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RESEARCH ARTICLE

Optimization of the Recruitment Quota Allocation in Intra-Organizational Networks

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ABSTRACT In a decentralized organization such as a university, recruitment is critical for the development of departments. With the limited resources for recruitment, how to allocate the recruitment quotas to different departments is an essential problem for the human resource management center of the organization. Specifically, for a recruitment process that includes multiple phases, a proper number of quotas should be allocated to different departments at each recruitment phase to guarantee the recruitment performance of the whole organization. However, it is difficult since the performance of the whole recruitment process is prior unknown at each recruitment phase. Traditionally, a recruitment quota allocation scheme that evenly allocates recruitment quotas at different phases of a recruitment process is generally adopted, which is somewhat subjective due to the lack of quantitative analysis and may not achieve satisfying recruitment performance. Therefore, in this paper, a recruitment quota allocation scheme is proposed to provide a more objective and theoretical method that may achieve optimal performance. In the proposed scheme, we evaluate its performance by considering the competence of applicants and the number of potential applicants and obtain an improved recruitment quota allocation policy using the Markov decision process approach. Specifically, we first define the recruitment utility as the performance metric for the recruitment process. The recruitment quota allocation problem is formulated using the Markov decision process approach, where the effect of the information of potential applicants is innovatively taken into account. Then, the recruitment quota allocation is optimized by maximizing the recruitment utility to achieve optimal recruitment performance. In addition, a scheme that evenly allocates recruitment quotas at different phases of a recruitment process, which is traditionally adopted in the recruitment of a university, is used for comparison with the optimized scheme of the paper. Simulation results show that it is better to appropriately allocate more recruitment quotas in the early phases of a recruitment process than to allocate the quotas evenly over phases. Besides, it is also shown that the proposed scheme can improve the efficiency of recruitment quota allocation significantly.

INDEX TERMS Recruitment, quota allocation, organizational network, Markov decision process.

I. INTRODUCTION

Organizations are goal-directed social entities that execute activities among actors and interact with external environments [1]. With specific goals to achieve, the whole organization should guarantee highly efficient operations, which is challenging in practice, especially for decentralized organizational systems. The intent of achieving the global optimal

performance may be hindered by their branches due to the decentralized management having limited influence on the behaviors of branches as well as their individual ambitions as semi-autonomous decision makers. This type of situation can be evident in organizations consisting of a number of individual decision-making units under the control of a central principle, such as bank branches and university departments. In these scenarios, unfavorable competitions within the organization, which are caused by branches competing for more shared resources, may occur frequently and thus lead to

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inefficiency of operations [2]. Therefore, central management approaches to address the problems mentioned above appear necessary for such intra-organizational networks, causing a centralized resource allocation problem.

In a decentralized organization such as a university, the recruitment process plays a critical role in its development, while the recruitment quota allocation for different departments is a critical influence factor for the efficiency of recruitment, which can be considered a centralized resource allocation problem. Therefore, this paper focuses on the recruitment quota allocation problem in universities. Specifically, the human resource management center holds a fixed number of recruitment quotas that will be used to determine the maximum number of people recruited by each department at different recruitment phases. Generally, each department may attempt to recruit as many talents as possible for its development, while the human resource management center needs to consider the requirements of all departments to allocate finite recruitment quotas, to maximize the global recruitment performance. However, to the best of our knowledge, no other paper has investigated the recruitment quota allocation problem in a decentralized organization.

For example, to obtain maximal academic output, scarce resources should be reasonably and efficiently allocated to different university departments, with a context where all departments attempt for larger fractions of that. To this end, as a promising tool for studying resource allocation, the data envelopment analysis (DEA) method is widely used to reduce consumption or increase output [3], [4], [5]. Based on a DEA model, novel performance measures were proposed in [4] for providing incentive mechanisms. In [6], resource allocation plans in intra-organizational and inter-organizational systems with two-stage structures were studied. Moreover, DEA was also employed in analyzing productivity for universities in [7]. The DEA method shows the advantages of its data-driven characteristic, without requiring to know functional relationships between inputs and outputs [8]. However, this strength can be viewed as a weakness in some scenarios where the underlying reasons behind the results are to be studied [9]. Specifically, the centralized recruitment quota allocation to university departments is more dependent on the institutional context. Although resource allocation planning is widely investigated to maximize the profit or minimize the cost of organizations by reallocating human and non-human resources [10], it has been little studied in relation to recruitment quotas in decentralized organizations such as university departments.

In addition, the matching theory has also been studied for recruitment [11], [12]. However, the recruitment-related parts of [11] and [12] mainly focus on the applicant's options and choices instead of the recruitment quota allocation. Furthermore, the match between the positions and the candidates in recruitment also receives a lot of attention [13]. In [14], a novel neural network model was proposed based on the person-job fit, which can measure the matching degree of the position requirements and the candidate experiences.

A recruitment framework that uses systems thinking skills as a supplemental selection tool for recruiting employees was proposed in [15] to help find candidates that fit the position. However, recent research on recruitment mainly focuses on implementing recruiting strategies while generally neglecting the recruitment quota allocation before implementation [16], [17], [18], and many studies are conceptual where the relationship between recruitment performance and its influencing factors is unclear.

Motivated by this, we study the recruitment quota allocation problem in the university. It is noteworthy that in order to improve the efficiency of recruitment quota allocation, potential applicants to different departments need to be considered. It is a waste of resources if excessive recruitment quotas are allocated to a department that has few potential applicants. Besides, a recruitment quota allocation process may include several phases, while each implementation affects the state of the system, e.g., the number of unused recruitment quotas. Therefore, in this paper, we first theoretically model the recruitment quota allocation with the consideration of the impact of the potential applicants. Then, the recruitment quota allocation problem is formulated using a Markov decision process approach [19], which has also been utilized in manpower planning [20] and resource planning [21] in organizations to utilize resources efficiently. Traditionally, a simple recruitment quota allocation scheme, which equally allocates total recruitment quotas among each phase and then allocates the recruitment quotas available in each phase to different departments according to their need, is generally adopted. Moreover, since no other advanced recruitment quota allocation scheme has been proposed, the scheme mentioned above is used as the baseline to evaluate the proposed recruitment quota allocation scheme. The contributions of this paper are summarized as follows.

