Refugee Resettlement by Extending Group Multirole Assignment

Qian Jiang, *Graduate Student Member, IEEE*, Haibin Zhu, *Senior Member, IEEE*, Yan Qiao, *Senior Member, IEEE*, Dongning Liu, *Member, IEEE*, and Baoying Huang, *Graduate Student Member, IEEE*

***Abstract*—The World Bank estimates that the number of refugees worldwide will reach 140 million by 2050 due to global warming and local wars. Considering the rapid increase in the number of refugees, an efficient and feasible assignment method is required for refugee resettlement. This article formalizes the refugee resettlement issue using the Environments-Classes, Agents, Roles, Groups, and Objects (E-CARGO) model. A novel solution is designed for Refugee reSettling (RS) by extending the Group MultiRole Assignment (GMRA), which applies the agent stability evaluation method as a feedback mechanism while optimally resettling refugees. With this proposed solution, decision-makers can swiftly resettle refugees from multiple suffering countries while appropriately ensuring host countries' benefit. Finally, large-scale simulation experiments based on the Python PuLP platform are carried out to demonstrate the practicability and robustness of the proposed solution. The simulation results provide a solid decision-making reference for the leaders of the world.**

***Index Terms*—Collaboration, Environments-Classes, Agents, Roles, Groups, and Objects (E-CARGO), Group MultiRole Assignment (GMRA), refugee resettlement, Refugee reSettling (RS), role-based collaboration (RBC), social computational strategy.**

Nomenclature

$\mathcal{A}$	A set of agents.
$\mathcal{R}$	A set of roles.
m	Size of the agent set $\mathcal{A}$.
n	Size of the role set $\mathcal{R}$.
$i_0, i_1, i_2, \ldots$	The indices of agents.
$j_0, j_1, j_2, \ldots$	The indices of roles.
r	A role.
a	An agent.
L	The role range vector.
Q	The qualification matrix.
L^a	The agent ability limit vector.
T	The role assignment matrix.
Υ	Υ represents the *threshold matrix*, and $\Upsilon[i, j]$ is the maximum value for the control variable $T[i, j]$.
P	P is a vector that represents the population of the host countries.
σ	The group performance.
Λ^a	Λ^a represents the *climate evaluation vector*, and $\Lambda^a[i]\in[0, 1]$ expresses the severity of drought on agent i.
$\Diamond$	$\Diamond$ represents the *cultural evaluation matrix*, and $\Diamond[i, j]\in[0, 1]$ expresses the intimacy of bilateral culture between agent i and role j.
Γ^a	Γ^a represents the *life quality evaluation vector*, and $\Gamma^a[i]\in[0, 1]$ expresses the quality of life or well-being of the host country (agent) i.
$\aleph$	$\aleph$ represents the *language evaluation matrix*, and $\aleph[i, j]\in[0, 1]$ expresses the linguistic proximity between agent i and role j.
Ξ	Ξ represents the *criteria evaluation matrix*, and $\Xi[i, j]=[\Lambda^a[i], \Diamond[i, j], \Gamma^a[i], \aleph[i, j]]$.
$\mathcal{P}$	$\mathcal{P}$ represents a *role preference matrix*, and $\mathcal{P}[j]$ expresses preferences of role j for the abovementioned four quantitative criteria.
$\mathcal{P}^a$	P^a represents the *agent preference matrix*, and $\mathcal{P}^a[i]$ expresses preferences of agent i for the abovementioned four quantitative criteria.
φ	φ represents the *agent loss coefficient*, and it is a rate that the loss of national stability of agents, and $\varphi \in (0, 1)$.
ϑ^a	$\vartheta^a[i]\in \mathbb{R}^+$ ($\mathbb{R}^+$ is the set of positive real numbers) express the appropriate number of refugees that the host country (agent) i can hold while guaranteeing its national stability. The superscript of ϑ^a represents that ϑ^a is a definition for the agents.

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Qian Jiang, Yan Qiao, and Baoying Huang are with the Institute of Systems Engineering and the Collaborative Laboratory for Intelligent Science and Systems, Macau University of Science and Technology, Macao 999078, China (e-mail: jiangqian@mail2.gdut.edu.cn; yqiao@must.edu.mo; baoyhuang@126.com).

Haibin Zhu is with the Collaborative Systems Laboratory (CoSys Laboratory), Nipissing University, North Bay, ON P1B 8L7, Canada (e-mail: haibinz@nipissingu.ca).

Dongning Liu is with the School of Computer Science and Technology, Guangdong University of Technology, Guangzhou 510006, Guangdong, China (e-mail: liudn@gdut.edu.cn).

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I. Introduction

The Refugee reSettling Problem (RSP) has become an inevitable issue since the number of refugees is increasing dramatically. The World Bank conservatively predicts that the number of refugees in the world will reach 140 million by 2050 [1]. Refugees have positive impacts on the host countries if the refugees are naturalized gradually in a long-term and well-planned schedule. However, if the host countries accept too many refugees in a short time, it may lead to a decline in their national stability and ultimately lead to a series of contradictions, such as the conflict of local resources or culture. Thus, there is an urgent need for an efficient and reliable strategy for resettling refugees.

The RSP is essentially a many-to-many (M-M) assignment [2] issue between the countries where the refugee is located (suffering countries) and those willing to accept refugees (host countries). This means that one suffering country can send refugees to different host countries, and a host country may simultaneously receive refugees from multiple suffering countries. There are many criteria and requirements to be considered when assigning refugees from suffering countries to host countries. Meanwhile, each country has its own preferences among criteria and requirements due to the different development levels. Moreover, since the limited resources of host countries, the number of refugees that they can accept is limited for maintaining national stability. These constraints complicate the M-M assignment problem. This article attempts to solve this complex M-M assignment problem through formalizing and modeling by Refugee reSettling (RS). It extends from Group MultiRole Assignment (GMRA) [3], [4], while GMRA is an extended form of group role assignment (GRA) [5], [6], which is a significant step of role-based collaboration (RBC) [7]. Collaboration has been revealed as a complex process throughout the life cycle of RBC [8]–[10]. Since the RSP is a typical distribution problem, the roles and agents defined in RBC [5] and related models, such as E-CARGO, GRA, and GMRA, are two well-specified components to meet the distribution requirement of the RSP. Therefore, we can use agents to express host countries and roles suffering countries. Therefore, RBC, GRA, and GMRA are practical methodologies allowing decision-makers to manage task assignments, where agents (task executer) and roles (tasks) are used as modeling components.

