{j=1}^{s}\sum_{p=1}^{m} x_{ijp} T_{ijp} C_i \quad (3)$$

Objective function （1）of the model is to maximize the total skill increments of employees, which is equal to the sum of added values for all employees. Objective function （2）is to minimize the R&D period of the IT product R&D portfolio, which is equal to the time when the last project of the portfolio is finished. Objective function （3）is to minimize the costs of the portfolio which is equal to the sum of salaries for all selected employees.

s.t.

$$T_{ijp} = \frac{T_{pj}^{\min}}{E_{ijp}^{s}} \quad (4)$$

$$T_p = f(x_{ijp}, \mathrm{T}_{ijp}) \quad (5)$$

$$t_p^f = t_p^s + T_p \quad (6)$$

$$\max_{p' \in PS_p} \left\{ t_{p'}^f \right\} \le t_p^s \quad (7)$$

$$E_{ijp}^{s} = \begin{cases} E_{ij}^{s}\left(\sum_{p' \in PE} x_{ijp'} T_{ijp'}\right)^{a_{ij}} & \exists x_{ijp'} = 1 \quad for \quad p' \in PE \\ E_{ij}^{s} & \forall x_{ijp'} = 0 \quad for \quad p' \in PE \end{cases} \quad (8)$$

$$E_{ijp}^{s} = 1 \quad if \quad E_{ijp}^{s} > 1 \quad (9)$$

$$E_{ij}^{f} = \begin{cases} E_{ij}^{s}\left(\sum_{p=1}^{m} x_{ijp} T_{ijp}\right)^{a_{ij}} & \exists x_{ijp} = 1 \\ E_{ij}^{s} & \forall x_{ijp} = 0 \end{cases} \quad (10)$$

$$E_{ij}^{f} = 1 \quad if \quad E_{ij}^{f} > 1 \quad (11)$$

$$\sum_{i=1}^{n} x_{ijp} = R_p^j \quad \forall j, p \quad (12)$$

$$\sum_{j=1}^{s} x_{ijp} \le 1 \quad \forall i, p \quad (13)$$

$$\sum_{j=1}^{s}\sum_{p=1}^{m} y_{ijpt} \le 1 \quad \forall i, t \quad (14)$$

$$\Delta E_{ij} = E_{ij}^{f} - E_{ij}^{s} \quad \forall i, j \quad (15)$$

$$E_{ijp}^{s} \in [0,1] \quad and \quad E_{ij}^{f} \in [0,1] \quad \forall i, j, p \quad (16)$$

$$x_{ijp} \in \{0,1\} \quad and \quad y_{ijpt} \in \{0,1\} \quad \forall i, j, p, t \quad (17)$$

Constraint (4) describes time employee i spends on project p with skill j. Constraint (5) calculates the durations of each project. If the skills are parallel, then we make the maximum duration from all skills as the project makespan. If the skills are serial, then we make the sum of durations for all skills as the project makespan. If the relationships between skills are both parallel and serial, then we can compute the duration of project p according to the critical chain rule[18]. Constraint (6) shows the end time of project p is the sum of start time and duration. Constraint (7) shows project p must start after all precedence projects are finished. Constraints (8) and (9) calculate the efficiency level of skill j of employee i at the beginning of project p. Constraints (10) and (11) calculates final the efficiency level of skill j of employee i at the end of project portfolio. Constraint (12) indicates if a skill is needed by project p, it must be performed by an employee and also not be performed by more than one person. Constraint (13) denotes one employee can only use one skill to participate a project, in order to insure the continuity of work and enhance the efficiency of specialized division. Constraint (14) denotes the constraint of time for each employee. That is to say, if an employee is assigned with a skill, she/ he will have no more time to be occupied by another work on the condition that we don’t consider working overtime. Constraint (15) calculates the skill increments of each employee. Constraints (16) and (17) are for limiting the values of variables.