- We theoretically model the recruitment quota allocation in a university, while the potential applicants are taken into account to improve the recruitment quota allocation efficiency.
- A Markov decision process approach is adopted to formulate the recruitment quota allocation problem. Then, by solving the problem, an optimized recruitment quota allocation scheme is obtained, which can improve the efficiency of recruitment quota allocation.
- The optimized recruitment quota allocation scheme is compared with a traditional recruitment quota allocation scheme. Simulation results show that the proposed scheme can improve the efficiency of quota allocation significantly.

In addition, the difference between the proposed work and the existing work is listed in TABLE 1.

The rest of this paper is organized as follows. The system model for recruitment and the problem formulation are introduced in Section II. The recruitment quota allocation is optimized in Section III. Simulation results of the recruitment quota allocation are presented in Section IV. Finally, we conclude the paper in Section V.

TABLE 1. Difference between the proposed work and the existing work.

	[4]	[14]	[15]	[17]	[18]	Proposed work
Resource allocation	✓					✓
Recruitment strategy			✓	✓	✓	✓
Selection strategy		✓	✓	✓	✓	✓
Intra-organizational network	✓					✓
Quantitative analysis	✓	✓	✓			✓

Notation: $\mathcal{B}(n, r, p) = \binom{n}{r} p^r (1-p)^{n-r}$ denotes the probability mass function of a binomial distribution with parameters n, r , and p . Boldface letters represent vectors and $\mathbf{0}$ denotes the zero vector. The 1-norm is denoted by $\|\cdot\|_1$. $\mathbb{E}[\cdot]$ is the expectation operator. \mathbb{N} indicates the set of natural numbers. Besides, $\min\{\cdot\}$ is the function that returns the minimum value of inputs.

II. SYSTEM MODEL AND PROBLEM FORMULATION

In this section, we describe the system model and then introduce the problem formulation.

A. SYSTEM MODEL

In this paper, an organizational network consisting of a center for human resource management, several departments, and several clusters of potential applicants are considered. The potential applicants are individuals who satisfy basic recruitment requirements posed by the departments, which are further classified into different clusters according to their fitness with different departments. Potential applicants may only apply to the departments related to their majors when submitting their job applications. Besides, recruitment is conducted by departments in such a decentralized organization, while the allocation of recruitment quotas to departments is decided by the center, as illustrated in Fig. 1. Since quotas of recruitment of an organization are generally finite due to limited resources in terms of finance, offices, laboratories, etc., developing appropriate quota allocation schemes is crucial to ensure the recruitment quality of the whole organizational network. Therefore, the main focus of this paper is on the recruitment quota allocation problem from the perspective of the human resource management center.

Specifically, we take the university as an example. The total number of recruitment quotas is always limited due to its limited scale and development plan. Then, how many quotas should be allocated to each department in each recruitment cycle is a critical problem to ensure the development of the whole university. If the university allocates a few quotas to a department with numerous potential applicants, it may cause a number of talents to be missed. On the contrary, if too many quotas are allocated to a department with few potential applicants, the quality of recruitment can not be guaranteed. Therefore, the university requires to determine an effective recruitment quota allocation scheme for several years to utilize these quotas efficiently, and it is the most important objective of this paper. The formulation of the above problem

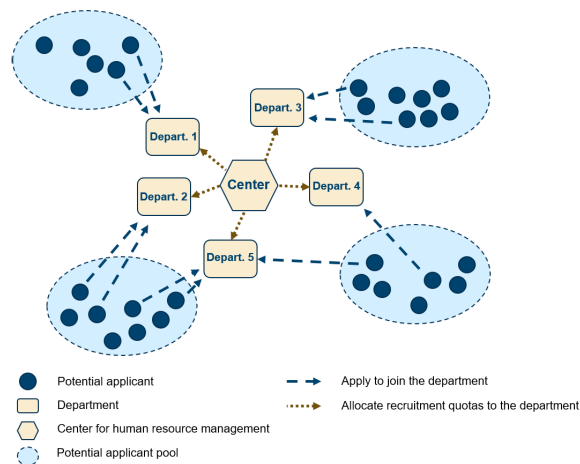


FIGURE 1. Illustration of the organizational network.

is introduced in the next subsection. Before that, we present a detailed description of the recruitment process at first.

Let us consider the recruitment process of a university with S departments and a total of I recruitment quotas during the next Y years. The recruitment process is conducted every year and each year can be divided into T phases (e.g., quarters). In addition, the potential applicant pools in different phases are assumed to be independent. Accordingly, the recruitment allocation scheme can be described by a two-dimensional table, where the entry $q_{s,t}^m$ denotes the number of quotas given to the s -th department at the n -th phase and I_m is the number of quotas for the m -th year in the future, as illustrated in Fig. 2. Taking the m -th year as an example, the organization needs to determine the number of I_m and its allocation, $\mathbf{q}_1^m, \dots, \mathbf{q}_T^m$, where $\mathbf{q}_t^m = [q_{1,t}^m, \dots, q_{S,t}^m]$.

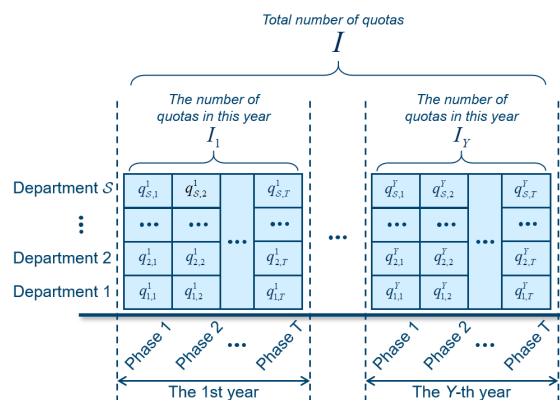


FIGURE 2. Illustration of a quota allocation scheme.

