# Extending Group Role Assignment With Cooperation and Conflict Factors via KD45 Logic

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***Abstract*—Group role assignment with cooperation and conflict factors (GRACCFs) is a creative social computing method for team establishment. It can maximize the new team's performance through role assignment considering potential cooperation or conflict factors among agents. However, this method has two bottlenecks in practical applications. First, in the scenario of establishing a new team from several existing teams, collecting the pertinent cooperation or conflict information encounters challenges. Second, GRACCF merely takes the CCFs as a part of the objective function for team performance, but this will underestimate the CCFs' impacts on the sustainable development of the team. This article tackles these issues by extending GRACCF from a new viewpoint. It first designs a KD45 logic algorithm based on the KD45 logic system, which can discover the implicit cognitive CCFs through logical inferences with closure calculations. Then, it proposes an original team evaluation method that can help decision-makers determine the weights of team performance and CCFs' impacts based on their demands. Large-scale simulation experiments indicate that the proposed solution is practicable and robust. The proposed method provides a solid decision-making reference for administrators when establishing a sustainable team.**

***Index Terms*—Group role assignment with cooperation and conflict factors (GRACCFs), KD45 logic algorithm, role-based collaboration (RBC), social computational strategy, team evaluation method.**

## Nomenclature

| | |
|---|---|
| $\mathcal{A}$ | Set of agents. |
| $\mathcal{R}$ | Set of roles. |
| $m$ | Size of the agent set $\mathcal{A}$. |
| $n$ | Size of the role set $\mathcal{R}$. |
| $i_0, i_1, i_2, \ldots$ | Indices of agents. |
| $j_0, j_1, j_2, \ldots$ | Indices of roles. |
| $r$ | Role. |
| $a$ | Agent. |
| $L$ | Role range vector. |
| $Q$ | Qualification matrix. |
| $C^f$ | Cooperation and conflict factors (CCFs) matrix. |
| $\mathrm{C}^{cf}$ | Compact CCF matrix. |
| $k$ | Index of the matrix $C^{cf}$. |
| $T$ | Role assignment matrix. |
| $\bar{T}$ | CCF assignment vector. |
| $\sigma^{\mathrm{GRA}}$ | Group performance without considering the impacts of CCFs. |
| $\sigma^{\mathrm{GRACCF}}$ | Group performance after considering the impacts of CCFs. |
| $R$ | Cooperation (conflict) relationship for the elements in $\mathcal{G}$. |
| $C^f_{kd45}$ | Modified CCF matrix $C^f$ after applying Algorithm 1. |
| $\tau$ | Teamwork coefficient. |
| $\theta_{\mathrm{coop}}$ | Cooperation threshold. |
| $\theta_{\mathrm{conf}}$ | Conflict threshold. |
| *step* | It is a value that expresses the increasing *step* length of the teamwork coefficient $\tau$. |
| $\sigma^{e-\mathrm{GRACCF}}$ | Group performance obtained by the extended group role assignment with CCF (GRACCF) model. |
| $T^{\mathrm{GRA}}$ | Matrix $T$ obtained by the group role assignment (GRA) model. |
| $L(\sigma)$ | Loss of the group (team) performance $\sigma$ acceptable to the team leaders, i.e., $\sigma - \sigma^{\mathrm{GRA}}$. |
| $\sigma^{\mathrm{real-GRACCF}}$ | Real team performance. |
| $\lambda_1$ | $(\sigma^{\mathrm{e-GRACCF}} - \sigma^{\mathrm{GRACCF}} / \sigma^{\mathrm{GRACCF}})$. |
| $\lambda_2$ | $(\sigma^{\mathrm{e-GRACCF}} - \sigma^{\mathrm{real-GRACCF}} / \sigma^{\mathrm{real-GRACCF}})$. |

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## I. Introduction

GROUP role assignment [1], [2] with cooperation and conflict factors (GRACCFs) [3] offer an innovative way to establish a new team. It extends from GRA,

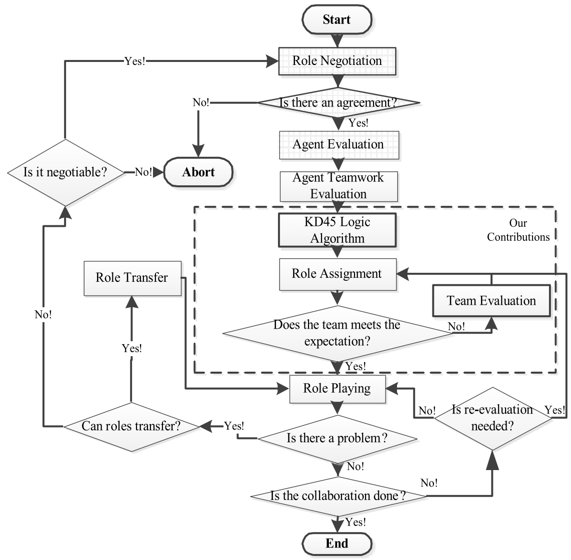


Fig. 1. Revised RBC process [5], [7], and [17] in the extended GRACCF.

which is a team management methodology derived from the environments—classes, agents, roles, groups, and objects (E-CARGO [2], [4], [5]), while E-CARGO is the fundamental model of role-based collaboration (RBC) [6]. Collaboration has been revealed as a complex process throughout the life cycle of RBC [7]–[9]. RBC, GRA, and GRACCF have been developed into a practical modeling methodology allowing decision-makers to manage task assignments. But in actual applications, GRACCF still meets two nontrivial challenges. The first challenge is that when gathering the cooperation [10]–[13] and conflict [14] factors (CCFs) between candidates through by questionnaire, the recommended method in [3] (i.e., the role negotiation process in Fig. 1), the number of obtained CCFs is sparse since these candidate employees from different teams rarely have the experience to work across teams. The limited number of the CCFs makes it difficult to obtain a complete CCF matrix, i.e., $C^f$ in GRACCF. Second, the definition of the objective function of GRACCF [3] may underestimate the impacts of CCFs, which will lead to a decline in the teams' sustainability. Hence, decision-makers need to reconsider these two aspects when conducting GRACCF.

For these concerns, this article overcomes the abovementioned challenges by extending GRACCF with two innovative methods (i.e., the part enclosed by the dashed rectangle in Fig. 1). First, for mining the potential CCFs, it designs the KD45 logic algorithm based on the KD45 logic system [15]. This algorithm is an efficient method for multiagent relational reasoning [16], and it can discover the implicit cognitive CCFs between candidates through logical inferences and closure calculations. With this algorithm, the GRACCF model can be improved to provide a more accurate assignment in the sense of team performance.

Then, we introduce a new phase called team evaluation between role assignment and role-playing (see Fig. 1) to tune the team performance and CCFs' impact. We propose an innovative teamwork coefficient in this phase to distinguish the contribution of team performance and CCFs' impacts on

TABLE I

REQUIRED POSITIONS OF THE NEW TEAM

| **Position** | Algorithm Engineer | Front-end Engineer | Back-end Engineer | Tester |
|---|---|---|---|---|
| **Required Number** | 1 | 2 | 4 | 2 |

the optimization result. Therefore, administrators can adjust this coefficient based on their demands.

The contributions of this article include the following.

1) This article extends the original GRACCF for better practical applications.
2) To mine the potential CCFs between agents, this article extends GRACCF with the KD45 logic algorithm.
3) Finally, we introduce a team evaluation method for helping administrators to tune the team performance and CCFs' impact.

This article is organized as follows. It first discusses a real-world scenario related to the proposed problem in Section II. Then, in Section III, it formally defines the problem via the GRACCF model. Section IV introduces the KD45 logic algorithm and innovative team evaluation method in the RBC process. The results of large-scale simulation experiments are provided in Section V. Section VI describes the related research efforts. This article concludes and points out future work in Section VII.

## II. Real-World Scenario

Company X is specializing in information technology (IT). According to [3], X in the scenario in this section is a hypothetical company, and we believe that a real-world scenario should be similar to it because X satisfies reasonable criteria and requirements. Ann, the Chief Executive Officer (CEO), hopes to establish a new business team for autonomous driving. She asks Bob, the Chief Technology Officer (CTO), to accomplish this task. Bob lists the positions and quantity required by the new team according to business requirements, as shown in Table I.

Simultaneously, Bob finds suitable candidates for the new team. These candidates are chosen from different existing business teams based on their performance. Then, Bob evaluates these candidates' abilities for each possible position based on their past performance [3] (Table II). For convenience, all the values in Table II are normalized.