3. IMPROVED ANT COLONY OPTIMIZATION ALGORTTHM

RCMPSP has been known as NP-hard[19]and further more the multi-skill project portfolio scheduling and staff assignment problem in our paper is also NP-hard. Since the decision model contains three objectives and several non-linear constraints, we develop an improved ACO algorithm based on Pareto set. From the algorithm we can obtain the Pareto-optimal set. From the view of practice, managers still have to make a choice from the Pareto-optimal set in practice, because only one solution will be executed finally. Considering the preference of decision-makers, we get the final optimum solution by a weighted ideal point method.

3.1 Population initialization

ACO is proposed by Marco Dorigo[20]. It can get the shortest path by simulating foraging behavior of ant colony. It has been applied in various kinds of combinational optimization problem, so as RCPSP [21]. In project portfolio scheduling problem, each ant generates schedule scheme through gradually expanding local schedule scheme. In our problem, starting from the first skill of the first project, an ant selects an employee who masters the skill to perform the skill. For the staffing of skill j, candidates must belong to the set of I_j. The selection probability of ant k from employee i_1 to employee i_2 can be calculated as follows:

$$P_{i_1 i_2}^k = \begin{cases} \dfrac{\left[\tau_{i_1 i_2}(t)\right]^\alpha * \left[\eta_{i_1 i_2}(t)\right]^\beta}{\sum\limits_{s\in I_j}\left[\tau_{i_1 i_s}(t)\right]^\alpha * \left[\eta_{i_1 i_s}(t)\right]^\beta} & s \in I_j \\ 0 & s \notin I_j \end{cases} \tag{18}$$

$\tau_{i_1 i_2}(t)$ indicates the pheromone concentration between i_1 and i_2 at time t ($\tau_{i_1 i_2}(0)=0$). $\eta_{i_1 i_2}(t)$ indicates the heuristic function. α and β denote the importance of pheromone and heuristic function.

3.2 Pheromone updating

According to section 3.1, we can get multiple staff scheduling schemes. Calculate three objective values of the scheduling scheme from each ant and compare the values of each objective, and then we get the Pareto solutions (also called non-dominated solution). If all objectives of solution x_1 are equal or superior to objectives of solution x_2, and at least one objective of x_1 superior to objective of solution x_2, then we call solution x_1 dominates solution x_2. If a solution is not dominated by any other solutions, it is a non-dominated solution. For each Pareto solution, the pheromone concentration can be updated as follows:

$$\begin{aligned} &\tau_{i_1 i_2}(t+1) = (1-\rho)\,\tau_{i_1 i_2}(t) + \triangle\tau_{i_1 i_2} \quad 0<\rho<1 \\ &\triangle\tau_{i_1 i_2} = \sum_{k=1}^{N} \triangle\tau_{i_1 i_2}^k \end{aligned} \tag{19}$$

ρ indicates the volatilization rate of pheromone. $\triangle\tau_{i_1 i_2}^k$ denotes the pheromone concentration released from ant k at period t between i_1 and i_2. It can be calculated as follows.

$$\begin{aligned} &\triangle\tau_{i_1 i_2}^k = \begin{cases} \dfrac{Q}{L_k} & \text{if ant } k \text{ has moved from } i_1 \text{ to } i_2 \\ 0 & \text{otherwise} \end{cases} \\ &L_k = \frac{E_{\max}}{E_k} + \frac{T_k}{T_{\min}} + \frac{C_k}{C_{\min}} \end{aligned} \tag{20}$$

L_k indicates the integrated objective value; Q is a constant; E_k , T_k and C_k denote the objective values of skill increments, time and costs respectively. $E_{\max}$, $T_{\min}$ and $C_{\min}$ represent the optimum values of the three objectives in current iteration, which are used to normalize the objective values.