In addition, the typical recruitment process of a university can be summarized as shown in Fig. 3. For potential applicants within a certain pool, a typical implementation of recruitment is presented as follows:

- 1) an applicant decides to submit an application to a certain department;

- 2) a qualification examination is held by the department;
- 3) (a) the applicant passes the qualification examination and becomes an effective applicant;
- 3) (b) the applicant that fails to pass the qualification examination will not be employed;
- 4) assessment is conducted for all effective applicants, while applicants are then ranked accordingly;
- 5) if there are q available recruitment quotas, top q effective applicants will be employed based on their rankings.

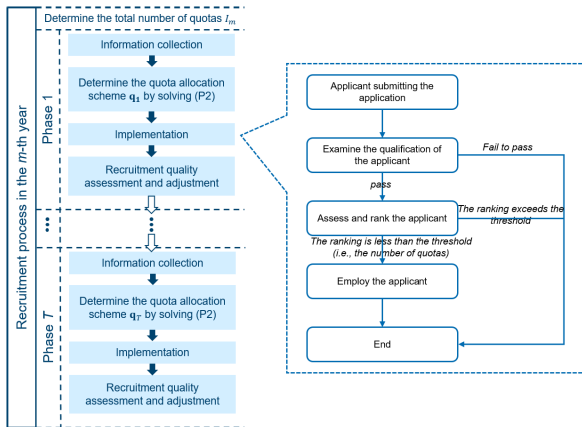


FIGURE 3. Illustration of the recruitment process.

B. PROBLEM FORMULATION

As mentioned above, the aim of this paper is to determine the optimal recruitment quota allocation scheme for recruitment with the restriction of total recruitment quotas. Suppose that recruitment processes in different years are independent, and the abilities of applicants in different years have identical statistical characteristics. Therefore, the total number of annual recruitment quotas for subsequent Y years can be determined mainly based on the proportion of the number of applicants in these years, that is,

$$I_m = \left\lceil \frac{s_m}{\sum_{i=m}^Y s_i} \left(I - \sum_{j=1}^{m-1} I_j \right) \right\rceil, \quad m \in \{1, \dots, Y\}, \quad (1)$$

where $\lceil \cdot \rceil$ represents the function that rounds the variable to the nearest integer greater than or equal to it and s_m denotes the number of applicants in the subsequent m -th year, which can be obtained via some linear [22] or nonlinear [23], [24] forecasting methods. Accordingly, the recruitment quota allocation for each year can be optimized independently. Without loss of generality, we take the recruitment in the m -th year as an example to specify the quota allocation problem. In addition, for simplicity, the superscripts of \mathbf{q}_t^m and \mathbf{q}_r^m are omitted below.

For the recruitment quota allocation, we simply divide its influencing factors into three aspects: the number of idle resources, the importance of vacant positions, and the competence of applicants, where competence is the term reflecting the performance perspective of required skills to

do the job [13]. The idle resources refer to the resources corresponding to the vacant positions. The total number of recruitment quotas is always less or equal to the number of idle resources. Besides, the recruitment we considered is for the same type of position. Therefore, the importance of a vacant position in a certain department is related to the number of vacant positions that have been filled. For example, a certain department of the university expects a number of employees to fill the vacancies in some research fields, however, only several vacant positions are necessary to be filled since there are few students interested in these fields [16]. In addition, the performance of recruitment is positively related to the competence of applicants.

Accordingly, we define the recruitment utility as the performance metric of the recruitment quota allocation scheme. The utility in the n -th phase is written as

$$r_n(\mathbf{d}_n, \mathbf{q}_n, \lambda_n) = \sum_{s=1}^S \min\{k_{s,n}, q_{s,n}\} \sum_{k=1}^{d_{s,n}} a_s(d_{s,n}, k) c_{s,n,k}(\mathbf{x}_{s,n}), \quad (2)$$

where $\mathbf{d}_n = [d_{1,n}, \dots, d_{S,n}]$, $\lambda_n = (\mathbf{x}_{1,n}, \dots, \mathbf{x}_{S,n})$, $\mathbf{x}_{s,n} = [x_s(1, k_{s,n}), \dots, x_s(k_{s,n}, k_{s,n})]$, $d_{s,n}$ denotes the number of vacancies of the department s that have been filled until the beginning of the n -th phase, and $x_s(i, j)$ represents the competence score of the i -th individual among a total of j effective applicants. Besides, $a_s(d_{s,n}, k)$ describes the importance of the k -th vacancy of the department s in the n -th phase when there have been $d_{s,n}$ filled vacancies, while $c_{s,n,k}(\mathbf{x}_{s,n})$ indicates the competence of the k -th employed applicant of the department s in the n -th phase. The effective applicants are ranked in descending order of the competency score. In addition, $d_{s,n}$ is determined by $d_{s,n-1}$, $k_{s,n}$, and $q_{s,n}$, which can be expressed as

$$d_{s,n} = d_{s,n-1} + \min(q_{s,n}, k_{s,n}), \quad (3)$$

where $k_{s,n}$ denotes the number of effective applicants of the department s in the n -th phase. Moreover, $d_{s,n}$ is also used to indicate the state of idle resources. It should be noted that for the n -th phase, the determination of the quota allocation scheme \mathbf{q}_n is prior to the implementation. Therefore, given \mathbf{d}_n and \mathbf{q}_n , the expected utility is expressed as

$$r_n(\mathbf{d}_n, \mathbf{q}_n) = \mathbb{E}_\lambda [r_n(\mathbf{d}_n, \mathbf{q}_n, \lambda_n)]. \quad (4)$$

Let π denote the quota allocation policy. Given \mathbf{d}_n , we can determine the quota allocation scheme $\mathbf{q}_n = \pi(\mathbf{d}_n)$. Therefore, the recruitment quota allocation problem for the T phases can be formulated by means of a Markov decision process. Furthermore, the overall recruitment utility of a certain year under the policy π and the initial resource state \mathbf{d}_1 is given by

$$V_T(\pi, \mathbf{d}_1) = \sum_{n=1}^T \mathbb{E}_{\mathbf{d}} [r_n(\mathbf{d}_n, \mathbf{q}_n)]. \quad (5)$$

As a result, the basic recruitment quota allocation problem is formulated as

$$(P1): \max_{\pi} V_T(\pi, \mathbf{d}_1)$$

$$\text{s.t. } d_{s,n} + q_{s,n} \leq R_s, \quad s = 1, \dots, S, \quad n = 1, \dots, T, \quad (6)$$

$$\|\mathbf{d}_n\|_1 + \|\mathbf{q}_n\|_1 \leq I_m, \quad n = 1, \dots, T. \quad (7)$$

where R_s is the number of vacant positions of the s -th department and $\mathbf{d}_1 = \mathbf{0}$.