In this research, the whole process of refugee resettlement can be taken as a revised RBC process (see Fig. 1). First, in the role negotiation part, we take suffering countries as roles because they represent different numbers of refugees. Then, we need to know who the participants (agents) are, in the collaboration. It is obviously reasonable to take host countries as agents because they can accept refugees.

After role negotiation, the agent evaluation part can be conducted. Host countries (agents) accept the appropriate number of refugees from suffering countries (roles). This is one of the key processes in the life cycle of RBC (the first solid black box in Fig. 1). Although there are many criteria for quantifying refugee resettlement issues, through the analysis of relevant research [11], these criteria can be roughly divided into four categories: bilateral climate [12], [13], culture [14], [15], life quality [16], and language [17], [18]. In this article, these four criteria are reasonably quantified as the agent evaluation method, and the preferences of the suffering and host countries for them are also considered.

After agent evaluation, role assignment is straightforward by using a similar solution to GMRA: the decision-makers resettled refugees from suffering countries to corresponding host countries based on such an assignment method. Role-playing occurs when the refugees arrive in the host countries and begin to live in the corresponding shelters.

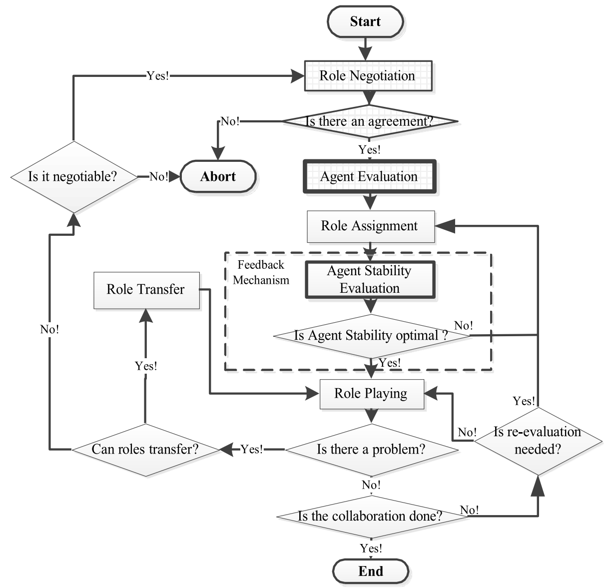

Fig. 1. Revised RBC process [5], [8] applied in the RSP.

To make role assignment more pertinent in the overall RBC process, RS introduces a new phase of calculating agent stability between role assignment and role-playing (the black slash box in Fig. 1). Because the resources of host countries (agents) are limited, sheltering too many refugees may lead to a nontrivial decline in the national stability of the host countries. Also, the large number of refugees from different countries may bring a series of conflicts, such as religious and cultural conflicts. Hence, this article revises the RBC process by adding an agent stability process and proposes an agent loss coefficient for calculating it. This process also acts as a feedback mechanism for RS.

With respect to this proposed solution, plenty of refugees were efficiently resettled to different host countries while properly guaranteeing the host countries' stability. Please note that this article focuses on the emigration of refugees among countries, i.e., internationally but not internally. In addition, this article studies permanent emigration, not a short-term one.

The contributions of this article include the following.

1) This article formalizes the first time the RSP for multiple countries to multiple countries via extending group multirole assignment, i.e., RS.
2) To properly protect the national stability of host countries, this article introduces the process of calculating agent stability and uses this process as a feedback mechanism in RBC.
3) Finally, by RS, we provide a swift way to assign refugees from multiple suffering countries to different host countries while appropriately maintaining the national stability of host countries.
4) The simulation results provide a solid reference for the world leaders.

This article is organized as follows. It first discusses a real-world scenario related to the proposed problem in Section II. Then, Section III formally defines the problem via RBC and its Environments—Classes, Agents, Roles, Groups, and Objects (E-CARGO) model. Section IV introduces the agent evaluation method in RBC and relevant RS algorithms. 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

Organization X is specializing in immigration consultation and countermeasures. Ann, the Chief Executive Officer (CEO), hopes to conduct refugee resettlement research since the United Nations High Commission on Refugees (UNHCR) estimates that global forced displacement has surpassed 80 million in mid-2020 [19].

In order to effectively solve the refugee resettlement problem, she requests a branch, the director of which is Bob, to accomplish this task. After analyzing the past refugee data [1] and related research [20], [21], Bob takes the following relatively vulnerable countries as research objects (suffering countries): country B, country M, country S, country U, and country V. Simultaneously, since the refugee problem is largely related to carbon dioxide emissions, Bob selected the following countries as host countries based on the national statistics of carbon dioxide emissions and development levels: country (1), country (2), country (3), country (4), country (5), country (6), country (7), country (8), country (9), and country (10). To avoid political arguments and suspicions of profit, we express all countries here by pseudonyms.

Bob drafts the number of refugees in suffering countries in Table I and the maximum accepted capacity of the host countries for refugees in Table II. Considering that refugees may migrate in the form of families or regions, the minimum unit of refugee migration number is 10 000.

By consulting related literature [8]–[10], Bob learns that the RBC and E-CARGO models have become an effective method to solve the M-M assignment problem. Hence, he decides to use them to solve the RSP. However, there are some challenges for Bob to apply GMRA. First, GMRA needs a pertinent qualification matrix Q, which is highly domain-oriented and needs to explore the specialties of the domain carefully. Another challenge is that the number of refugees on the national stability of host countries should be seriously considered. To this end, we provide the following solutions.

For rationally analyzing the problem of refugee emigration, the prior condition is the quantitative evaluation index, but the criteria for measuring refugee resettlement are subjective and diverse. To this end, through relevant research and analysis [11], we empirically divided the measurement indicators of refugee emigration into four main criteria: bilateral climate [12], [13], culture [14], [15], life quality [16], and language [17], [18].

Moreover, for the sake of increasing the satisfaction of both suffering countries and host countries with the refugee resettlement program when making decisions, we introduce the concept of preference for evaluating emigration criteria. That means that different countries have a different emphasis on the abovementioned four evaluation indicators. For example, country (10) may pay more attention to the indicator of culture, while country (8) may pay more attention to the language indicator. We use a range from 0 to 1 to quantify the degree of preference on the evaluation indicators, and 0 means not important at all, while 1 is vital. Tables III and IV, respectively, indicate the preferences of the suffering countries and host countries for the four evaluation indicators. These preference data are all randomly generated. In order not to lose generality, we will conduct large-scale experiments in Section V. Finally, our result will be illustrated in Section IV. The following of this article depicts the details of our method.