To enable the new team to have more sustainable execution, Ann and Bob meet the existing business team leaders when assigning the positions to the candidates. Some team leaders report that some candidates presented cooperation or conflict intentions in past projects. Ann asks the team leaders to accumulate all the cooperation or conflict factors between candidates. These team leaders collect all the CCFs between candidates by distributing a questionnaire (Fig. 2), and the collected result is shown in Table III. As pointed out in Fig. 2 (#2), the values of 0 in Table III mean no conflict or cooperation. The values less than 0 in Table III mean conflict, but those larger than 0 indicate cooperation. Please note that the questionnaire here aims to build a long-term cooperative team, and the cooperation and conflict between team members

TABLE II
CANDIDATES AND EVALUATIONS ON REQUIRED POSITIONS

| Candidates | Positions | | | |
|---|---|---|---|---|
| | Algorithm Engineer | Front-end Engineer | Back-end Engineer | Tester |
| Adam | 0.18 | 0.82 | 0.29 | 0.01 |
| Bret | 0.35 | 0.80 | 0.58 | 0.35 |
| Chris | 0.84 | 0.85 | 0.86 | 0.36 |
| David | 0.96 | 0.51 | 0.45 | 0.64 |
| Edward | 0.22 | 0.33 | 0.68 | 0.33 |
| Fred | 0.96 | 0.50 | 0.10 | 0.73 |
| George | 0.25 | 0.18 | 0.23 | 0.39 |
| Harry | 0.56 | 0.35 | 0.80 | 0.62 |
| Jack | 0.49 | 0.09 | 0.33 | 0.58 |
| Joe | 0.38 | 0.54 | 0.72 | 0.20 |
| Kris | 0.91 | 0.31 | 0.34 | 0.15 |
| Larry | 0.85 | 0.34 | 0.43 | 0.18 |
| Matt | 0.44 | 0.06 | 0.66 | 0.37 |

Name: __(#3)__.
If I work in __(#1)__, I __(#2)__ to cooperate with __(#3)__ in __ (#1)__.
If I work in __(#1)__, I __(#2)__ to cooperate with __(#3)__ in __ (#1)__.
If I work in __(#1)__, I __(#2)__ to cooperate with __(#3)__ in __ (#1)__.
If I work in __(#1)__, I __(#2)__ to cooperate with __(#3)__ in __ (#1)__.
If I work in __(#1)__, I __(#2)__ to cooperate with __(#3)__ in __ (#1)__.
If I work in __(#1)__, I __(#2)__ to cooperate with __(#3)__ in __ (#1)__.
If I work in __(#1)__, I __(#2)__ to cooperate with __(#3)__ in __ (#1)__.
If I work in __(#1)__, I __(#2)__ to cooperate with __(#3)__ in __ (#1)__.

#1: a) Algorithm Engineer; b) Front-end Engineer; c) Back-end Engineer; d) Tester.
#2: a) From 0 to 1 means the degree of like, from weakly like to strongly like; b) From 0 to -1 means the degree of dislike, from weakly dislike to strongly dislike.
#3: a) Adam; b) Bret; c) Chris; d) David; e) Edward; f) Fred; g) George; h) Harry; i) Jack; j) Joe; k) Kris; l) Larry; m) Matt.

Fig. 2. Questionnaire [3] about CCFs for each candidate.

will directly affect the respondents' interests. Thereby, it is assumed that there is no questionnaire bias [17]–[20] in the obtained questionnaire results.

Bob learns that the E-CARGO model and its relevant extended GRACCF model have become an effective method to solve the team forming problem while considering CCFs between candidates. Hence, he decides to use them to solve the team establishment problem. Bob follows the steps of the GRACCF model and obtains the assignment result of the team establishment, as shown in Table IV. Values of 1 in Table IV candidates hold corresponding positions, while values of 0 mean not. For example, the front-end engineer positions of the new team are held by Adam and Bret.

Then, Bob reports to Ann his statistics and the results of the assignment result of the new team obtained by GRACCF. Ann is not satisfied with this assignment result and points out two problems. First, Ann notices that Table III is a sparse matrix, and the potential relationships that may greatly affect the quality of the team are ignored. For this reason, Ann hopes that Bob can find out the potential relationships between candidates. Second, Ann hopes that Bob can quantify the relationships between team performance and CCFs to formulate a sustainable team with high cooperation and low conflict potentials. Now, Bob encounters new challenges including the following.

1) The surveyed questionnaires are not complete and implicit cooperation or conflict potentials should be mined.
2) He needs to know exactly the quantitative relationship between team performance and the CCFs. Fortunately, we can solve this kind of problem by extending GRACCF. The following of this article depicts the details of our solutions, which can help Bob accomplish his task.

## III. PROBLEM FORMALIZATIONS WITH E-CARGO MODEL

To solve the abovementioned team establishment problem, we first formalize it with the E-CARGO model, GRA model, and GRACCF model. With the E-CARGO model [21], [22], a system $\sum$ can be described as a nine-tuple $\sum ::= \langle C, O, \mathcal{A}, \mathcal{M}, \mathcal{R}, \mathcal{E}, \mathcal{G}, s_0, \mathcal{H}\rangle$, where $C$ is a set of classes, $O$ is a set of objects, $\mathcal{A}$ is a set of agents, $\mathcal{M}$ is a set of messages, $\mathcal{R}$ is a set of roles, $\mathcal{E}$ is a set of environments, $\mathcal{G}$ is a set of groups, $s_0$ is the initial state of the system, and $\mathcal{H}$ is a set of users. In such a system, $\mathcal{A}$ and $\mathcal{H}$, $\mathcal{E}$, and $\mathcal{G}$ are tightly coupled sets. A human user and her/his agent perform a role together. Every group should work in an environment. An environment regulates a group.

When discussing role assignment problems, environments ($e$) and groups ($g$) are simplified into vectors and matrices, respectively. Furthermore, we use nonnegative integers $m$ ($=|\mathcal{A}|$, where $|\mathcal{A}|$ is the cardinality of set $\mathcal{A}$) to express the size of the agent set $\mathcal{A}$, $n$ ($=|\mathcal{R}|$) the size of the role set $\mathcal{R}$, $i, i_1, i_2, \ldots$ the indices of agents, and $j, j_1, j_2, \ldots$ the indices of roles.

Here, we use the real-world scenario mentioned in Section II as an example to describe RBC and its extended GRACCF model better. The following brings up the specific definitions of the team establishment.

*Definition 1:* A role [7]–[9] is defined as $r ::= \langle id, ®\rangle$, where *id* is the identification of $r$ and ® is the set of requirements of properties for agents to play $r$.

*Note:* In the team establishment problem, roles are the position types needed to form a new team. Thus, ® indicates the abilities required for the corresponding position.

*Definition 2:* An agent [7]–[9] is defined as $a ::= \langle id, Ⓠ\rangle$, where *id* is the identification of $a$ and Ⓠ is the set of $a$'s values corresponding to the abilities required in the group.

Note that agents refer to candidate employees for the new team in the scenario of Section II, and Ⓠ expresses the agents' historical performances about ®.

*Definition 3:* A *role range vector* [1] $L$ is a vector of the number of agents required for roles in the environment ($e$) of group ($g$).

*Note:* $L$ is a valuable component of the E-CARGO model. It indicates the minimum number of candidate employees required for each position in the new team. Based on Table I, the $L$ vector is [1, 2, 4, 2].

*Definition 4:* A *qualification matrix* [5], [23] $Q$ is an $m \times n$ matrix, where $Q[i, j] \in [0, 1]$ expresses the qualification