However, according to the evaluation for the recruitment in the previous phase, the organization may make some adjustments, which affects the quota allocation in the subsequent phases. Therefore, (P1) may need to be reformulated as (P2) for subsequent phases, which is also discussed in the next section.

III. RECRUITMENT QUOTA ALLOCATION OPTIMIZATION

In this section, we first model the recruitment process in terms of the potential applicant information collection, recruitment quota allocation, and the recruitment quality assessment. Then, the recruitment quota allocation is optimized via maximizing the recruitment utility.

A. INFORMATION COLLECTION IN RECRUITMENT

In order to obtain the optimal recruitment quota allocation scheme, it is necessary for the organization to collect some crucial information of potential applicants before quota allocation in each phase, including their competence, the probabilities that they apply to a certain department and pass the qualification examination, etc.

Assume that the probability of one individual in the i -th potential applicant pool submitting applications to the department s is $p_{\text{apply}}^{i,s,n}$, and the probability of an applicant passing the qualification test is p_{pass} . The applicants who pass the qualification test are called effective applicants. Moreover, denote by $p_{\text{effective}}^{i,s,n}$ the probability that one individual in the potential applicant pool i becomes an effective applicant of the department s , which is given by $p_{\text{effective}}^{i,s,n} = p_{\text{apply}}^{i,s,n} p_{\text{pass}}$. Let v_i represent the number of potential applicants in the i -th pool, $z_{i,s,n}$ denote the number of effective applicants of the department s from the pool i in the n -th phase, and θ_s indicate the number of potential applicant pools associated with the department s . Therefore, the probability that there are k effective applicants of the department s in the n -th phase is given by

$$p_{s,n}(k) = \sum_{\mathbf{z}_{s,n} \in \ell_s(k)} \prod_{i=1}^{\theta_s} \mathcal{B}(v_i, z_{i,s,n}, p_{\text{effective}}^{i,s,n}), \quad (8)$$

where $\mathbf{z}_{s,n} = [z_{1,s,n}, \dots, z_{\theta_s,s,n}]$ and

$$\ell_s(k) = \left\{ \mathbf{z}_{s,n} \mid \sum_i z_{i,s,n} = k \right\}. \quad (9)$$

Another critical information for the recruitment quota allocation is the competence of applicants. The competence score can be obtained by some classical competence assessing methods such as the competence reference model [13]. Therefore, we model the competence score of an applicant as a random variable following the truncated Gaussian distribution, while the mean and the variance of the parent Gaussian distribution are both set to 1 [26]. Besides, the truncation interval is set to $1 \leq x \leq 5$ for simplicity. In practice, more precise distribution can be extracted from the past data by statistical methods, which is beyond our focus.

For the case of $k_{s,n}$ effective applicants applying for positions in the s -th department the expected competence score of the k -th largest competence score is given by

$$\bar{c}_{s,n,k}(k_{s,n}) = \mathbb{E}[c_{s,n,k}(\mathbf{x}_{s,n})] = \int_{-\infty}^{+\infty} x f_{k_{s,n}-k+1}(x) dx, \quad (10)$$

where $f(x)$ denotes the probability density function of the truncated Gaussian distribution and $f_{k_{s,n}-k+1}(x)$ represents the probability density function of the k -th largest random variable among the $k_{s,n}$ random variables, which is given by [27]

$$f_i(x) = \frac{n!}{(i-1)!(n-i)!} F(x)^{i-1} [1-F(x)]^{n-i} f(x). \quad (11)$$

B. RECRUITMENT QUOTA ALLOCATION

With the collected information, the recruitment quota allocation scheme can be determined by maximizing the recruitment utility. Let $\bar{k}_{s,n}$ denote the maximal number of effective applicants of the department s in the n -th phase. Then, according to (8) and (10), we can rewrite (4) as

$$r_n(\mathbf{d}_n, \mathbf{q}_n) = \sum_{s=1}^S r_{s,n}(d_{s,n}, q_{s,n}), \quad (12)$$

where $r_{s,n}(d_{s,n}, q_{s,n})$ is given by

$$r_{s,n}(d_{s,n}, q_{s,n}) = \sum_{k=0}^{\bar{k}_{s,n}} p_{s,n}(k) \sum_{m=1}^{\min\{k, q_{s,n}\}} a_s(d_{s,n}, m) \bar{c}_{s,n,m}(k). \quad (13)$$

For $a_s(d_{s,n}, k)$, it is assumed that the importance of a vacant position of a department is negatively related to the number of filled vacancies of the department. Specifically, departments of a university generally expect more employees to fill the vacancies in research or education aspects, aiming at better developing themselves. However, from an overall perspective, some vacancies of a department may be unnecessary to be filled or less of importance compared with other departments. Therefore, $a_s(d_{s,n}, k)$ is modeled as

$$a_s(d_{s,n}, k) = \beta^{1 - \frac{1}{R_s}(d_{s,n}+k)}, \quad (14)$$

where β is a constant over the range of $0 < \beta \leq 1$ that describes the importance of a vacant position.