TABLE I

Number of Refugees in the Suffering Countries

Country	B	M	S	U	V
Number (Unit in Ten Thousand)	280	38	42	2	97

III. Problem Formalizations With the Condensed E-CARGO Model

To solve the above-mentioned RSP, we first formalize it in a similar way to GMRA. With the E-CARGO model [22], [23], a system $\sum$ can be described as a nine-tuple $\sum ::= <\mathcal{C}, \mathcal{O}, \mathcal{A}, \mathcal{M}, \mathcal{R}, \mathcal{E}, \mathcal{G}, s_0, \mathcal{H}>$, where $\mathcal{C}$ is a set of classes, $\mathcal{O}$ 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 $\mathcal{H}$, and $\mathcal{E}$ 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 E-CARGO model better. Based on the analysis above, we define suffering countries as roles since they consist of refugees. Meanwhile, we define the host countries as agents because they can accept the refugees. The following brings up the specific definitions of RS.

Definition 1: A role [8]–[10] is defined as $r ::= <$ id, ® $>$, where id is the identification of r and ® is the set of requirements of properties for agents to play r.

Note: Intuitively, roles are the refugees (i.e., requirements), but refugees are resettled in groups in the RSP. Thus, the roles for the RSP are the suffering countries where refugees come from and ® = {"Climate," "Culture," "Life Quality," "Language"}.

Definition 2: An agent [8]–[10] is defined as $a ::= <$ id, (Ⓠ)$>$, where id is the identification of a and (Ⓠ) is the set

TABLE II
MAXIMUM ACCEPTED CAPACITY OF THE HOST COUNTRIES FOR REFUGEES

Country	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Capacity (Unit in Ten Thousand)	60	159	42	56	53	47	63	62	57	55

TABLE III
PREFERENCES OF THE SUFFERING COUNTRIES

Country	Evaluation Criteria for Refugee Resettlement			
	Climate	Culture	Life Quality	Language
B	0.45	0.75	0.85	0.31
M	0.65	0.40	0.62	0.59
S	0.75	0.90	0.79	0.68
U	0.71	0.66	0.88	0.84
V	0.69	0.81	0.71	0.58

TABLE IV
PREFERENCES OF THE HOST COUNTRIES

Country	Evaluation Criteria for Refugee Resettlement			
	Climate	Culture	Life Quality	Language
(1)	0.45	0.85	0.75	0.31
(2)	0.65	0.40	0.79	0.59
(3)	0.75	0.90	0.82	0.68
(4)	0.71	0.66	0.58	0.84
(5)	0.69	0.81	0.71	0.58
(6)	0.40	0.65	0.31	0.85
(7)	0.90	0.75	0.59	0.62
(8)	0.66	0.71	0.68	0.79
(9)	0.81	0.69	0.84	0.88
(10)	0.55	0.62	0.65	0.75

of a's values corresponding to the properties required in the group.

Note that, in our above scenario, agents refer to those host countries that can accept refugees, and (Ⓠ) expresses the comprehensively qualified evaluation of ®.

Definition 3: A *role range vector* [3] L is a vector of the number of refugees for roles in the environment $\mathscr{e}$ of group $\mathscr{g}$.

Note: L is a valuable component of the E-CARGO model. It indicates the minimum number of refugees required to be resettled for each role within a properly functioning group in RS. Based on Table I, the L vector is [280, 38, 42, 2, 97], and the minimum unit of the elements in the L vector is 10 000.

Definition 4: An *ability limit vector* [24] L^a is an m-vector, where $L^a[i]$ $(0 \le i < m)$ indicates the number of refugees that can be assigned to agent i. The superscript of L^a indicates that L^a is a definition for the agents.

From *Definition 4*, we introduce a new constraint, i.e., $|a_i.R_p| + 1 \le L^a[i]$ $(0 \le i < m)$, where $a_i.R_p$ means the set of potential roles. The number of refugees assigned to agent i should be less than the number of refugees that agent i can accept. Due to the different economic levels and resources, host countries' capacity of refugees is different and limited. For example, as Table II illustrated in our scenario, $L^a =$ [60, 159, 42, 56, 53, 47, 63, 62, 57, 55], and the minimum unit of the elements in the L^a vector is also 10 000.

$$\begin{pmatrix} 0.00 & 0.03 & 0.05 & 0.02 & 0.02 \\ 0.53 & 0.49 & 0.63 & 0.61 & 0.52 \\ 0.25 & 0.24 & 0.92 & 0.31 & 0.27 \\ 0.33 & 0.29 & 0.33 & 0.35 & 0.29 \\ 0.41 & 0.30 & 0.37 & 0.42 & 0.32 \\ 0.02 & 0.05 & 0.39 & 0.02 & 0.01 \\ 0.19 & 0.29 & 0.38 & 0.29 & 0.28 \\ 0.46 & 0.42 & 0.59 & 0.55 & 0.47 \\ 0.54 & 0.51 & 1.00 & 0.61 & 0.52 \\ 0.36 & 0.40 & 0.45 & 0.46 & 0.41 \end{pmatrix}$$

Fig. 2. Q matrix in our scenario.

Definition 5: A *qualification matrix* [5], [6] Q is an $m \times n$ matrix, where $Q[i, j] \in [0, 1]$ expresses the qualification value of agent i $(0 \le i < m)$ for role j $(0 \le j < n)$. $Q\ [i, j] = 0$ 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 this article, as the assignment method with PuLP [25] has been ready to use, creating Q is our major concern. Please note that a pertinent Q matrix in RS is not trivial and needs a significant effort, especially when the criteria for measuring refugee resettlement are subjective and diverse. Although [12] proposed some quantitative indexes in climate for evaluating the host countries, other vital factors, such as life quality and language, which may to some extent influence the refugees' quality of life, are not taken into consideration. The preference of host countries and refugee countries on the evaluation criteria also greatly affects the effectiveness and stability of the resettlement program. Consequently, we propose a more comprehensive agent evaluation method to create Q in Section IV, and Fig. 2 depicts the normalized Q matrix calculated by our proposed agent evaluation method for the scenario in Section II.

Definition 6: A *role assignment matrix* T is defined as an $m \times n$ matrix, where $T[i, j] \in \mathbb{N}(0 \le i < m,\ 0 \le j < n)$ indicates whether or not agent i is assigned to role j. $T[i, j] \in \mathbb{N}^+$ means yes and 0 no.

Definition 7: A *threshold matrix* Υ is an $m \times n$ matrix. It satisfies the equation that $\Upsilon[i, j] = min\{L[j], L^a[i]\}$. This equation represents that $\Upsilon[i, j]$ is the maximum value for the control variable $T[i, j]$ to take.