TABLE III
CCFs*

| Person (Position) \ Person (Position) | Adam (FE) | Adam (BE) | Bret (FE) | Bret (BE) | Bret (T) | Edward (FE) | Edward (BE) | Edward (T) | Fred (AE) | Fred (FE) | Fred (T) | Larry (AE) | Larry (BE) | Matt (BE) | Matt (T) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Adam (FE) | 0 | 0 | -0.3 | 0.35 | 0.35 | 0 | 0 | 0 | -0.4 | 0 | 0 | 0 | 0 | 0.8 | 0.9 |
| Adam (BE) | 0 | 0 | -0.2 | -0.2 | 0.2 | 0 | 0 | 0 | -0.5 | 0 | 0 | 0 | 0 | 0.5 | 0.6 |
| Bret (FE) | -0.2 | 0.2 | 0 | 0 | 0 | 0.2 | 0.2 | 0.3 | 0 | 0 | 0 | -0.3 | 0.35 | 0.7 | 0.6 |
| Bret (BE) | -0.35 | -0.2 | 0 | 0 | 0 | 0.2 | 0.2 | 0.3 | 0 | 0 | 0 | -0.2 | -0.2 | 0 | 0 |
| Bret (T) | 0.35 | 0.4 | 0 | 0 | 0 | 0.2 | 0.2 | 0.2 | 0 | 0 | 0 | -0.3 | 0.35 | 0 | 0 |
| Edward (FE) | 0 | 0 | 0.2 | 0.2 | 0.3 | 0 | 0 | 0 | -0.5 | -0.4 | -0.3 | 0 | 0 | 0.6 | 0.7 |
| Edward (BE) | 0 | 0 | 0.2 | 0.2 | 0.3 | 0 | 0 | 0 | -0.4 | -0.45 | -0.3 | 0 | 0 | 0 | 0 |
| Edward (T) | 0 | 0 | 0.2 | 0.2 | 0.2 | 0 | 0 | 0 | -0.2 | -0.2 | -0.3 | 0 | 0 | 0 | 0 |
| Fred (AE) | 0 | 0 | 0 | 0 | 0 | 0.3 | 0.2 | 0.3 | 0 | 0 | 0 | 0 | 0 | 0.8 | 0.7 |
| Fred (FE) | 0 | 0 | 0 | 0 | 0 | -0.4 | -0.45 | -0.2 | 0 | 0 | 0 | 0 | 0 | 0.6 | 0.5 |
| Fred (T) | 0 | 0 | 0 | 0 | 0 | -0.2 | -0.2 | -0.3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Larry (AE) | 0.3 | 0.2 | -0.3 | 0.35 | 0.35 | 0.3 | 0.2 | 0.1 | -0.5 | -0.4 | -0.3 | 0 | 0 | 0.7 | 0.7 |
| Larry (BE) | 0 | 0 | -0.2 | -0.2 | 0.2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.6 | 0.6 |
| Matt (BE) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | -0.4 | 0 | 0 | 0.8 | 0.6 | 0 | 0 |
| Matt (T) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | -0.3 | 0 | 0 | 0.8 | 0.6 | 0 | 0 |

*Note: 1) The other person (position) pairs not in the table are all 0; 2) AE: Algorithm Engineer, FE: Front-end Engineer, BE: Back-end Engineer, and T: Tester.

value of agent $i$ $(0 \leq i < m)$ for role $j$ $(0 \leq j < n)$. $Q[i, j] = 0$ indicates the lowest value and 1 the highest.

*Note:* A $Q$ matrix is the result of the agent evaluation step of RBC. It can be obtained by comparing all the qualifications of agents with all the requirements of roles. In our scenario, the $Q$ matrix is illustrated in Table II. Please note that the value of the matrix $Q$ correlates with some real-world team performance metrics (e.g., software product quality and reliability and time to completion). Since different types of teams have different comprehensive team performance metrics, we use the value of 0–1 to generalize these metrics, i.e., $Q[i, j] \in [0, 1]$.

*Definition 5:* A *CCF matrix* [3] $C^f$ is an $(m \times n) \times (m \times n)$ matrix and $C^f[i_1, j_1, i_2, j_2] \in [-1, 1]$. $C^f[i_1, j_1, i_2, j_2] > 0$ $(<0)$ means that there is a cooperation (conflict) effect when agent $i_1$ $(0 \leq i_1 < m)$ plays role $j_1$ $(0 \leq j_1 < n)$ and agent $i_2$ $(0 \leq i_2 < m)$ plays role $j_2$ $(0 \leq j_2 < n)$.

*Note*: In our scenario, the *CCF matrix* $C^f$ is illustrated in Table III. For example, when Adam works as a front-end engineer and Bret works as a tester, there is a cooperation effect between them, and its value is 0.35, i.e., $C^f[\langle \text{Adam, Front-end Engineer} \rangle, \langle \text{Bret, Tester} \rangle] = 0.35$.

*Definition 6:* A *compact CCF matrix* [3] $C^{cf}$ is an $n_c \times 5$ matrix, where $C^{cf}[k, 4] \in [-1, 0) \cup (0, 1]$ $(0 \leq k < n_c)$ expresses that the degree of cooperation or conflict effect when agent $C^{cf}[k, 0]$ plays role $C^{cf}[k, 1]$ and agent $C^{cf}[k, 2]$ plays role $C^{cf}[k, 3]$. $n_c$ represents the total number of nonzero elements in $C^f$.

*Note:* In our scenario, since the *CCF matrix* $C^f$ in Table III is sparse, we define a new matrix $C^{cf}$ [3] to replace $C^f$ for dimensionality reduction. For example, in Table III, the first nonzero element $C^{cf}[0]$ is [Adam, Front-end Engineer, Bret, Front-end Engineer, $-0.3$].

*Definition 7:* A *role assignment matrix* [1] $T$ is defined as an $m \times n$ matrix, where $T[i, j] \in \{0, 1\}$ $(0 \leq i < m, 0 \leq j < n)$ indicates whether or not agent $i$ is assigned to role $j$. $T[i, j] = 1$ means yes and 0 means no.

*Definition 8:* A *CCF assignment vector* $\bar{T}$ is an $n_c$-vector, where $\bar{T}[k] \in \{0, 1\}$ $(0 \leq k < n_c)$ indicates whether or not cooperation or conflict factor $\bar{T}[k]$ is chosen. $\bar{T}[k] = 1$ means yes and 0 means no.

*Definition 9:* The *group performance* $\sigma^{\text{GRA}}(\cdot)$ of group $(g)$ is defined as the sum of the assigned agents' qualifications, that is

$$\sigma^{\text{GRA}}(T) = \sum_{i=0}^{m-1} \sum_{j=0}^{n-1} Q[i, j] \times T[i, j].$$

*Note:* The social meaning of $\sigma^{\text{GRA}}(\cdot)$ is the team performance without considering the impacts of CCFs.

*Definition 10:* The *group performance* $\sigma^{\text{GRACCF}}(\cdot)$ of group $(g)$ is defined as the sum of the assigned agents' qualifications, that is

$$\begin{aligned}\sigma^{\text{GRACCF}}&(T)\\ &= \sum_{i=0}^{m-1} \sum_{j=0}^{n-1} Q[i, j] \times T[i, j]\\ &\quad + \sum_{k=0}^{n_c-1} C^{cf}[k, 4] \times Q\big[C^{cf}[k, 0], C^{cf}[k, 1]\big] \times \bar{T}[k].\end{aligned}$$

*Note:* The social meaning of $\sigma^{\text{GRACCF}}(\cdot)$ is the team performance with taking CCFs' impact into consideration. The first part on the right side of the equation represents the individual performance, and the second part represents the benefits of CCFs' impacts. If the two candidates can bring cooperation benefits, it means $1 + 1 > 2$; otherwise, it indicates $1 + 1 < 2$.

*Definition 11:* Role $j$ is *workable* [1] in group $(g)$ if it has been assigned enough agents, that is

$$\sum_{i=0}^{m-1} T[i, j] \geq L[j].$$

*Definition 12:* $T$ is *workable* if each role $j$ is workable [1], i.e., $\sum_{i=0}^{m-1} T[i, j] = L[j] (0 \le j < n)$. Group $g$ is *workable* if $T$ is workable. From the above definitions, group ($g$) can be expressed by an $L$, $L^a$, $Q$, $C^{cf}$, $T$, and $\bar{T}$.

*Definition 13:* The GRA [1] model is to find a workable $T$ to

$$\max \sigma^{\text{GRA}}(T) = \sum_{i=0}^{m-1}\sum_{j=0}^{n-1} Q[i, j] \times T[i, j]. \quad (1)$$

Subject to

$$T[i, j] \in \{0, 1\} (0 \le i < m, 0 \le j < n) \quad (2)$$

$$\sum_{i=0}^{m-1} T[i, j] = L[j] (0 \le j < n) \quad (3)$$

$$\sum_{j=0}^{n-1} T[i, j] \le 1 (0 \le i < m) \quad (4)$$

where expressions (2)–(4) are the constraints for the control variables $T[i, j]$.

*Definition 13:* The GRACCF [3] model is to find a workable $T$ to

$$\begin{aligned} &\max \sigma^{\text{GRACCF}}(T) \\ &= \sum_{i=0}^{m-1}\sum_{j=0}^{n-1} Q[i, j] \times T[i, j] \\ &\quad + \sum_{k=0}^{n_c-1} C^{cf}[k, 4] \times Q\left[C^{cf}[k, 0], C^{cf}[k, 1]\right] \times \bar{T}[k]. \end{aligned} \quad (5)$$

Subject to (2)–(4), and

$$\bar{T}[k] \in \{0, 1\} (0 \le k < n_c) \quad (6)$$

$$\begin{aligned} 2\bar{T}[k] \le\ & T\left[C^{cf}[k, 0], C^{cf}[k, 1]\right] \\ & + T\left[C^{cf}[k, 2], C^{cf}[k, 3]\right] (0 \le k < n_c) \end{aligned} \quad (7)$$

$$\begin{aligned} & T\left[C^{cf}[k, 0], C^{cf}[k, 1]\right] + T\left[C^{cf}[k, 2], C^{cf}[k, 3]\right] \\ & \le \bar{T}[k] + 1 (0 \le k < n_c) \end{aligned} \quad (8)$$

where expressions (6)–(8) are the constraints for the vector $\bar{T}$. As illustrated in Definitions 6 and 8, $\bar{T}[k]$ satisfies the equation $\bar{T}[k] = T[C^{cf}[k, 0], C^{cf}[k, 1]] \times T[C^{cf}[k, 2], C^{cf}[k, 3]]$, but it is not a linear constraint. Fortunately, since the variables in the objective of the GRACCF problem only take 0 or 1 as their values, i.e., $T[i, j] \in \{0, 1\}$, Zhu *et al.* [3] leverage expressions (7) and (8) to transfer the objective of the GRACCF problem into a linear one and ensure that the solution results of $T$ and $\bar{T}$ are consistent.