3.3 Decision making for the best solution

To determine the best solution from the Pareto set, we use a weighted ideal point method as follows:

$$D_1^k = \sum_{r=1}^{R} \lambda_r f_1(O_r, O_r^+) \quad (21)$$

$$D_2^k = \sum_{r=1}^{R} \lambda_r f_2(O_r, O_r^-) \quad (22)$$

$$D^k = \frac{D_1^k}{D_1^k + D_2^k} \quad (23)$$

O_r , O_r^+ and O_r^- denote the objective value of the Pareto solution k , the optimal value and the worst value under objective r respectively. D_1^k is the distance between solution k and positive ideal points, D_2^k is the distance between solution k and negative ideal points, and D^k is the relative approaching degree which is used to denote the final evaluation value of k . λ_r is the weight of the rth objective($\sum_{r=1}^{R} \lambda_r = 1, \lambda_r \in [0,1]$). The form of function $f_1(O_r, O_r^+)$ is determined by the type of objective r . If it is a benefit objective, then $f_1(O_r, O_r^+) = \frac{O_r}{O_r^+}$; otherwise, if it is a cost objective, then $f_1(O_r, O_r^+) = \frac{O_r^+}{O_r}$. For the form of function $f_2(O_r, O_r^-)$, if it is a benefit objective, then $f_2(O_r, O_r^-) = \frac{O_r^-}{O_r}$; otherwise, if it is a cost objective, then $f_2(O_r, O_r^-) = \frac{O_r}{O^-}$.

3.4 Improved ACO flow

The improved ACO flow is described as follows, which we introduce the crossover and mutation to increase the diversity of ant population.

Step 1 Set algorithm parameters of maximum generation G , number of initial ants N , crossover probability P_c , mutation probability P_m , etc.

Step 2 Start loop iteration. Initialize ant population by local extension mechanism. Each skill is allocated with an employee whose selected probability can be calculated through equation (16). Generate new ants by N times of crossover and mutation respectively from the current population. Merge the current population, the new ants and the Pareto optimal set (initial Pareto set is a null set). Delete the repetitive ants in the new population.

Step 3 Each ant generates a staffing scheme. According to each scheme, calculate each project's duration by serial schedule generation scheme (SSGS)[22] and compute each selected employee's skill efficiency and costs. Then we can get the three objective values. Checking out constraints, if constraint (12) is infeasible, replace the current employee with another feasible one; if constraint (13) is infeasible, give each objective value a penalty value.

Step 4 According to each ant objective values, acquire the Pareto solution set by pairwise comparison. For each ant with Pareto solution, update pheromone concentration according to section 3.2 .

Step 5 Repeat steps 2-4 until the maximum generation, and then turn into step 6.

Step 6 Calculate the final evaluation value for each Pareto solution according to equations (19), (20) and (21). Make the one with highest final evaluation value as the best solution.

4. APPLICATION TO AN EXAMPLE

The R&D portfolio for a new distribution network automation monitoring terminal product from a leader electrical device company in china can be used to demonstrate and verify our model and algorithm. Table 1-4 gives the data of the problem. Skills in each project are parallel. According to the experts' experience and the time records of past R&D projects for staff, the learning rate is obtained as 0.95. Further, considering factors such as market competition, corporate talent strategy and financial budget for the new product, decision-makers give $\lambda_1 = 0.5$, $\lambda_2 = 0.3$, $\lambda_3 = 0.2$.

Table 1. Precedence relationship of subprojects in project portfolio

R&D project portfolio for a new distribution network automation monitoring terminal product		
Project ID	Project name	Precedence projects
P1	Station monitoring terminal controller	Null
P2	Feeder terminal controller	Null
P3	Distribution transformer terminal controller	Null
P4	Switching station monitoring terminal	P10
P5	Ring main unit monitoring terminal	P10
P6	Centralized feeder terminal	P4,P5
P7	Voltage-time feeder terminal	P4,P5
P8	Boundary feeder terminal	P4,P5
P9	Panel feeder terminal	P4,P5
P10	Distribution network terminal maintenance software	P1,P2,P3

The proposed algorithm for above instance has been implemented by MATLAB 7.11.0 (R2010b) on a computer (Intel（R）Core（TM）i5-3470 CPU@3.20GHz). We adjust the parameters through trial and error. According to the quality of solutions in experiments, parameters are set as follows: $G = N = 100$, $P_c = 0.9$, $P_m = 0.2$, $\eta=\beta=Q=1$, $\alpha=1$, $\rho=0.1$.