By substituting (12) and (14) into (5), the recruitment utility can be obtained. Then, the optimal recruitment utility and the corresponding optimal policy can be obtained from as in (15) and (16), shown at the bottom of the page, respectively, where $p(\mathbf{d}_{n+1} | \mathbf{d}_n, \mathbf{q}_n)$ is the transition probability and $u_n^*(\mathbf{d}_n)$ is the sum of the recruitment utility from the n -th phase to the T -th phase with the resource state \mathbf{d}_n under the optimal policy. In addition, $\mathcal{A}_{n+1}(\mathbf{d}_n)$ is the set consisting of all available quota allocation schemes with the resource state \mathbf{d}_n in the n -th phase while \mathcal{D}_{n+1} is the set consisting of all available resource states in the next phase with the resource state \mathbf{d}_n and the quota allocation scheme \mathbf{q}_n , which are given by

$$\mathcal{A}_{n+1}(\mathbf{d}_n) = \{ \mathbf{q}_n | q_{s,n} + d_{s,n} \leq R_s, s = 1, \dots, \mathcal{S}; \|\mathbf{q}_n\|_1 + \|\mathbf{d}_n\|_1 \leq I_m \}, \quad (17)$$

$$\mathcal{D}_{n+1}(\mathbf{d}_n, \mathbf{q}_n) = \{ \mathbf{d}_{n+1} | d_{s,n+1} \leq d_{s,n} + q_{s,n} \}. \quad (18)$$

Moreover, the transition probability $p(\mathbf{d}_{n+1} | \mathbf{d}_n, \mathbf{q}_n)$ is expressed as

$$p(\mathbf{d}_{n+1} | \mathbf{d}_n, \mathbf{q}_n) = \prod_{s=1}^{\mathcal{S}} p(d_{s,n+1} | d_{s,n}, q_{s,n}), \quad (19)$$

where $p(d_{s,n+1} | d_{s,n}, q_{s,n})$ is

$$p(d_{s,n+1} | d_{s,n}, q_{s,n}) = \begin{cases} p_{s,n}(d_{s,n+1} - d_{s,n}), & \text{if } d_{s,n+1} - d_{s,n} < q_{s,n} \\ 1 - \sum_{m=0}^{q_{s,n}-1} p_{s,n}(m), & \text{if } d_{s,n+1} - d_{s,n} = q_{s,n} \end{cases}, \quad (20)$$

It is noteworthy that directly solving (16) is generally intractable, when \mathcal{S} and I_m are relatively large (e.g., $\mathcal{S} = 20$ and $I_m = 100$). Specifically, the number of resource states can be larger than 10^{13} with $\mathcal{S} = 20, R_s = 5$ for

$s \in \{1, \dots, \mathcal{S}\}$, and $I_m = 100$. Therefore, it is necessary to solve (16) by approximations. Let $I_{m,s}$ denote the number of quotas that can be utilized by the department s , satisfying

$$\sum_{s=1}^{\mathcal{S}} I_{m,s} = I_m, I_{m,s} \in \mathbb{N}, I_{m,s} \leq R_s. \quad (21)$$

With the restriction of $I_{m,s}$, similar to (15) and (16), the optimal recruitment utility and the optimal policy of the department s are given by as in (22) and (23), shown at the bottom of the page, respectively. Accordingly, (P1) can be approximately solved by

$$\max_{\{I_{m,1}, \dots, I_{m,\mathcal{S}}\}} \sum_{s=1}^{\mathcal{S}} \tilde{u}_{s,1}^*(d_{s,1}). \quad (24)$$

Therefore, based on (22), (23), and (24), with the optimal partition $\{I_{m,1}^*, \dots, I_{m,\mathcal{S}}^*\}$, the approximately optimal recruitment quota allocation policy $\tilde{\pi}^*$ can be obtained by the dynamic programming method, which is a common approach to solve Markov decision process problems [28], [29]. Specifically, for the resource state $d_{s,n}$, the number of quotas to be allocated is $q_{s,n} = \tilde{\pi}_s^*(d_{s,n})$, and $\tilde{\pi}^*$ is written as

$$\tilde{\pi}^* = \{ \tilde{\pi}_s^*(d_{s,n}) | s = 1, \dots, \mathcal{S}; n = 1, \dots, T \}.$$

In the above recruitment quota allocation scheme, the basic idea of obtaining the recruitment quota allocation scheme for phase $t, t \in \{1, \dots, T\}$ is as follows. In the first step, let $\tilde{I}_{m,s} = R_s, \forall s \in \{1, \dots, \mathcal{S}\}$. In the second step, for each $s \in \{1, \dots, \mathcal{S}\}$, we separately update $\tilde{I}_{m,s}$ to $\tilde{I}_{m,s} - 1$ while keeping $\tilde{I}_{m,i}$ for $\forall i \neq s$ unchanged, and then solve the problem of allocating $\tilde{I}_{m,s}$ quotas to the department s , which is a classical finite-horizon Markov decision process problem. The complexity of this step is $\mathcal{O}(R_s^3)$. The update which leads to the largest overall recruitment utility is selected and reserved, i.e., only one $\tilde{I}_{m,s}$ is updated to $\tilde{I}_{m,s} - 1$ while other $\tilde{I}_{m,i}, i \neq s$ are not updated. Since the overall recruitment utility is computed \mathcal{S} times, the complexity of this step is $\mathcal{O}(\mathcal{S}(\sum_{s=1}^{\mathcal{S}} R_s^3))$. Finally, by repeating the second step until

$$u_n^*(\mathbf{d}_n) = \max_{\mathbf{q}_n \in \mathcal{A}_n(\mathbf{d}_n)} \left\{ r_n(\mathbf{d}_n, \mathbf{q}_n) + \sum_{\mathbf{d}_{n+1} \in \mathcal{D}_{n+1}(\mathbf{d}_n, \mathbf{q}_n)} u_{n+1}^*(\mathbf{d}_{n+1}) p(\mathbf{d}_{n+1} | \mathbf{d}_n, \mathbf{q}_n) \right\}, \quad (15)$$

$$\pi^*(\mathbf{d}_n) = \arg \max_{\mathbf{q}_n \in \mathcal{A}_n(\mathbf{d}_n)} \left\{ r_n(\mathbf{d}_n, \mathbf{q}_n) + \sum_{\mathbf{d}_{n+1} \in \mathcal{D}_{n+1}(\mathbf{d}_n, \mathbf{q}_n)} u_{n+1}^*(\mathbf{d}_{n+1}) p(\mathbf{d}_{n+1} | \mathbf{d}_n, \mathbf{q}_n) \right\}. \quad (16)$$

$$\tilde{u}_{s,n}^*(d_{s,n}) = \max_{q_{s,n} \in \mathcal{A}_{s,n}(d_{s,n}, I_{m,s})} \left\{ r_{s,n}(d_{s,n}, q_{s,n}) + \sum_{d_{s,n+1} \in \mathcal{D}_{s,n+1}(d_{s,n}, q_{s,n})} \tilde{u}_{s,n+1}^*(d_{s,n+1}) p(d_{s,n+1} | d_{s,n}, q_{s,n}) \right\}, \quad (22)$$

$$\tilde{\pi}_s^*(d_{s,n}) = \arg \max_{q_{s,n} \in \mathcal{A}_{s,n}(d_{s,n}, I_{m,s})} \left\{ r_{s,n}(d_{s,n}, q_{s,n}) + \sum_{d_{s,n+1} \in \mathcal{D}_{s,n+1}(d_{s,n}, q_{s,n})} \tilde{u}_{s,n+1}^*(d_{s,n+1}) p(d_{s,n+1} | d_{s,n}, q_{s,n}) \right\}. \quad (23)$$