From the above formalization, the team establishment problem is expressed as a linear programming problem. Then, it can be solved using an industry-standard optimization tool like the PuLP linear programming tool kit [24], an open-source package of Python. The solution result of the $T$ matrix obtained by the GRACCF model is illustrated in Table IV. The optimal group performance $\sigma^{\text{GRACCF}}(T)$ calculated by PuLP is 9.45, while $\sigma^{\text{GRA}}(T) = 6.96$.

The above method remains some problems. First, since the CCF matrix $C^f$ is sparse and the potential CCFs between candidates will affect the assignment result, a proper method is required to mine more candidates' CCFs. Second, GRACCF's objective function merely mixes the individual performance and the impacts of CCFs. It is difficult for decision-makers to differentiate the relationship between team performance and the impact of CCFs based on such an objective function. Consequently, the GRACCF model needs to be properly improved for better team establishment.

TABLE IV
ASSIGNMENT RESULT OBTAINED BY GRACCF*

| Candidates | Positions | | | |
|---|---|---|---|---|
| | Algorithm Engineer | Front-end Engineer | Back-end Engineer | Tester |
| Adam | 0 | 1 | 0 | 0 |
| Bret | 0 | 0 | 0 | 1 |
| Chris | 0 | 1 | 0 | 0 |
| David | 0 | 0 | 0 | 1 |
| Edward | 0 | 0 | 1 | 0 |
| Fred | 0 | 0 | 0 | 0 |
| George | 0 | 0 | 0 | 0 |
| Harry | 0 | 0 | 1 | 0 |
| Jack | 0 | 0 | 0 | 0 |
| Joe | 0 | 0 | 1 | 0 |
| Kris | 0 | 0 | 0 | 0 |
| Larry | 1 | 0 | 0 | 0 |
| Matt | 0 | 0 | 1 | 0 |

*Note: Values 1 indicate those candidate employees who will eventually take up the position.

## IV. EXTENDED GRACCF MODEL

As mentioned in Section III, there are two nontrivial challenges left for the practical application of the GRACCF model. The first one is how to mine the potential CCFs between candidates. The second is the method to differentiate the relationship between team performance and the impacts of the CCFs. Thus, this section first introduces the KD45 logic algorithm to discover the implicit cognitive CCFs. Then, it designs a team evaluation method, which can quantify the impacts of CCFs and team performance based on decision-makers' preferences.

### A. KD45 Logic Algorithm

Mining the potential CCFs between candidates is essentially the relational reasoning problem between multiagents, and the modal logic system is an efficient way of solving multiagent relational reasoning [16]. It can discover the implicit cognitive relationship between agents through logical rules and closure operations. Different modal logic axiom systems are proposed based on different understandings and requirements of knowledge. The more commonly used modal logic systems are *K* [25], *KD45* [26], *S4* [27], *S5* [28], [29], and so on, among which *KD45* is widely used in the representation and reasoning of multiagent knowledge and belief [30]. Hence, here we apply the KD45 logic system in exploring the potential relationship between agents. The *KD45* logic system consists of four axioms, as shown in Table V.

TABLE V
KD45 LOGIC SYSTEM*

| Axiom Name | Axiom | Meaning | Condition on Frames |
|---|---|---|---|
| **K** | $\Box(A\rightarrow B)\rightarrow(\Box A\rightarrow\Box B)$ | Distributive | Kripke's relational semantics |
| **D** | $\Box A\rightarrow\Diamond A$ | Serial | $\forall x, \exists y \Rightarrow xRy$ |
| **4** | $\Box A\rightarrow\Box\Box A$ | Transitive | $\forall x, y, z, xRy \wedge yRz \Rightarrow xRz$ |
| **5** | $\Diamond A\rightarrow\Box\Diamond A$ | Euclidean | $\forall x, y, z, xRy \wedge xRz \Rightarrow yRz$ |

*Note: Symbols $\Box$ and $\Diamond$ respectively represent obligatorily and permissibly in modal logic, and $A$, $B$ are both propositions. $xRy$ represents that elements $x$ and $y$ have a relationship $R$.

To use the *KD45* logic system to explore the potential relationships, the prior thing is to prove that the *KD45* logic system is suitable for the team establishment problem. Hence, Theorem 1 is proven. Here, we define special symbols as follows for a better description for Theorem 1.

1) $\mathcal{G}$ is a set of groups, and $\mathcal{G} = \mathcal{A} \times \mathcal{R} = \{\langle a, r\rangle | a \in \mathcal{A} \wedge r \in \mathcal{R}\}$, and $|\mathcal{G}| = m \times n$, where $m = |\mathcal{A}|$ and $n = |\mathcal{R}|$. To simplify the description, without loss of generality, we ignore the effect of $O$ and $C$, and then, $\mathcal{G}$ is simplified as $\mathcal{A} \times \mathcal{R}$.
2) $R$ represents the cooperation (conflict) relationship for the elements in $\mathcal{G}$.

*Theorem 1:* The *KD45* logic system is suitable for team establishment.

*Proof:* Theorem 1 is to prove that the team establishment problem satisfies the four axioms of the *KD45* logic system. Regarding Axiom **K**, it is obvious that the team establishment problem satisfied this Axiom [25]. Therefore, it turns to prove Axioms **D**, **4**, and **5**.

Since no isolated team member exists in a team, $\forall x \in \mathcal{A}$, $\exists y \in \mathcal{A}$, $xRy$. Consequently, Axiom **D** also holds. Then, as for Axioms **4** and **5**, whether team members are equivalent depends on whether the equation $xRy = yRx$ holds. Since the equation $xRy = yRx$ does not hold because of the subjectivity among team members, Axioms **4** and **5** are all valid for the team establishment problem. Here, we first prove Axiom **4**. $\forall x$, $y, z \in \mathcal{G}$, if there exist $xRy$ and $yRz$, it is reasonable to infer that $xRz$. The proof of Axiom **5** is similar to Axiom **4**. In summary, the *KD45* logic system is suitable for team establishment. Hence, we can conclude the proof.

*Theorem 1* is proven. ■

*Example:* Here, we use the scenario in Section II as an example to illustrate Theorem 1. In Table II, there exists cooperative relationships: ⟨Adam (FE), Bret (T)⟩, ⟨Bret (T), Larry (BE)⟩, and ⟨Adam (FE), Matt (T)⟩. Leveraging Axioms **4** and **5**, we can catch the implicit cooperative relationships: ⟨Adam (FE), Larry (BE)⟩, ⟨Matt (T), Bret (T)⟩, and ⟨Bret (T), Matt (T)⟩.

*Based on Theorem 1*, we propose a KD45 logic algorithm to mine the potential collaboration and conflict relationships between team members. Here, for clarity, we introduce several additional symbols:

1) $C^f_{kd45}$ is the modified CCF matrix $C^f$ after applying the KD45 logic algorithm.
2) *classifyRelationship* ($C^f$) is a function to separate the cooperative relationship and conflict relationship in $C^f$ and return two corresponding types of sets, i.e., $C^f_{\text{coop}}$ and $C^f_{\text{conf}}$.
3) *transitiveClosure*$(\cdot)$ is a function to achieve Axiom **4**, that is, to find the transitive closure of $\mathcal{G}$.
4) *EuclideanClosure*$(\cdot)$ is a function to achieve Axiom **5**, that is, to find the Euclidean closure of $\mathcal{G}$.
5) *integrateRelationship*$(C^f, C^f_{\text{coop}}, C^f_{\text{conf}}, \mathcal{G})$ is a function to integrate $C^f_{\text{coop}}$ and $C^f_{\text{conf}}$ and retain the initial relationships in $C^f$.