Table 2. Shortest time for each skill in all projects (month)

Skill name /ID	Project ID									
	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
Industrial design/S1	1	1	1	—	—	—	—	—	—	—
Hardware design/S2	2	2	2	—	—	—	—	—	—	—
Electrical design/S3	—	—	—	3	2	3	2	2	2	—
Embedded soft-ware design/S4	10	8	8	—	—	—	—	—	—	4
System software design/S5	—	—	—	—	—	—	—	—	—	8
Software test/S6	2	2	2	2	1	2	1	1	1	3
Hardware test/S7	1	1	1	2	1	2	1	1	1	—
Electrical test/S8	—	—	—	1	1	1	1	1	1	—

Table 3. Staff Salaries

Employee ID	Salaries (CNY/month)
1~10	（7000,4000,6000,6000,5500,5500,8000,7500,7000,4000）
11~20	（7000,4000,7500,5000,6000,8000,7000,4000,9000,6500）
21~30	（6500,4500,6000,6000,5000,4000,7000,6500,6000,5000）
31~40	（6500,4000,6000,4000,5000,6500,5000,4000,5500,8500）

Table 4. Initial skill values of employees

Skill ID	Staff ID	Initial skill value
S1	(1,2,3,4,5,6,8,27,28,34,37)	(1.0,0.6,0.8,0.8,0.6,0.7,0.6,0.8,0.8,0.5,0.8)
S2	(1,2 ,4,5,6,7,8,9,10,11,20,21,22,25,27,28, 29,30)	(0.6,0.5,0.8,0.8,0.8,1.0,0.9,0.8,0.6,0.8,0.6,0.6,0.5,0.6,0.6,0.8, 0.8,0.6)
S3	(3,6,27,28,29,30,32,36,39)	(0.8,0.5,1.0,0.8,0.8,0.8,0.6,0.9,0.8)
S4	(15,16,17,18,19,20,21,22,23,24,25,40)	(0.6,0.9,0.8,0.5,1.0,0.8,0.8,0.6,0.8,0.6,0.6,0.9)
S5	(13,14,15,16,31,40)	(1.0,0.7,0.8,0.6,0.5,0.9)
S6	(13,15,17,19,23,24,26,31,40)	(0.5,0.8,0.8,0.8,0.6,0.9,0.6,1.0,0.6)
S7	(7,8,9,11,12,21,22,33,35,)	(0.8,0.8,0.8,1.0,0.6,0.5,0.5,0.8,0.8)
S8	(33,35,36,37,38,39)	(1.0,0.8,0.6,0.8,0.6,0.6)