$\sum_{s=1}^S \tilde{I}_{m,s} = I_m$, for a total of $\sum_{s=1}^S R_s - I_m$ iterations, the proposed recruitment quota allocation scheme can be obtained, and the time complexity of the solution becomes $\mathcal{O}\left(S \left(\sum_{s=1}^S R_s - I_m\right) \left(\sum_{s=1}^S R_s^3\right)\right)$. In addition, it should be noted that the complexity of the solution mentioned above is already acceptable since the human resource management center usually has relatively ample time to solve the recruitment quota allocation problem.

C. RECRUITMENT QUALITY ASSESSMENT AND ADJUSTMENT

When the recruitment in the n -th phase is completed, the result will be evaluated before the quota allocation in the next phase. The recruitment quality of the previous phase is generally used as a critical reference to adjust the recruitment quota allocation of the next phase.

Specifically, there may exist transparency and objectivity issues in the recruitment process [30]. Once certain departments adopt undesirable recruitment strategies lacking transparency and objectivity, the recruitment utility of these departments will be lower than expected. In such situations, the recruitment quotas are more desirable to be allocated to other departments that can effectively utilize them. Therefore, the weights of recruitment utility for departments are introduced. These weights reflect the recruitment quality in the previous phase while affecting the quota allocation in the next phase. The setting for the weights generally needs to be based on practical considerations. For simplicity, we only model the weights in terms of the competence of employed applicants.

Recall that $\mathbf{x}_{s,n-1} = [x_s(1, k_{s,n-1}), \dots, x_s(k_{s,n-1}, k_{s,n-1})]$ denotes the competence scores of effective applicants of the department s in the $(n-1)$ -th phase, where the competence scores are ranked in descending order. The weight of the department s that will be applied in the n phase is defined as

$$w_s = \frac{\sum_{m=1}^{\min\{k_{s,n-1}, q_{s,n-1}\}} \hat{x}_s(m, k_{s,n-1})}{\sum_{m=1}^{\min\{k_{s,n-1}, q_{s,n-1}\}} x_s(m, k_{s,n-1})}, \quad (25)$$

where $\hat{x}_s(m, k_{s,n-1})$ denotes the competence score of the m -th applicant employed by the department s in the $(n-1)$ -th phase. Accordingly, if the recruitment practice is driven primarily by the preferences of the department, then the weight may be relatively small. On the contrary, if the recruitment practice is driven strictly by the preferences of the organization (i.e., applicants with high competency scores are preferred), then the weight becomes 1. In addition, since the weights are intractable to predict, the recruitment quota allocation policy needs to be updated after each phase while (P1) needs to be reformulated.

Taking account of (25), (13) is rewritten as

$$\hat{r}_{s,n}(d_{s,n}, q_{s,n}) = w_s r_{s,n}(d_{s,n}, q_{s,n}). \quad (26)$$

Furthermore, given the resource state \mathbf{d}_n , by substituting (26) into (22), the recruitment allocation problem for the

n -th phase is reformulated as

$$(P2): \quad \max_{\{\hat{I}_{m,1}, \dots, \hat{I}_{m,S}\}} \sum_{s=1}^S \tilde{u}_{s,n}^*(d_{s,n})$$

$$\text{s.t.} \quad \sum_{s=1}^S \hat{I}_{m,s} = I_m - \|\mathbf{d}_n\|_1, \quad (27)$$

$$\hat{I}_{m,s} \leq R_s - d_{s,n}, \quad \hat{I}_{m,s} \in \mathbb{N}, \quad s \in \{1, \dots, S\}. \quad (28)$$

Note that the weight vector $\mathbf{w} = [w_1, \dots, w_S]$ is updated at the end of each phase. Therefore, in each phase, (P2) needs to be reformulated and solved based on the weight vector obtained from the previous phase. In addition, after solving the (P2) for the n -th phase, only the policy for the current phase (i.e., $\{q_{s,n} = \tilde{\pi}_s^*(d_{s,n}) | s = 1, \dots, S\}$) is adopted while the others (i.e., $\{\tilde{\pi}_s^*(d_{s,t}) | s = 1, \dots, S; t = n+1, \dots, T\}$) are discarded.

TABLE 2. Simulation parameters.

Total number of quotas, I_m	100
Number of departments of the organization, S	20
The constant describing the importance of a vacant position, β	0.8
Number of phases in a recruitment process, T	4
Number of potential applicant pools	15
The probability of passing the qualification test, p_{pass}	0.9

IV. SIMULATION RESULTS

In this section, simulation results are presented to validate the optimized quota allocation scheme in terms of the cumulative recruitment utility (CRU) and the cumulative occupied quotas to idle resource ratio (COIR). The CRU and the COIR for the recruitment in the n -th phase are respectively expressed as

$$\text{CRU}_n = \sum_{t=1}^n r_t(\mathbf{d}_t, \mathbf{q}_t, \lambda_t),$$

$$\text{COIR}_n = \frac{\sum_{s=1}^S \sum_{t=1}^n k_{s,t}^*}{\sum_{s=1}^S R_s}, \quad (29)$$

where $k_{s,n}^*$ is the number of employed applicants in the n -th phase. Besides, it is noteworthy that CRU_n and COIR_n are calculated at the end of the n -th phase, while \mathbf{d}_n , \mathbf{q}_n , and λ_n are determined at that moment. The above metrics measure the recruitment quota allocation scheme in terms of recruitment quality and recruitment efficiency, respectively. For example, a high CRU means that applicants of high quality are employed, while a high COIR indicates that vacancies can be filled in a fast manner.