There are three vital steps for the KD45 logic algorithm: calculating transitive closure, calculating the Euclidean closure, and integrating the mined relationships. As for calculating the transitive closure, a mature algorithm called the Floyd–Warshall algorithm was already proposed in [31]–[33]; hence, we use it to calculate the transitive closure. The time complexity of this algorithm is $O((m \times n)^3)$, where $m = |\mathcal{A}|$ and $n = |\mathcal{R}|$. Regarding the Euclidean closure, there is no existing mature algorithm for it; hence, we designed Algorithm 2 to calculate the Euclidean closure of the set.

Based on the above pseudocode of Algorithm 2, the time complexity is $O((m \times n)^3)$, where $m = |\mathcal{A}|$ and $n = |\mathcal{R}|$. To clarify whether Algorithm 2 can find the Euclidean closure of $C^f$, we prove Theorem 2.

*Theorem 2:* Algorithm 2 can find the Euclidean closure of a set.

*Proof:* Let $C^f_t$ denote the CCF matrix $C^f$ obtained by Algorithm 2 in the $t$th times' outer loop, and $w^t(x, y)$ represents the relationship result obtained through $t$ intermediate nodes with $x$ as the starting point and $y$ as the ending point. Proving the correctness of Theorem 2 is equivalent to proving (9) below holds

$$\forall x, y \in |\mathcal{G}|, C^f_t(x, y) = w^t(x, y)(0 \le t < |\mathcal{G}|). \tag{9}$$

Based on the nature of Axiom **5**, we can get the following recurrence relation:

$$w^q(x, y) = \min{}^*\left\{w^{q-1}(x, y), w^{q-1}(q, x) + w^{q-1}(q, y)\right\} \quad (0 < q \le t) \tag{10}$$

where $w^0(x, y)$ is the initial relationship between $x$ and $y$ and $w^0(x, y) = C^f_0(x, y)$. Note that (10) represents the conflicted relationship; if it represents the cooperative relationship, then min turns into max. Then, we use mathematical induction to prove that (9) holds.

*Base Case:* Initially, when $q = 1$, $w^1(x, y) = \min\{w^0(x, y), w^0(1, x) + w^0(1, y)\} = \min\{C^f_0(x, y), C^f_0(x, 1) + C^f_0(1, y)\} = C^f_1(x, y)$. Therefore, Theorem 1 is trivially true.

*Induction hypothesis:* When $q = t - 1$, we suppose that $w^{t-1}(x, y) = {C^f}_{t-1}(x, y)$ holds.

*Induction step:* When $q = t$, there exists $w^t(x, y) = \min\{w^{t-1}(x, y), w^{t-1}(t, x) + w^{t-1}(t, y)\} = \min\{C^f_{t-1}(x, y)$, and $C^f_{t-1}(x, t) + C^f_{t-1}(t, y)\} = C^f_t(x, y)$. Consequently, when $q = t$, (9) still holds. Hence, we can conclude the proof.

*Theorem 2* is proven. ■

The last vital step of the KD45 algorithm is to integrate the mined cooperative and conflict relationships into the CCF matrix $C^f$. The specific process is shown in Algorithm 3.

The time complexity of Algorithm 3 is $O((m \times n)^2)$, where $m = |\mathcal{A}|$ and $n = |\mathcal{R}|$. In summary, the time complexity of our proposed KD45 algorithm is $O((m \times n)^3)$.

After applying the KD45 algorithm to extend the CCF matrix $C^f$ in GRACCF, the number of conflicts and collaborations in $C^f$ increased from 91 to 201. The solution result of the $T$ matrix obtained by this extended GRACCF is the same as the original GRACCF one (see Table IV). Please note that the equal $T$ matrices of these two models are only a special case obtained in this scenario. We will conduct a large-scale experiment in Section V to compare the $T$ matrices obtained by these two models. The group performance $\sigma(T)$ of the extended GRACCF model is 10.87, while the original GRACCF obtains 9.45. From this comparison, the KD45 algorithm evidently affects the group performance, i.e., (10.87–9.45)/9.45 = 15%. Note that the original GRACCF only using the CCFs may have a lower team performance in practice because many implicit cooperation impacts are not considered and many potential conflicts are not avoided. That means the revised GRACCF may obtain more benefits than the original ones.

### B. Team Evaluation

Another key issue of extending the GRACCF model is quantifying the relationship between team performance and teamwork contributions (the impacts of the CCFs) to help the decision-makers make tradeoffs. In response to this problem, we propose a team evaluation method. To better describe this method, we propose some new definitions.

*Definition 14:* A *teamwork coefficient* $\tau$ represents the impacts of cooperation or conflict factors (CCFs) between members expected by the administrators, and $\in \tau[0, 1]$.

*Note:* Since administrators are more inclined to form teams with more CCF impacts, we design the *teamwork coefficient* $\tau$ to help screen those candidate team members with large CCF values. We introduce the following Definitions 15 and 16 to help elaborate the physical meaning of $\tau$.

*Definition 15:* A *cooperation threshold* $\theta_{\text{coop}}$ is a value that represents the degree of cooperation expected by the team leader between candidate employees, and $\theta_{\text{coop}} \in [0, 1]$.

*Note*: In this article, we set $\theta_{\text{coop}} = \tau$ to find the candidate employees with high cooperation.

*Definition 16:* A *conflict threshold* $\theta_{\text{conf}}$ is a value that represents the level of conflict acceptable to the team leader between candidate employees, and $\theta_{\text{conf}} \in [-1, 0]$.

*Note*: In this article, we set $\theta_{\text{conf}} = \tau - 1$ to find the candidate employees with low conflict.

Here, we use the scenario in Section II to illustrate the physical meaning of $\tau$. When the administrators set $\tau = 0.6$, that is, $\theta_{\text{coop}} = 0.6$ and $\theta_{\text{conf}} = -0.4$. That is, if $-0.4 < C^f[i_1, j_1, i_2, j_2] < 0.6$ $(0 \le i_1, i_2 < m, 0 \le j_1, j_2 < n)$, the relationship between them will be ignored, e.g., $\langle$*Bret (FE), Adam (BE)*$\rangle = 0$ *and* $\langle$*Adam (FE), Bret (FE)*$\rangle = 0$.

The above new definitions introduce the extended GRACCF model

$$\max \sigma^{e-\text{GRACCF}}(T) = \sum_{i=0}^{m-1}\sum_{j=0}^{n-1} Q[i,j] \times T[i,j] + \sum_{k=0}^{n_c-1} C^{cf}[k,4] \times Q\big[C^{cf}[k,0], C^{cf}[k,1]\big] \times \bar{T}[k]. \quad (11)$$

Subject to (2)–(4), (6)–(8), and

$$C^{cf}[k,4] = 0\big(0 \le k < n_c, C^{cf}[k,4] < \theta_{\text{coop}}\big) \quad (12)$$

$$C^{cf}[k,4] = 0\big(0 \le k < n_c, C^{cf}[k,4] > \theta_{\text{conf}}\big) \quad (13)$$

where $\sigma^{\text{e}-\text{GRACCF}}$ represents the team performance of the extended GRACCF model, and expressions (12) and (13) cooperatively screen those candidate team members with high cooperation and low conflict potentials in the extended GRACCF model.

With the abovementioned definitions and constraints, we propose the team evaluation method (see Algorithm 4). Here, we define additional symbols as follows to simplify our descriptions.

1) *step* is a value that expresses the increasing *step* length of the teamwork coefficient $\tau$, and the range of *step* is [0, $\tau$]. In our scenario, we randomly set it to 0.05. Without loss of generality, we will carry out large-scale random experiments in Section V.
2) GRA(·) is a function to call the GRA solution [9], [34] based on Python PuLP. GRA can obtain the optimal team execution without considering the collaboration and conflict relationship between team members.
3) *e*-GRACCF(·) is a function to call the extended GRACCF solution [see expression (11)] based on Python PuLP.
4) $T^{\text{GRA}}$ is the assignment result obtained by the GRA.
5) $L(\sigma)$ represents the loss of the group (team) performance $\sigma$ acceptable to the team leaders, i.e., $\sigma - \sigma^{\text{GRA}}$. Here, we randomly set $L(\sigma) = 0$.
6) $T'$ is a tentative matrix to record $T$.
7) $\sigma'$ is a tentative variable to record $\sigma$.

Algorithm 4 elaborates the proposed team evaluation method, which can differentiate the impacts of CCFs and team performance based on decision-makers' demands. Because the time complexity of the extended GRACCF model is NP-hard [3], then that of the team evaluation method is also NP-hard, but the PuLP solution [24] is a practical way for some scales based on experimentation.