Note: In our scenario, $L[j]$ represents the number of refugees in country j (role j), while $L^a[i]$ represents the maximum refugee capacity for host country i (agent i). Therefore, the value of $\Upsilon[i, j]$ is $min\{L[j], L^a[i]\}$.

Definition 8: The *group performance* σ of group $\mathscr{g}$ is defined as the sum of the assigned agents' qualifications, that is,

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

Note that the social meaning of σ is the benefit obtained by the whole world through refugee resettlement.

Definition 9: Role j is *workable* in group $\mathcal{g}$ if it has been assigned enough agents, that is,

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

Definition 10: T is *workable* if each role j is workable, i.e., $\sum_{i=0}^{m-1} T[i, j] = L[j]$ $(0 \leq j < n)$. Group $\mathcal{g}$ is *workable* if T is workable. From the above definitions, group $\mathcal{g}$ can be expressed by L, L^a, Υ, Q, and T.

Definition 11: RS formalized by the GMRA is to find a workable T to

$$max\ \sigma^{GMRA} = \sum_{i=0}^{m-1} \sum_{j=0}^{n-1} Q[i, j] \times T[i, j]$$

subject to

$$0 \leq T[i, j] \leq \Upsilon[i, j] (0 \leq i < m, 0 \leq j < n) \tag{1}$$

$$\sum_{i=0}^{m-1} T[i, j] = L[j] (0 \leq j < n) \tag{2}$$

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

where

1) Expression (1) is an integer constraint, and it depicts the threshold of the control variable $T[i, j]$.
2) Expression (2) indicates that each role must be assigned to enough agents.
3) Expression (3) depicts that each agent can only be assigned to a limited number of roles.

Note Definition 11: is to apply the traditional GMRA [4] model to solve the RSP, and it can obtain an optimal solution since each role is assigned to the optimal agent(s).

From the above formalization, the RSP is expressed as a linear programming problem. Then, it can be solved using an industry-standard optimization tool, such as the PuLP linear programming toolkit [25], which is an open-source package of Python. Fig. 3 is a T matrix, following the constraints L = [280, 38, 42, 2, 97] and L^a = [60, 159, 42, 56, 53, 47, 63, 62, 57, 55]. The group performance σ is 237.10, which is an optimal result. Based on *Definition 11*, calculating qualification matrix Q is the key part of GMRA, and it is also the foundation for the RSP to be solved. Moreover, considering that the increase in the number of refugees may bring conflicts, such as religious conflicts to the host countries, it may need to introduce national stability to feedback on the RSP.

IV. Extended E-CARGO Model for the RSP

As mentioned in Section III, there are two main challenges in solving the RSP. The first one is how to rationally calculate the qualification matrix Q in the agent evaluation part of RBC. The second is the method to reduce the impact of the increase in the number of refugees on the national stability of host countries. Thus, in this section, we will introduce the agent evaluation method and agent stability evaluation method in the RS.

$$\begin{pmatrix} 0 & 0 & 0 & 0 & 0 \\ 139 & 0 & 0 & 2 & 18 \\ 0 & 0 & 42 & 0 & 0 \\ 31 & 0 & 0 & 0 & 0 \\ 53 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 62 \\ 57 & 0 & 0 & 0 & 0 \\ 0 & 38 & 0 & 0 & 17 \end{pmatrix}$$

Fig. 3. T matrix obtained by the GMRA in our scenario.

$$\begin{pmatrix} 0.01 & 0.00 & 0.04 & 0.00 & 0.00 \\ 0.01 & 0.00 & 0.18 & 0.00 & 0.00 \\ 0.05 & 0.00 & 1.00 & 0.00 & 0.00 \\ 0.00 & 0.00 & 0.00 & 0.00 & 0.00 \\ 0.00 & 0.00 & 0.00 & 0.00 & 0.00 \\ 0.02 & 0.00 & 0.81 & 0.00 & 0.00 \\ 0.01 & 0.00 & 0.14 & 0.00 & 0.00 \\ 0.01 & 0.00 & 0.13 & 0.00 & 0.00 \\ 0.05 & 0.00 & 0.88 & 0.00 & 0.00 \\ 0.00 & 0.00 & 0.00 & 0.00 & 0.00 \end{pmatrix}$$

Fig. 4. $\Diamond$ matrix in our scenario.

A. Agent Evaluation

In a simple format, we can state that $Q[i, j]$ = AE (Host Country i, Suffering Country j) $(0 \leq i < m, 0 \leq j < n)$, where AE is a function from a tuple of <agent, role > to a real number. Our major idea is to properly quantify $Q[i, j]$ from four dimensions: bilateral climate [12], [13], culture [14], [15], life quality [16], and language [17], [18]. To formalize the agent evaluation method in RS, we need to introduce several new concepts.

Definition 12: A *climate evaluation vector* Λ^a is an m-vector, where $\Lambda^a[i] \in [0, 1]$ expresses the severity of drought on agent i. $\Lambda^a[i] = 0$ indicates that the climate of host country i is extremely dry and 1 especially wet. The superscript of Λ^a represents that Λ^a is a definition for the agents.

Note: Here we use the normalized standardized precipitation evapotranspiration index (SPEI) [26], [27] to quantify the climate's influence since this newer index comprehensively considers both characteristics of multiple time scales and the sensitivity of temperature. This article uses the normalized SPEI index of host country i in 2020 to represent $\Lambda^a[i]$. The vector Λ^a of the scenario in Section II is [0.33, 0.66, 0.53, 0.22 0.00, 0.37, 0.68 0.64, 0.58, 1.00].

Definition 13: A *cultural evaluation matrix* $\Diamond$ is an $m \times n$ matrix, where $\Diamond[i, j] \in [0, 1]$ expresses the intimacy of bilateral culture between agent i and role j. $\Diamond[i, j] = 0$ represents that there is no cultural change between the host country i and the suffering country j, while 1 represents they have a close cultural exchange.

Note: Lanati and Venturini [28] pointed out that the export of bilateral cultural goods (BCG) can be used to evaluate bilateral cultural intimacy. They also gave the specific definition of BCG ([28, Table 14]) and related datasets. Therefore, this article applied the BCG data accumulated from 2018 to 2020 to represent $\Diamond[i, j]$ and normalized it with the max–min normalization method. Fig. 4 illustrates the matrix $\Diamond$ of the scenario in Section II.