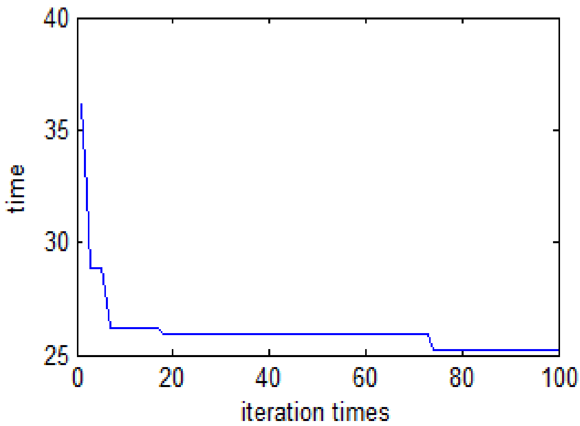

Figure 1. Evolution of R&D cycle

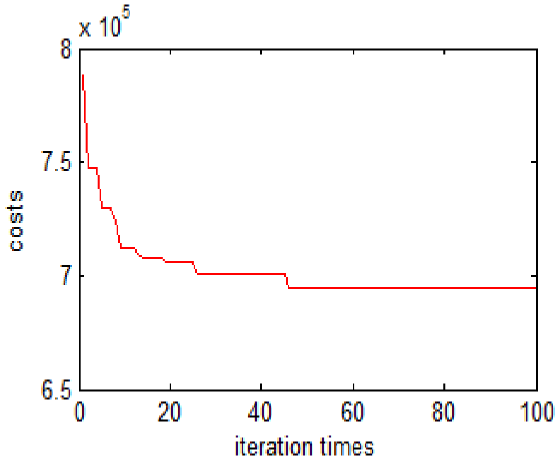

Figure 2. Evolution of R&D costs

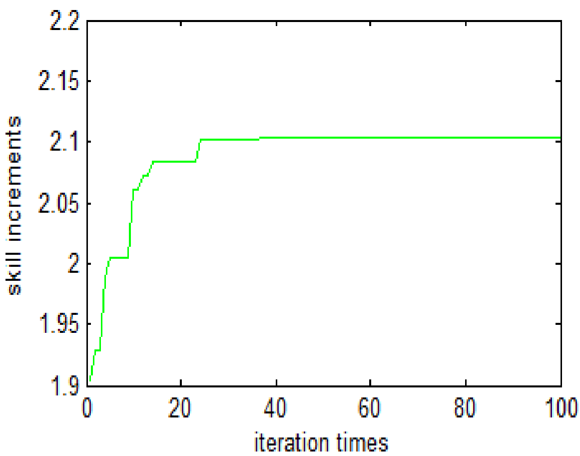

Figure 3. Evolution of skill increments

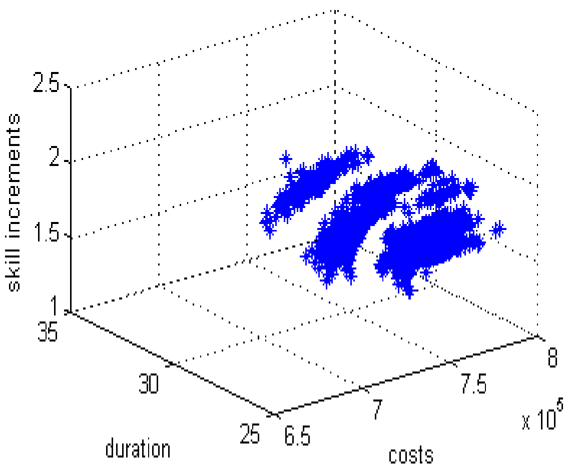

Figure 4. Pareto front

Table 5. Results of the best solution

Best solution	Project ID index: skill ID index (P1:S1,S2,S4,S6,S7 // P2:S1,S2,S4,S6,S7 // P3:S1,S2,S4,S6,S7 // P4:S3,S6,S7,S8 // P5:S3,S6,S7,S8 // P6:S3,S6,S7,S8 // P7:S3,S6,S7,S8 // P8:S3,S6,S7,S8 // P9:S3,S6,S7,S8 // P10:S4,S5,S6)		
Staff ID	(2 5 40 15 21 // 3 5 17 15 12 // 2 4 20 15 33 // 23 13 26 36 // 26 8 35 30 // 31 12 39 30 // 24 33 38 3 // 13 7 38 29 // 26 35 33 39 // 23 22 35)		
objective value	$E = 1.8866$	$T = 25.9486$	$C = 734235.52$

5. CONCLUSIONS

This paper investigates a model for IT product R&D portfolio scheduling and multi-skilled staffing problem. There are three conflicting objectives in the decision model, which are skill efficiency increment, R&D cycle and cost. A mixed integer nonlinear programming is formulated to model the decision problem. An improved ACO algorithm is designed to solve the nonlinear and multi-objective model. In the algorithm, SSGS is used to generate the schedule of portfolio and the skill values of staff are calculated in the process. A Pareto optimal set is obtained by the proposed algorithm and the final solution is evaluated by a weighted ideal point method. An instance is introduced to prove the validity of the proposed model and algorithm.

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