Fig. 3 illustrates that when the teamwork coefficient $\tau$ increases, the team performance $\sigma$ decreases at this time. Due to stricter requirements for the CCF's impacts, the performance of CCFs' impacts decreases. Besides, since the extended GRACCF needs to consider the impacts of CCFs, the individual performance of it is lower than GRA at the end. Fig. 3 also elaborates that, when $\tau > 0.85$, too much pursuit of teamwork may lead to lower team performance than that without considering the CCFs. That is, when $\tau$ =0.85,

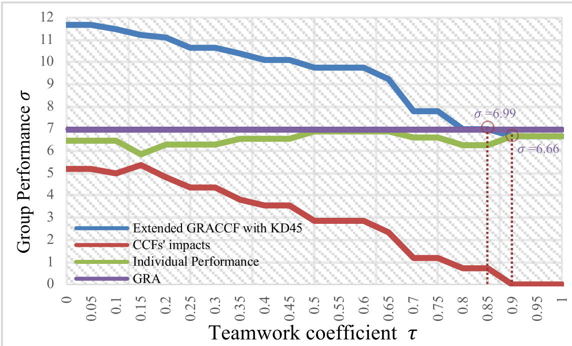


Fig. 3. Changes in group performance $\sigma$ when teamwork coefficient $\tau$ increases$*$. $*$Note: The group performance of the extended GRACCF is composed of the individual performance and CCFs' impacts.

$$\begin{pmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

Fig. 4. $T$ matrix$*$ obtained by Algorithm 4 at $\tau = 0.85$. $*$Note: The rows of the $T$ matrix represent candidates, and the columns represent positions required for the new team.

TABLE VI

CONFIGURATION OF THE EXPERIMENTAL PLATFORM

| **Hardware** | |
|---|---|
| **CPU** | Apple M1 |
| **Memory** | 16GB |
| **Software** | |
| **OS** | macOS Big Sur Version 11.2.3 |
| **Editor** | Visual Studio Code Version 1.56.2 |
| **Python** | Python 3.8.5 |

Algorithm 4 obtained the proper team performance while ensuring the new team with high cooperation and low conflict potentials. At this time, the $T$ matrix obtained by Algorithm 4 is depicted by Fig. 4, and the group performance $\sigma$ is 6.99.

## V. EXPERIMENT

To verify the efficiency and robustness of our proposed method, we performed large-scale random simulation experiments on a laptop configured, as shown in Table VI.

In the simulation, we choose two different typical sizes of the team, i.e., ($m = 10$, $n = 5$) and ($m = 30$, $n = 6$), where $m$ represents the number of candidates (agents) and $n$ represents the number of position types (roles). These two sizes of the team are common in small and middle-sized companies or factories. Since our proposed solution is mainly concerned with predefined parameters $n_c$, $Q[i, j]$, $C^{cf}[k, 4]$, $L[j]$, $\tau$, and *step*, we will conduct our simulation experiments thousands of times based on the ranges of these parameters in Table VII.

Also, to simplify the description, we introduce the following symbols.

1) $n_a$ denotes the number of required candidate employees (agents), i.e., $n_a = \sum_{j=0}^{n-1} L[j]$.

TABLE VII

RANGES OF THE PREDEFINED PARAMETERS$*$

| Parameters | Ranges |
|---|---|
| $n_c$ | $m \times v$ |
| $Q[i, j]$ $(0 \le i < m, 0 \le j < n)$ | [0, 1] |
| $C^{cf}[k, 4]$ $(0 \le k < n_c)$ | [-1, 0) ∪ (0, 1] |
| $L[j]$ $(0 \le j < n)$ | $[1, \frac{m}{n}]$ |
| $\tau$ | [0, 1] |
| *step* | $[0, \tau]$ |

*Note: The parameter $v$ represents the increasing step of $n_c$ and $v$ is from 1 to 10 with a step of 1.

TABLE VIII

SIMULATION AVERAGES$*$ $\{m = 10, n = 5, 1 \le L[j] \le 2\ (0 \le j < 5)\}$

| $n_c$=m× | $\sigma^{GRACCF}$ | $\sigma^{e\text{-}GRACCF}$ | $\sigma^{real\text{-}GRACCF}$ | $n_a$ | $\lambda_1$ | $\lambda_2$ |
|---|---|---|---|---|---|---|
| 1 | 5.48 | 5.49 | 5.48 | 6 | 0.21% | 0.07% |
| 2 | 5.64 | 5.75 | 5.69 | 6 | 1.86% | 1.07% |
| 3 | 5.75 | 6.14 | 5.93 | 6 | 6.69% | 3.64% |
| 4 | 5.80 | 6.36 | 6.09 | 6 | 9.49% | 4.70% |
| 5 | 5.93 | 6.81 | 6.25 | 6 | 14.65% | 9.07% |
| 6 | 5.99 | 7.06 | 6.44 | 6 | 17.63% | 10.01% |
| 7 | 6.07 | 7.56 | 6.59 | 6 | 24.10% | 16.02% |
| 8 | 6.18 | 8.05 | 6.94 | 6 | 30.13% | 16.46% |
| 9 | 6.19 | 8.16 | 6.81 | 6 | 31.80% | 21.96% |
| 10 | 6.31 | 9.02 | 7.00 | 6 | 42.39% | 34.41% |

*Note: The results of each group of $n_c$ are the average values of thousands of random experiments.

2) $C^{cf}_{kd45}$ represents the *compact CCF matrix* of $C^{f}_{kd45}$.

3) $T^{\text{GRACCF}}$ represents the $T$ matrix obtained from the original GRACCF model.

4) $\bar{T}^{\text{GRACCF}}$ is the CCF assignment result $\bar{T}$ obtained from the original GRACCF model.

5) $\sigma^{\text{real-GRACCF}}$ denotes the real team performance, which is formalized as follows:

$$\begin{aligned} &\sigma^{\text{real}-\text{GRACCF}} \\ &= \sum_{i=0}^{m-1}\sum_{j=0}^{n-1} Q[i,j] \times T^{\text{GRACCF}}[i,j] \\ &\quad + \sum_{k=0}^{n_c-1} C^{cf}_{kd45}[k,4] \times Q\Big[C^{cf}_{kd45}[k,0], C^{cf}_{kd45}[k,1]\Big] \\ &\quad \times \bar{T}^{\text{GRACCF}}[k]. \end{aligned} \tag{14}$$

6) $\lambda_1$ is defined as $(\sigma^{\text{e}-\text{GRACCF}} - \sigma^{\text{GRACCF}}/\sigma^{\text{GRACCF}})$, and $\lambda_2$ is defined as $(\sigma^{\text{e}-\text{GRACCF}} - \sigma^{\text{real}-\text{GRACCF}}/\sigma^{\text{real}-\text{GRACCF}})$.

First, we analyze the benefit of extending GRACCF with the KD45 logic algorithm. Here, we compare the group performance of the extended GRACCF with the original GRACCF under two team sizes, and Tables VIII and IX illustrate the simulation results. As shown in Tables VIII and IX, when CCFs' impacts increase, mining potential relationships between these candidates using Algorithm 1 can greatly increase the team's overall performance, $\sigma^{\text{e}-\text{GRACCF}}$ in (11). Fig. 5 shows the comparison of the average group performance of the GRACCF

**Algorithm 1** KD45 Logic Algorithm

**input**: $C^f$, $\mathcal{G}$ /*$C^f$ is the pre-defined CCF matrix*/
**output**: $C^f_{kd45}$
**begin**
$C^f_{kd45} \leftarrow \emptyset$; /*$\emptyset$ represents the empty set */
/* Pre-classification to meet the *KD45* logic system */
$C^f_{coop}$, $C^f_{conf} \leftarrow classifyRelationship(C^f)$;
/* Finding transitive closure first and then Euclidean closure can greatly avoid reflexivity. */
$C^f_{coop} \leftarrow transitiveClosure(C^f_{coop}, \mathcal{G})$;
$C^f_{coop} \leftarrow EuclideanClosure(C^f_{coop}, \mathcal{G})$;
$C^f_{conf} \leftarrow transitiveClosure(C^f_{conf}, \mathcal{G})$;
$C^f_{conf} \leftarrow EuclideanClosure(C^f_{conf}, \mathcal{G})$;
$C^f_{kd45} \leftarrow integrateRelationship(C^f, C^f_{coop}, C^f_{conf}, \mathcal{G})$;
**return** $C^f_{kd45}$;
**end**

**Algorithm 2** Euclidean Closure($C^f$, $\mathcal{G}$)

**input**: $C^f$, $\mathcal{G}$
**output**: $C^f$
**begin**
**for** each $x \in \mathcal{G}$ **do**
  **for** each $y \in \mathcal{G}$ **do**
    **for** each $z \in \mathcal{G}$ **do**
      **if** $y \neq z$ **then**
        **if** $C^f$ is a $C^f_{coop}$ **then**
/* Here we use the nature of multiplication to indicate the weakening of the inferred relationships. */
          **if** $C^f[y][z] > C^f[x][y] \times C^f[x][z]$ **then**
            $C^f[y][z] = C^f[x][y] \times C^f[x][z]$;
          **end if**
        **else** /* Conflict relationship*/
          **if** $C^f[y][z] < -C^f[x][y] \times C^f[x][z]$ **then**
            $C^f[y][z] = -C^f[x][y] \times C^f[x][z]$;
          **end if**
        **end if**
      **end if**
    **end for**
  **end for**
**end for**
**return** $C^f$;
**end**