Definition 14: A *life quality evaluation vector* Γ^a is an m-vector, where $\Gamma^a[i] \in [0, 1]$ expresses the quality of life

$$\begin{pmatrix} 0.10 & 0.10 & 0.00 & 0.00 & 0.00 \\ 0.10 & 0.10 & 0.00 & 0.00 & 0.00 \\ 0.00 & 0.00 & 0.00 & 0.00 & 0.00 \\ 0.10 & 0.10 & 0.00 & 0.00 & 0.00 \\ 0.10 & 0.10 & 0.00 & 0.00 & 0.00 \\ 0.10 & 0.10 & 0.00 & 0.00 & 0.00 \\ 0.10 & 0.10 & 0.00 & 0.00 & 0.00 \\ 0.00 & 0.00 & 0.00 & 0.00 & 0.00 \\ 0.10 & 0.10 & 0.00 & 0.00 & 0.00 \\ 0.10 & 0.10 & 0.00 & 0.00 & 0.00 \end{pmatrix}$$

Fig. 5. $\aleph$ matrix in our scenario.

TABLE V
MEANING OF THE VALUE OF $\aleph[i, j]$

$\aleph[i,j]$	Description
0.00	The official languages of agent *i* and role *j* do not belong to any common language family.
0.10	The official languages of agent *i* and role *j* are only related at the most aggregated level of the linguistic.
0.25	The official languages of agent *i* and role *j* belong to the same first and second-linguistic tree level.
0.45	The official languages of agent *i* and role *j* share up to the third linguistic tree level.
0.70	The official languages of agent *i* and role *j* share the first four linguistic tree levels.
1.00	Agent *i* and role *j* have the same official language.

or well-being of the people in the host country (agent) i. $\Gamma^a[i] = 0$ indicates the lowest and 1 the highest. The superscript of Γ^a represents that Γ^a is a new structure to express the agents' properties.

Note: Goldstein [16] introduced a quantitative expression for life quality called the Physical Quality of LifeIndex (PQLI). It has gained widespread acceptance as a comprehensive measurement in the economic and social rights area. Therefore, this article uses PQLI to quantify $\Gamma^a[i]$ as

$$\Gamma^a[i] = \frac{r_i^{\mathrm{lr}} + \left(166 - r_i^{\mathrm{im}}\right) \times 0.625 + \left(r_i^{\mathrm{le}} - 42\right) \times 2.7}{3}$$

where r_i^{lr}, r_i^{im}, and r_i^{le} represent the latest literacy rate, infant mortality, and life expectancy of host country i, respectively. Besides, when using the PQLI expression to quantify the life quality of a country, the constants 166, 0.625, and 2.7 in this expression are fixed [16]. For convenience, we also use the max–min normalization method to normalize Γ^a. The vector Γ^a of the scenario in Section II is [0.00, 0.82, 0.28, 0.84, 1.00, 0.02, 0.06, 0.84, 0.74, 0.51].

Definition 15: A *language evaluation matrix* $\aleph$ is an $m \times n$ matrix, where $\aleph[i, j] \in [0, 1]$ expresses the linguistic proximity between agent i and role j. Table V depicts the meaning of the value of $\aleph[i, j]$.

Note: Adsera and Pytlikova [18] introduced a quantitative language measurement, which uses the location of official languages between two countries on the linguistic family tree to illustrate their relationship (see Table V). This article uses this quantitative method to evaluate matrix $\aleph$, and Fig. 5 shows the *language evaluation* matrix $\aleph$ of the scenario in Section II.

Definition 16: A *criteria evaluation matrix* Ξ is an $m \times n$ matrix, where $\Xi[i, j] = [\Lambda^a[i], \Diamond[i, j], \Gamma^a[i], \aleph[i, j]]$ is a vector that expresses the values of above-mentioned four quantitative criteria when role j is assigned to agent i. As an example, in our scenario, $\Lambda^a[1] = 0.33$, $\Diamond[1, 1] = 0.01$, $\Gamma^a[1] = 0.00$, and $\aleph[1, 1] = 0.10$; hence, $\Xi[1, 1]$ is [0.33, 0.01, 0.00, 0.10].

Definition 17: A *role preference matrix* $\mathcal{P}$ is an $n \times 4$ matrix, where $\mathcal{P}[j]$ expresses preferences of role j for the abovementioned four quantitative criteria. Table II drafts the matrix $\mathcal{P}$ of the scenario in Section II.

Definition 18: An *agent preference matrix* $\mathcal{P}^a$ is an $m \times 4$ matrix, where $\mathcal{P}^a[i]$ expresses preferences of agent i for the abovementioned four quantitative criteria. The superscript of $\mathcal{P}^a$ indicates that $\mathcal{P}^a$ is a definition for the agents. Table III shows the matrix $\mathcal{P}^a$ of the scenario in Section II.

With the definitions proposed above, the qualification matrix Q can be calculated as follows:

$$Q[i, j] = \left(\mathcal{P}^a[i] \circ \Xi[i, j]\right) \times \left(\mathcal{P}[j]\right)^{\mathrm{T}} (0 \le i < m, 0 \le j < n) \tag{4}$$

where symbol $\circ$ represents the Hadamard product of matrix [29] and $(\mathcal{P}[j])^{\mathrm{T}}$ is the transposed matrix of $\mathcal{P}[j]$. Since the values of vectors Λ^a and Γ^a, and matrices $\Diamond$ and $\aleph$ are independent and identically distributed, we use the weighted sum (WS) method to quantify Q, i.e., (4), because WS is well accepted to combine many numerical factors together to form one numerical indicator. For example, in our scenario, $\mathcal{P}^a[1] = [0.45, 0.85, 0.75, 0.31]$, $\mathcal{P}[1] = [0.45, 0.75, 0.85, 0.31]$, and $\Xi[1, 1]$ is [0.33, 0.01, 0.00, 0.10], so we can derive $\mathcal{P}^a[1] \circ \Xi[1, 1] = [0.45 \times 0.33, 0.85 \times 0.01, 0.75 \times 0.00, 0.31 \times 0.10] = [0.1485, 0.0085, 0, 0.0310]$ and $Q[1, 1] = 0.45 \times 0.33 \times 0.45 + 0.85 \times 0.01 \times 0.75 + 0.75 \times 0.00 \times 0.85 + 0.31 \times 0.10 \times 0.31 = 0.08$. The physical meaning of (4) is to get a more reasonable evaluation standard by considering the preferences of agents and roles to the abovementioned four criteria.

Besides, the qualification matrix Q can be normalized by the max–min normalization method

$$Q[i, j] = \frac{Q[i, j] - min\{Q\}}{max\{Q\} - min\{Q\}} (0 \le i < m, 0 \le j < n)$$

where $min\{Q\}$ is the minimum element in the matrix Q and $max\{Q\}$ is the maximum element.