In addition, one of the key points of the optimized recruitment quota allocation is to consider the impact of potential applicant pools. To show the advantage of the optimized scheme, a quota allocation scheme based on the number of vacant positions of departments (i.e., R_s) is used for comparison. Specifically, the recruitment quota allocation scheme

used for comparison is determined according to the following rules:

- 1) all the remaining quotas are equally allocated to the subsequent phases of the recruitment process;
- 2) the quotas at each phase are then allocated to departments according to the proportion of vacant positions in different departments.

Besides, simulation parameters are set as follows. The number of potential applicants in each potential applicant pool, v_i , is assumed to be uniformly distributed over the range of [300, 700]. The probability of a potential applicant applying to a related department, $p_{apply}^{i,s,n}$, is assumed to be uniformly distributed over the range of [0.0003, 0.0015] and [0.001, 0.005] for the cases of a small and a large number of effective applicants, respectively. Given a total of 100 quotas for a year, a small number of effective applicants means that the total number of effective applicants during the year is much less than 100, while a large number of effective applicants means that the total number of effective applicants during the year is much larger than 100. The number of idle resources of each department, R_s , in each year is assumed to be uniformly distributed over the range of [4, 8]. Other simulation parameters are summarized in TABLE 2. It is noteworthy that most individuals in potential applicant pools are considered to satisfy the basic requirements for applicants, while only a fraction of them may not pass the qualification test due to factors such as personality, attitude, etc. Therefore, a relatively high probability of passing the qualification test is assumed (i.e., $p_{pass} = 0.9$).

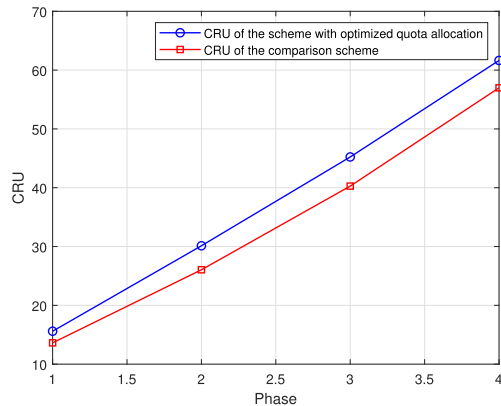


FIGURE 4. CRU of the optimized quota allocation scheme and that of the comparison scheme, with a small number of effective applicants.

In Fig. 4, CRUs of the optimized quota allocation scheme and the comparison scheme are presented, when the number of effective applicants is small. The observation shows that recruitment can achieve a higher CRU with the optimized quota allocation scheme. In addition, the observation shows that the improvement by the optimized scheme is not significant, since when the number of effective applicants is small, it is easier to employ most of the effective applicants even if the scheme with low efficiency is adopted. However, as the

number of effective applicants grows, the improvement of the optimized scheme becomes more obvious.

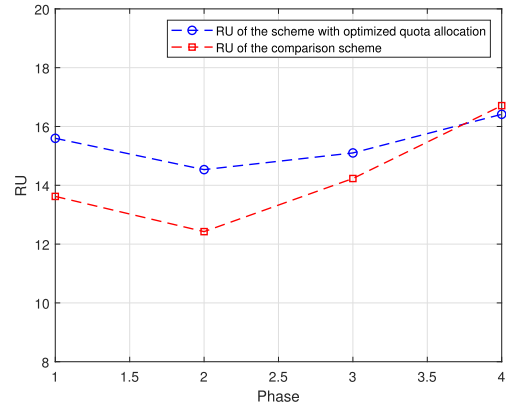


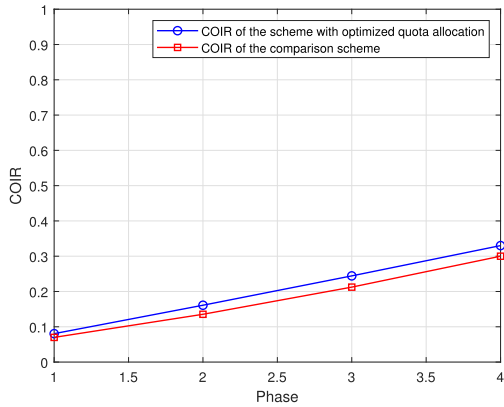
FIGURE 5. RU of the optimized quota allocation scheme and that of the comparison scheme, with a small number of effective applicants.

Fig. 5 depicts RUs of the optimized quota allocation scheme and the comparison scheme when the number of effective applicants is small. In the case of small effective applicants, it can be seen that the RU by the optimized scheme at each phase outperforms or is not much different from that by the comparison scheme. This is because the optimized scheme allocates more quotas at a phase when there are more potential applicants, thereby improving recruitment efficiency.

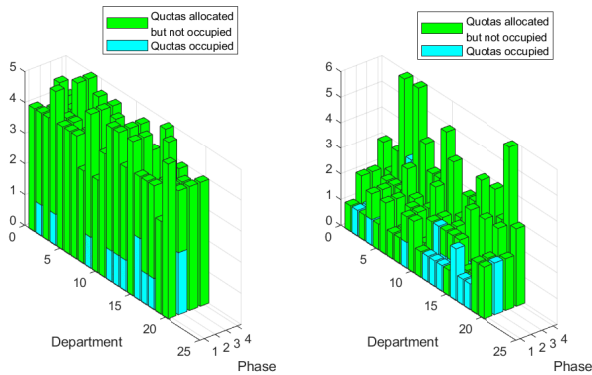
Fig. 6 shows the quota allocation and quota occupancy of the optimized scheme and the comparison scheme, with a small number of effective applicants. Fig. 6 (a) plots the COIRs of the optimized scheme and the comparison scheme, both of which are relatively low since there are few effective applicants that can fill the vacancies. Besides, the COIR of the optimized scheme is higher than that of the comparison scheme, indicating that vacancies will be filled more efficiently under the optimized scheme. Moreover, two specific cases of both schemes are illustrated in Fig. 6 (b) and Fig. 6 (c). We can see that only a few quotas are occupied in both cases, however, it is more likely to miss suitable effective applicants by the comparison scheme without considering the information of potential applicants.