**Algorithm 3** Integration Relationship($C^f$, $C^f_{coop}$, $C^f_{conf}$, $\mathcal{G}$)

**input**: $C^f$, $C^f_{coop}$, $C^f_{conf}$, $\mathcal{G}$
**output**: $C^f_{kd45}$
**begin**
$C^f_{kd45} \leftarrow C^f$; /* Retain the initial relationships in $C^f$. */
**for** each $x \in \mathcal{G}$ **do**
  **for** each $y \in \mathcal{G}$ **do**
    **if** $C^f_{kd45}[x][y] = 0$ **then**
      $C^f_{kd45}[x][y] = C^f_{coop}[x][y] + C^f_{conf}[x][y]$
    **end if**
  **end for**
**end for**
**return** $C^f_{kd45}$;
**end**

**Algorithm 4** Team Evaluation Method

**input**: $L$, $L^a$, $Q$, $C^f$, $\mathcal{G}$
**output**: $T$
**begin**
$step \leftarrow 0.05$;
$\tau \leftarrow 0$;
$\sigma' \leftarrow +\infty$; /* $+\infty$ means a very big number*/
$\sigma \leftarrow -1$;
**for** each $t \in T$ **do**
  $t \leftarrow 0$;
**end for**
$T' \leftarrow T$;
**while** $\tau \leq 1$ **do**
  $C^f_{kd45} = Algorithm\ 1(C^f, \mathcal{G})$;
  $T^{GRA}$, $\sigma^{GRA} \leftarrow GRA(L, L^a, Q)$;
  $T'$, $\sigma' \leftarrow e\text{-}GRACCF(L, L^a, Q, C^f_{kd45})$;
/* Acceptable loss of the group performance */
  **if** $\sigma'$ - $\sigma^{GRA} \geq L(\sigma)$ **then**
    $\sigma \leftarrow \sigma'$;
    $T \leftarrow T'$;
  **end if**
  $\tau \leftarrow \tau + step$;
**end while**
**return** $T$;
**end**

model and the extended GRACCF model with Algorithm 1 under two different-sized teams. Fig. 5 also demonstrates that our proposed KD45 logic algorithm can effectively improve the group performance. Since the KD45 logic algorithm has excavated more CCFs' impacts, the solution time of the extended GRACCF model has increased compared to the original GRACCF model, as elaborated in Fig. 6.

In addition, to verify the effectiveness of the KD45 algorithm, we compared the $T$ matrices obtained by the solution of the extended GRACCF model and the original GRACCF model in the middle-sized companies, i.e., $m = 30$, $n = 6$, and $n_a = 19$. Fig. 7 depicts that more complete relationships between candidate employees lead to a different $T$ matrix obtained by the extended GRACCF model different from that of the original GRACCF model.

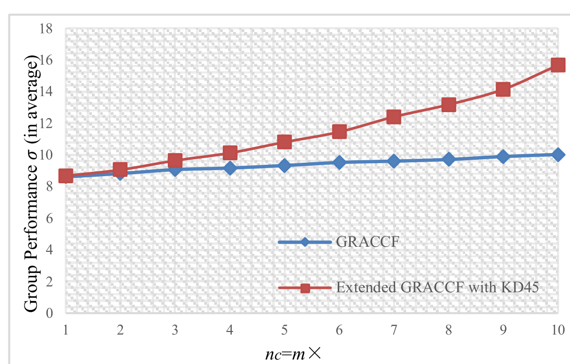


Fig. 5. Comparison of the average group performance $\sigma$.

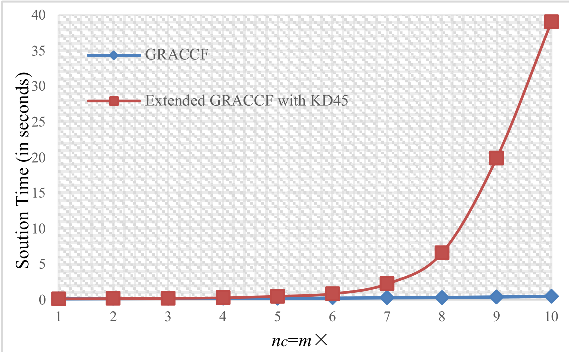


Fig. 6. Comparison of the solution time.

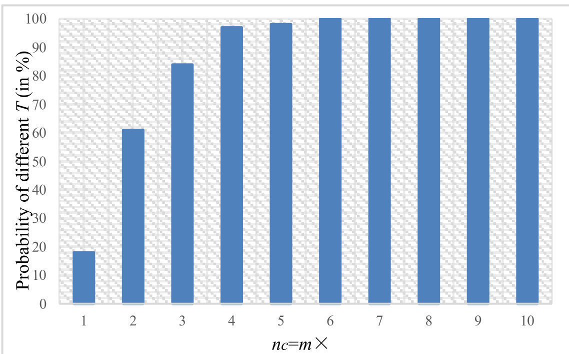


Fig. 7. Probability that the original GRACCF and the extended GRACCF get different $T$ matrices.

Then, we examine the validity of the team evaluation method (i.e., Algorithm 4) that weighs the team performance and the impacts of the CCFs. Similarly, we also use the abovementioned two sizes of the team to validate this method. Algorithm 4 is mainly related to the teamwork coefficient $\tau$ and parameter *step*. Since the optimal value of $\tau$ is dynamically searched by the team evaluation method, we start the search from the maximum value, i.e., $\tau = 1$. Figs. 8 and 9, respectively, depict the changes of different sizes of the group performance under different values of *step*. Figs. 8 and 9 demonstrate that when administrators want to build a sustainable development team with high CCFs' impacts, they need to appropriately sacrifice the individual performance. Meanwhile, Figs. 8 and 9 also show that since Algorithm 1 can mine more cooperation and conflict relationships between candidates, the real GRACCF curve [see (14)] has a higher starting point and a lower endpoint than the original GRACCF curve.

From the experiment above, we can conclude that:

1) Tables VIII and IX and Fig. 5 show that our proposed KD45 logic algorithm can effectively improve team performance by mining the potential relationships between candidate employees.
2) Figs. 8 and 9 illustrate that as the teamwork coefficient $\tau$ increases, the stricter requirements for the CCFs' impacts will lead to a decrease in the performance of CCFs' impacts. Besides, since the extended GRACCF needs to consider the impacts of CCFs, its individual performance is lower than GRA at the end.
3) Figs. 8 and 9 also demonstrate that, compared with the traditional GRACCF, our proposed team evaluation method can weigh team performance and CCFs' impacts. The decision-makers can tradeoff between team performance and CCFs' impacts by setting the value of the teamwork coefficient $\tau$ based on their demands.

TABLE IX
SIMULATION AVERAGES* $\{m = 30, n = 6, 1 \le L[j] \le 5\ (0 \le j < 6)\}$

| $n_c$=m× | $\sigma^{GRACCF}$ | $\sigma^{e\text{-}GRACCF}$ | $\sigma^{real\text{-}GRACCF}$ | $n_a$ | $\lambda_1$ | $\lambda_2$ |
|---|---|---|---|---|---|---|
| 1 | 18.12 | 18.32 | 18.26 | 19 | 1.04% | 0.32% |
| 2 | 18.75 | 19.62 | 19.23 | 19 | 4.70% | 2.01% |
| 3 | 19.18 | 20.65 | 20.05 | 19 | 7.58% | 3.04% |
| 4 | 19.69 | 22.54 | 21.08 | 19 | 14.26% | 6.97% |
| 5 | 20.10 | 24.39 | 22.13 | 19 | 21.14% | 10.08% |
| 6 | 20.39 | 26.50 | 23.10 | 19 | 29.85% | 14.91% |
| 7 | 20.75 | 28.84 | 24.03 | 19 | 38.71% | 20.01% |
| 8 | 21.21 | 32.27 | 25.16 | 19 | 51.95% | 28.39% |
| 9 | 21.46 | 35.86 | 26.79 | 19 | 66.77% | 34.82% |
| 10 | 21.95 | 39.96 | 27.77 | 19 | 81.48% | 39.91% |

*Note: The results of each group of $n_c$ are the average values of thousands of random experiments.