B. Agent Stability Evaluation

In RS, due to the peculiarities of the refugee resettlement problem, the rapid increase in the number of refugees may bring about religious conflicts, thereby reducing the agent's national stability. To this end, we introduce the agent stability evaluation method, which works as a feedback mechanism in RS to minimize the impact of refugees on the agent's national stability while maximizing the group performance σ. For describing the agent stability evaluation part in RS better, we propose some new definitions.

Definition 19: An *agent loss coefficient* φ is a rate that indicates the loss of national stability of agents, and $\varphi \in (0, 1)$. This coefficient essentially represents the loss of the host countries (agents).

Note: Since the stability of a host country (agent) is related to the number of received refugees, we use the percentage of the refugees to the total population, including the accepted refugees. For example, $\varphi = 0.05$ means that the number of refugees accepted by the host countries does not exceed 5% of the total population of the host countries after accepting refugees. For the scenario in Section II, φ is an indefinite value, which needs a method to search for its optimal value. Thereby, we randomly set the initial value of φ as the initial searching step length, i.e., $\varphi = 0.001$. Please note that the coefficient φ has the original range of [0, 1]. However, $\varphi = 0$ has no physical meaning. Furthermore, when φ is 1, RS will transform into GMRA. Consequently, we set the range of φ as (0, 1).

Definition 20: An *agent stability vector* ϑ^a is an m-vector, where $\vartheta^a[i] \in \mathbb{R}^+$ ($\mathbb{R}^+$ is the set of positive real numbers) express the appropriate number of refugees that the host country (agent) i can hold while guaranteeing its national stability. The superscript of ϑ^a represents that ϑ^a is a definition for the agents.

Note: To better describe ϑ^a, we denote P as a vector representing the host countries' population, and $P[i]$ is the population of the host country (agent) i. Then, we can formalize $\vartheta^a[i]$ as follows:

$$\vartheta^a[i] = \min\left\{\frac{P[i] \times \varphi}{1-\varphi}, L^a[i]\right\}. \tag{5}$$

Let us explain how (5) is obtained. Based on the physical meaning of φ, we can get as follows:

$$\frac{\sum_{j=0}^{n-1} T[i,j]}{P[i] + \sum_{j=0}^{n-1} T[i,j]} \le \varphi. \tag{6}$$

Since the denominator of (6) is greater than zero and $\varphi < 1$, we can transform (6) as

$$\sum_{j=0}^{n-1} T[i,j] \le \frac{P[i] \times \varphi}{1-\varphi}.$$

Moreover, because agent i can provide limited capacity for the refugees, i.e., $L^a[i]$, $\vartheta^a[i]$ can be formalized as (5).

With the above new definitions, the RS model is to find a workable T to

$$\max \sigma^{\text{RS}} = \sum_{i=0}^{m-1}\sum_{j=0}^{n-1} Q[i,j] \times T[i,j] \tag{7}$$

subject to (1), (2), and

$$\sum_{j=0}^{n-1} T[i,j] \le \vartheta^a[i] (0 \le i < m) \tag{8}$$

where (8) appropriately ensures the national stability of the agents in the RS model. To achieve the optimal assignment on the premise of the highest agent stability, we propose the RS algorithm. Here, we define some special symbols as follows for a better description of the RS algorithm.

1) P is a vector that represents the population of the host countries. In our scenario, P is [21270, 3811, 140005, 6715, 6002, 12601, 14620, 5182, 6680, 33007], and the minimum unit of P is 10 000.

Algorithm 1 Finding a Stable RS Solution

input: L, L^a, Q, Υ, P
output: T
begin
step $\leftarrow 0.005$;
$\varphi \leftarrow$ *step*;
$\sigma' \leftarrow +\infty$; / ∗ $+\infty$ means a very big number∗/
for each $t \in T$ **do**
  $t \leftarrow 0$;
end for
$T' \leftarrow T$;
while $\varphi < 1$ **do**
  Calculate ϑ^a based on (6);
  $T', \sigma' \leftarrow RS(L, L^a, Q, \Upsilon, \vartheta^a)$;
  if $\sigma' \neq -1$ **then** /∗ Successful assignment ∗/
    $\sigma \leftarrow \sigma'$;
    $T \leftarrow T'$;
    break while;
  end if
  $\varphi \leftarrow \varphi +$ *step*;
end while
return T;
end

2) *step* is a value that expresses the searching step length for the optimal value of the agent stability, and *step* $\in[0, \varphi]$. In our scenario, we randomly set it to 0.005. Without loss of generality, we will carry out large-scale random experiments in Section V.
3) $RS(L, L^a, Q, \Upsilon, \vartheta^a)$ is a function to solve the RS model (see Expression (6)) based on Python PuLP.
4) T' is a tentative value to record T.
5) σ' is a tentative value to record σ.

Algorithm 1 illustrates a practical way to find a stable RS solution. Because the complexity of GMRA is O (m^3) [4], [30], that of RS is O ($k \times m^3$), where m and k, respectively, represent the number of agents and the number of iterations of the *while* loop in Algorithm 1. Here, we propose *Theorem 1* to demonstrate the optimality of Algorithm 1.

Theorem 1: When the searching step length *step* is small enough, Algorithm 1 can get the optimal assignment plan for the RSP.

Proof: Since the RS model is formalized by the linear expression, it can find the optimal solution if the value of appropriate φ is determined. As shown in Algorithm 1, the value of φ is affected by the search *step*. Because the range of φ is from 0 to 1, and we randomly set the initial value of φ as 1, Algorithm 1 will converge to the optimal φ based on the current value of *step*. Consequently, when the value of *step* is small enough, Algorithm 1 can get the optimal assignment plan for the refugee resettlement problem.

Theorem 1 is proven. ■

Fig. 6 shows the changes in group performance σ in the RS algorithm. It illustrates that, when the agent's national stability increases, the agent loss coefficient φ decreases at this time. When $\varphi = 0.01$, the RS algorithm obtained the optimal group performance σ at current step length while reducing the impact of refugees on the agent's national stability. At this time, the T matrix obtained by the RS algorithm is depicted in Fig. 7, and the optimal group performance σ is 196.04.

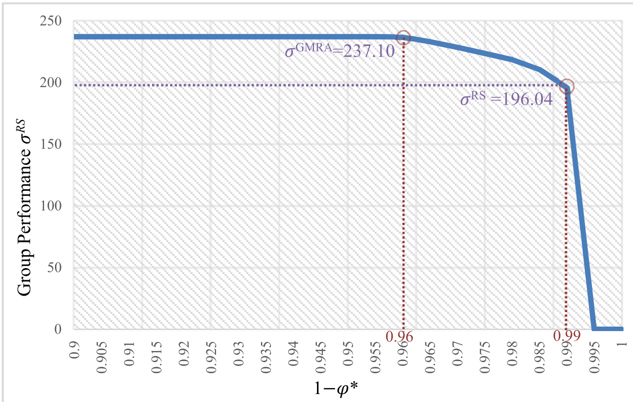

Fig. 6. Changes in group performance σ in RS. ∗Note: 1-φ represents the expected ratio of the native population in the host countries after accepting refugees. Here, we use 1-φ as the x-coordinate instead of φ for better comparing GMRA and RS.