In Fig. 7, CRUs of the optimized quota allocation scheme and the comparison scheme are presented, with a large number of effective applicants. It can be seen that the CRU of the optimized scheme outperforms the comparison scheme at each phase. Specifically, the overall RU in the figure is CRU_4 , while the CRU_4 of the optimized scheme is shown to be higher than that of the proposed scheme.

Fig. 8 illustrates RUs of the optimized quota allocation scheme and the comparison scheme, with a large number of effective applicants. The figure shows that the RU by the optimized scheme is higher than that of the comparison scheme in the first 3 phases. In addition, for the 4-th phase, although the RU of the comparison scheme may be higher



(a)



(b)

(c)

FIGURE 6. (a) The COIR of the optimized scheme and that of the comparison scheme, with a small number of effective applicants; (b) A specific case of the optimized scheme; (c) A specific case of the comparison scheme. Blue blocks mean the allocated quotas that are occupied, while green blocks indicate the allocated quotas that are not occupied.

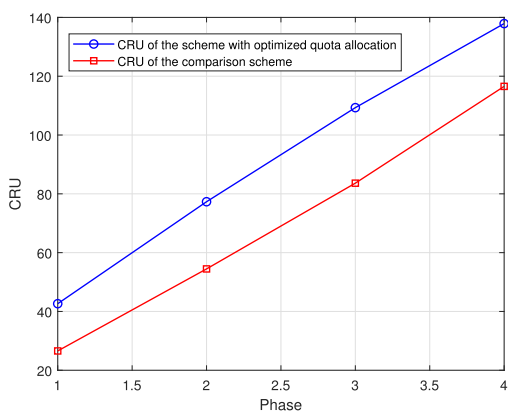


FIGURE 7. CRU of the optimized quota allocation scheme and that of the comparison scheme, with a large number of effective applicants.

than that of the optimized scheme, such an advantage comes at the cost of reducing the overall utility.

Fig. 9 shows the quota allocation and quota occupancy of the optimized scheme and the comparison scheme, with a

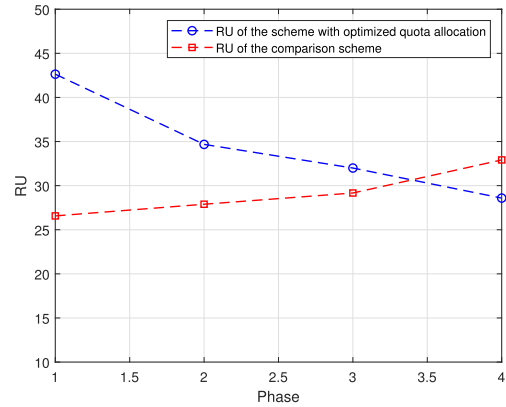
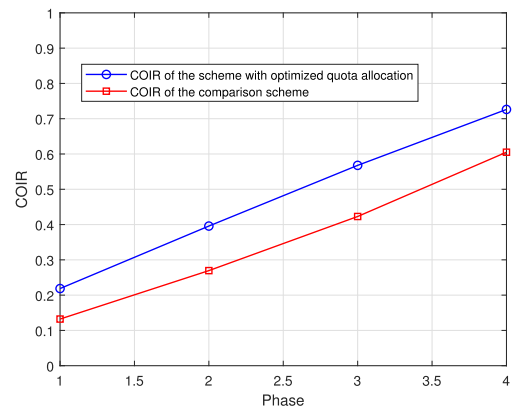
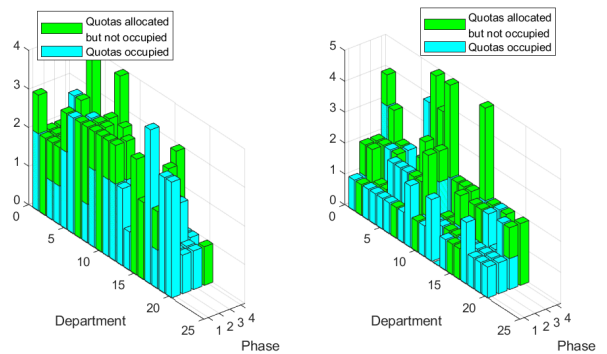


FIGURE 8. RU of the optimized quota allocation scheme and that of the comparison scheme, with a large number of effective applicants.



(a)



(b)

(c)

FIGURE 9. (a) The COIR of the optimized scheme and that of the comparison scheme, with a large number of effective applicants; (b) A specific case of the optimized scheme; (c) A specific case of the comparison scheme. Blue blocks mean the allocated quotas that are occupied, while green blocks indicate the allocated quotas that are not occupied.

large number of effective applicants. In Fig. 9 (a), COIRs of both schemes are presented. It can be seen that the COIR of the optimized scheme is higher than that of the comparison scheme, indicating that vacancies will be filled more efficiently under the optimized scheme. Moreover, two

specific cases of both schemes are illustrated in Fig. 9 (b) and Fig. 9 (c). Compared to the optimized scheme, the comparison scheme in Fig. 9 (c) shows a waste of quotas, which shows the low efficiency of the comparison scheme.

V. CONCLUSION

In this paper, we defined the recruitment utility as the performance metric for recruitment in a view of the intra-organizational network and formulated the recruitment quota allocation problem through a Markov process. In addition, we optimized the recruitment quota allocation by maximizing the recruitment utility. Furthermore, a recruitment quota allocation scheme for comparison was constructed to validate the advantage of the optimized scheme. Simulation results showed that it is better to appropriately allocate more recruitment quotas in the early phases of a recruitment process than to allocate the quotas evenly over phases. Besides, it was also shown that the efficiency of the optimized quota allocation scheme was significantly improved.

In future work, it is of great interest to further investigate the relationship between the recruitment process and the subsequent development of new employees. By jointly considering the influence on the subsequent development of new employees, it is expected to obtain a better recruitment quota allocation scheme that can result in a higher performance of the organization.

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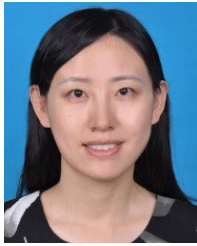
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