From the simulation results, we understand that:

1) When the *compact CCF matrix* $C^{cf}$ obtained through the questionnaire of candidate employees is complete enough, the KD45 logic algorithm can increase the team's performance by more than 80%.
2) Too much pursuit of high cooperation and low conflict teams, i.e., teamwork coefficient $\tau > 0.96$, may lead to a decrease in team performance.

## VI. Related Work

### A. Task Assignment

The team establishment problem is essentially a task assignment problem, which has received increasing attention since it is a general engineering problem in multiple fields, i.e., forest firefighting [35], communication task [36], [37], automated warehouse [38], [39], team organization [6], [40], and refugee resettlement [41]. In recent years, many scholars tend to solve the task assignment problem through multiagent systems (agent-based method [11], [42]–[44]).

For example, Chen *et al.* [35] investigate multiagent dynamic task assignments based on a forest fire point model to minimize task completion time. Moreover, Wang *et al.* [36] propose an intermittent cooperative protocol with the task assignment triggered strategy to solve the cooperative control problem for multiagent systems. The aforementioned studies of the agent-based method have achieved substantial results in the corresponding field. Still, there is rarely the latest literature on the agent-based method in the research on human team organization.

### B. RBC and Team Establishment

Recently, some scholars propose another option to solve the team establishment problem: RBC [1], [45]–[47] and its fundamental GRA model [48]–[50], which is characterized by centralized modeling and distributed execution [51]. As an

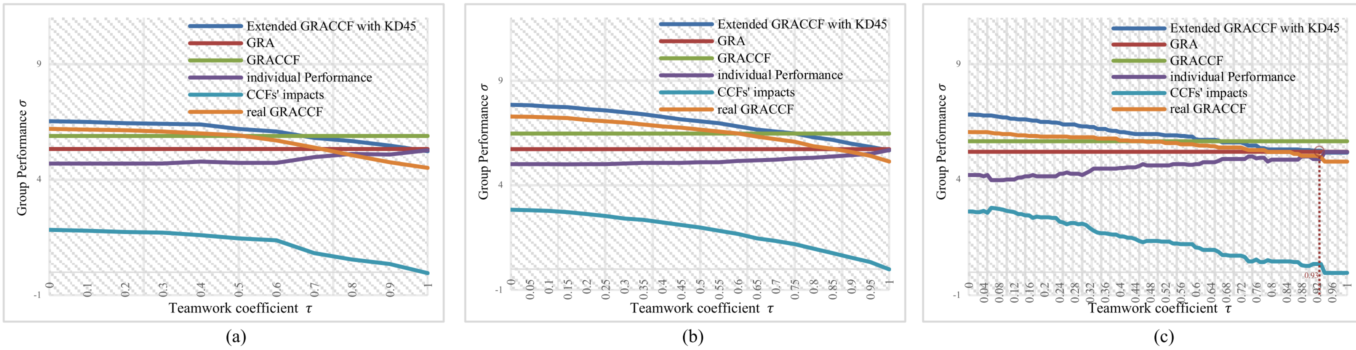


Fig. 8. Changes of the average group performance $\sigma$ in the small size of team under different values of the *step* ($m = 10$, $n = 5$, $1 \leq L[j] \leq 2$ $(0 \leq j < 5)$, $n_a = 6$)$*$. $*$Note: The group performance of the extended GRACCF is composed of the individual performance and CCFs' impacts. (a) *Step* $= 0.1$. (b) *Step* $= 0.05$. (c) *Step* $= 0.01$.

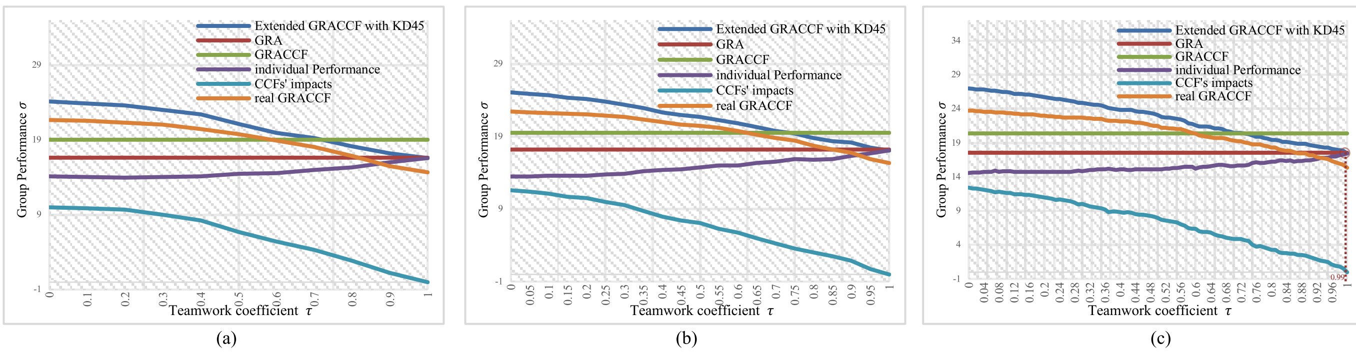


Fig. 9. Changes of the average group performance $\sigma$ in the large size of team under different values of the *step* ($m = 30$, $n = 6$, $1 \leq L[j] \leq 5$ $(0 \leq j < 6)$, $n_a = 19$)$*$. $*$Note: The group performance of the extended GRACCF is composed of the individual performance and CCFs' impacts. (a) *Step* $= 0.1$. (b) *Step* $= 0.05$. (c) *Step* $= 0.01$.

example, Zhu [22] proposes a practical solution to the agent categorization (AC) problem by combining the GRA+ algorithm with the simulated annealing (SA) algorithm, which demonstrates that RBC and E-CARGO are tools well suited to formalize and solve challenging collaboration and management problems. Additionally, Huang *et al.* [45] deal with the last-mile assignment problem (LMAP) for fresh produce via GRA with constraints (GRA+). Their proposed method not only assigns proper couriers for forming a team to deliver daily orders efficiently but also improves the quality of the team's service.

The aforementioned research has demonstrated that RBC and its GRA model have been a practical unified model for solving the team establishment problem.

### C. GRACAR and GRACCF

To make GRA better, Zhu [7] introduces the expressions of conflicts among agents to role assignment and proposes GRA with conflicting agents on roles (GRACAR) to avoid agents' conflicts by solving a well-specified assignment problem. Furthermore, not only conflicts but also cooperation factors should be considered in role assignment. It is inevitable to consider CCFs [52], [53] between team members based on their personalities, working styles, emotional issues, and political beliefs. For instance, Zhu *et al.* [3] design the GRACCF model, which considers both conflict and cooperation factors (CCF) and covers a situation where conflicting agents may be assigned in optimization. Large-scale simulation experiments illustrate that their method can help team leaders to form a team with higher performance and greatly helps a team to achieve the target that "1 + 1 > 2."

Here, there are still two problems that need to be seriously investigated for the practical application of the GRACCF model. First, when constructing the compact CCF matrix $C^{cf}$, Zhu *et al.* [3] used the form of a questionnaire, and this method may not be able to express the potential relationships between candidate team members. Second, the GRACCF model cannot help team leaders to make a tradeoff between teamwork and team execution (performance). Some leaders may value the former more, while others value the latter. For this concern, we first design the KD45 logic algorithm based on the KD45 logic system [16] to extend the GRACCF model. With this algorithm, the GRACCF model can mine the potential relationships between candidate team members. Then, we introduce an innovative team evaluation method in the RBC process, which offers a solid reference for decision-makers to balance the team performance and CCFs' impacts.

## VII. Conclusion

This article proposes an extension of the GRACCF model for practical application for establishing a new team.

This article first formalized the team establishment problem via the condensed GRACCF model. Since the potential relationships between candidate employees of a new team may affect the team's sustainability, it designs the KD45 logic algorithm based on the KD45 logic system to explore the potential relationships between candidate employees through logical rules and closure operations. Then, to help decision-makers to balance team performance and the impact of the CCFs, it introduces a team evaluation method in the RBC process. Lastly, thousands of varying scale simulation experiments are carried out to test the proposed assignment method's practicability and robustness.

The simulation results provide a solid reference for the administrators to weigh team performance and CCFs' impact based on their dynamic requirements.

From this article, further investigations on the extended GRACCF model may be conducted in the following directions.

1) We may need to compare the performance of the KD45 logic algorithm and some other machine learning algorithms in relationship discovery.
2) In the team evaluation part, we may use other forms of teamwork coefficient $\tau$, like the weighted sum method, to make a tradeoff between teamwork and team performance.
3) We may study a more complicated and comprehensive method to obtain the compact CCF matrix $C^{cf}$ between candidate employees.
4) Questionnaire respondents may be careless when filling out the questionnaire, which may lead to questionnaire biases, and we will perform preprocessing operations on such biases in the future.

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