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 1.54.2
Python	Python 3.8.5

V. EXPERIMENT

To verify the efficiency and robustness of our proposed method for the RSP, we performed large-scale random simulation experiments on a laptop configured, as shown in Table VI. Since the complexity of Algorithm 1 is mainly concerned with m, n, φ, and *step*, we will conduct our simulation experiments thousands of times based on the ranges of these parameters in Table VII. Considering that there are close to 200 sovereign countries worldwide, we set the range of parameters m and n in Table VII from 0 to 200.

First, to assure our agent stability evaluation method's correctness and robustness in RS, we analyze our model and algorithms' performance under different values of φ and *step*. Here, we use the control variates method to set the parameters other than φ and *step* as constants. We apply the parameters of the real-world scenario in Section II to carry out this experiment, that is, $m = 10$ and $n = 5$.

Fig. 8 shows the group performance σ obtained by the RS under different values of *step*. The experiment shows that the optimal agent stability will increase when *step* decreases. Moreover, as shown in Fig. 8 (*step* = 0.001 and 0.0001), when $1-\varphi < 0.993$ ($\varphi > 0.007$), the RS method can obtain optimal solution. The expression $\varphi > 0.007$ represents that the number of received refugees in a host country exceeds 0.7% of its population. It means that, if all the host countries accept less than 0.7% of their populations, there would be no solution to the RSP, which predicts a severe situation for the world.

Then, we analyze the validity of the RS algorithm compared with traditional GMRA on different scales of the RSP. Similarly, we also use the control variates method to set the parameters other than m or n as constants. That is to say, we randomly set $\varphi = 1$ and *step* = 0.01. In addition, because the number of suffering countries should be much smaller than the number of host countries, we first focus on the influence of the change of m on the RS and randomly set $n = 5$. Figs. 9–11, respectively, depict the averages of solution time, group performance, and agent stability of the RS and the traditional GMRA solutions. Since the traditional GMRA solution ignores the sacrifice of the agents' stability for optimal assignment for the roles, the GMRA solution can find a solution with higher performance and lower solution time compared with the RS algorithm, i.e., Figs. 9 and 10. Contradictorily, the RS takes the agent stability as a feedback mechanism to greatly improve the agent stability while partially sacrificing the time consumed and group performance, as demonstrated in Fig. 11. Such a scheme makes it easier to achieve a win–win situation for the host countries and suffering countries.

Moreover, we eventually analyze the performance of the RSP when both m and n increase. Due to the limited number of suffering countries, we empirically set $n = (m/4)$ and randomly select five groups of $n = \{10, 20, 30, 40, 50\}$. Fig. 12 shows the average solution time of the RS algorithm with different values of n.

TABLE VII
RANGES OF THE PREDEFINED PARAMETERS IN RS

Parameters	Ranges
m	[0, 200]
n	[0, 200]
φ	[0, 1]
step	[0, φ]

$$\begin{pmatrix} 0 & 0 & 0 & 0 & 0 \\ 38 & 0 & 0 & 0 & 0 \\ 0 & 0 & 42 & 0 & 0 \\ 56 & 0 & 0 & 0 & 0 \\ 53 & 0 & 0 & 0 & 0 \\ 27 & 17 & 0 & 0 & 0 \\ 0 & 21 & 0 & 0 & 42 \\ 49 & 0 & 0 & 2 & 0 \\ 57 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 55 \end{pmatrix}$$

Fig. 7. T matrix for Section II obtained by Algorithm 1.

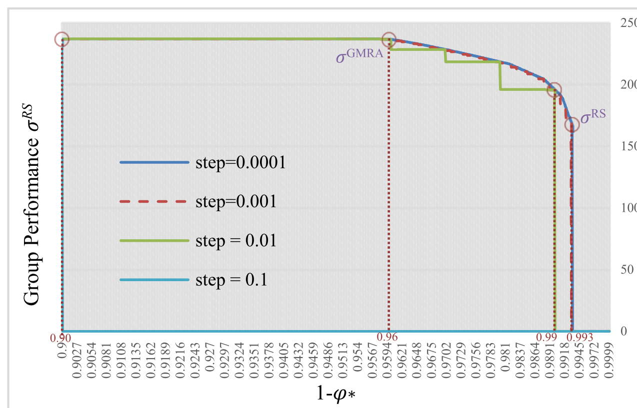

Fig. 8. Group performance σ obtained by RS under different parameters *step*. ∗Note: 1-φ represents the expected ratio of the native population in the host countries after accepting refugees. Here, we use 1-φ as the x-coordinate instead of φ for better comparing GMRA and RS.

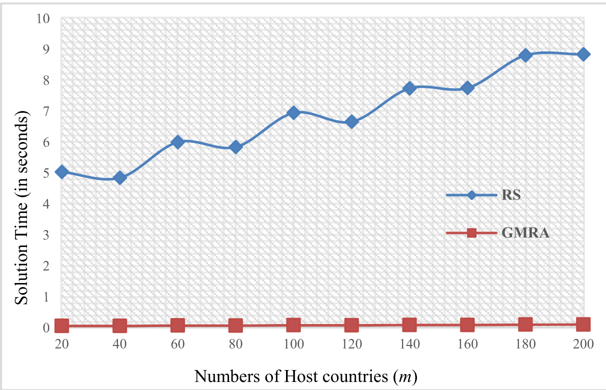

Fig. 9. Average solution time of Algorithm 1 for different scales.

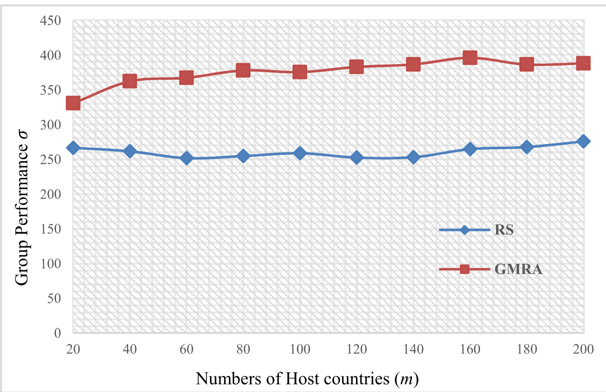

Fig. 10. Average group performance σ of Algorithm 1 for different scales.

From the experiment above, we can conclude that the following holds.

1) Fig. 8 shows that the agent stability evaluation method can effectively help the RS algorithm find the optimal group performance while appropriately maintaining the agent stability.
2) Figs. 9–11 demonstrate that, compared with traditional GMRA, our proposed RS can greatly improve the national stability of host countries while partially sacrificing the time consumed and group performance.
3) Fig. 12 illustrates that the designed RS can swiftly solve a large-scale RSP ($m = 200$) within one minute.

From the simulation results, we understand that the following holds.

1) When the number of received refugees in a host country exceeds 0.7% ($\varphi > 0.007$) of its total population, RS can guarantee the optimal immigration plan. Contradictorily, if all the host countries accept less than 0.7% of their populations, there would be no solution to the RSP, which predicts a serious situation for the world.
2) The whole world benefits σ obtained from refugee resettlement may drop by approximately 30% if we set up more restricted latches ($\Delta\varphi < 0.03$) for agents' national stability.

VI. Related Work

A. Refugee Resettling Problem

Refugees are among the world's most vulnerable populations [31], and in recent years, the number of refugees has increased sharply due to war, climate, and so on. Such

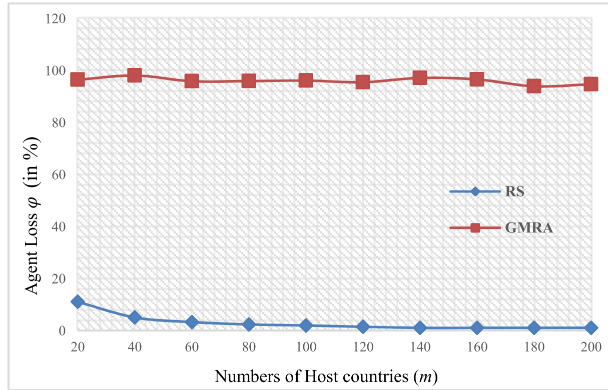

Fig. 11. Average agent loss of Algorithm 1 for different scales.

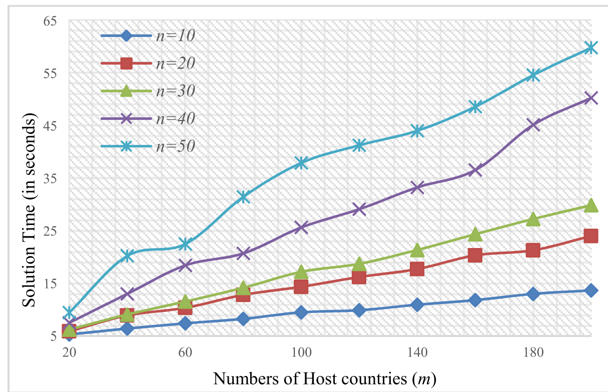

Fig. 12. Average solution time of Algorithm 1 with different values of n.

a situation makes the issue of refugee resettlement urgent. The existing refugee resettlement research is mainly divided into two categories: the assignment of refugees to different resettlement locations within a host country and the selection of the host countries for resettling refugees.

There exists much-related research focusing on the former category [20], [31], [32]. As an example, Bansak *et al.* [31] developed a flexible data-driven algorithm that assigns refugees across resettlement locations to improve integration outcomes. Their approach led to gains of roughly 40%–70%, on average, in refugees' employment outcomes relative to current assignment practices. This approach can provide governments with a practical and cost-efficient policy tool that can be immediately implemented within existing institutional structures. Also, Alfeo *et al.* [32] proposed a set of metrics to assess the integration of Syrian refugees in Turkey, by considering the similarities with locals in terms of calling behavior and collective mobility. Their results can help draw a few integration policy guidelines, which can accelerate the integration of the refugees, prevent the formation of ghettos, and encourage the shared use of city areas.

The aforementioned studies have achieved substantial results for refugee resettlement within a host country. However, this article studies the second type of refugee resettlement research, that is, the choice of the host countries.

B. Existing Modeling Methods for the RSP

Many scholars tend to apply the gravity model [12], [32], [33] to expose the nexus between refugees and corresponding host countries since the theoretical system of the gravity model is mature, and the model has been successfully applied on immigration issues.

For instance, Abel *et al.* [12] designed a comprehensive modeling method based on the gravity model to shed light on the quantified evaluation method between refugees and host countries while exposing the causalities underlying the climate–conflict–migration trinity. However, they ignore the impact of refugees on host countries. Besides, some studies [32], [34] convey that evaluation using the gravity model tends to fall with the distance, and the gravity model seems to be inappropriate for complex, recurrent, and dense flow patterns.

Some researchers [35], [36] propose another option to solve the RSP: the agent-based model (ABM) [37]–[39]. Relatedly, Hu *et al.* [35] apply the agent-based modeling [40] technique to develop a simulation platform, which can complete some simulation tasks for predicting the trend of human migration in the background of climate change. Still, the subject of these studies mainly focuses on outmigration at the individual and the household level, which may lead to a lack of objectivity in data sources. Moreover, they also ignore the impact of refugees on host countries.

The abovementioned methods provide reference options for solving the RSP. However, in this work, we need to consider more specific and complicated constraints of the RSP, which makes the aforementioned methods not applicable. First, the aforementioned research lacks consideration of the host countries' stability, and the underestimation of the decreased tolerance for refugees in those host countries may lead to more ethnic conflicts, which may directly reduce the national stability of the host countries. Second, due to the large scale and uneven distribution issues in RSP, a centralized unified model [5], [41] is more suitable because it is conducive to further research on flexible and reliable reassignment scheduling strategies [42] and adaptive human–machine collaboration mechanisms. It is noteworthy that rare research has been conducted to deal with RSP by using a centralized and unified model.

C. RBC and RS

There is some research into unified mathematical models [43], [44] that help build a robust model regardless of the distribution of the tasks, i.e., RBC [22], [23], [45], role-based access control (RBAC) [46], and Internet of Things (IoT) [41], [47], [48].

As an example, Zhu [23] proposes and formalizes the agent categorization (AC) problem as a GRA+ problem and proposes a practical solution to the problem by combining the GRA+ algorithm with the simulated annealing (SA) algorithm. His work demonstrates that RBC and E-CARGO are tools well suited to formalize and solve challenging collaboration and management problems.

In addition, Huang *et al.* [45] deal with the LMAP for fresh produce via GRA with constraints (GRA+). Their proposed method not only assigns couriers to deliver daily orders efficiently but also improves the quality of service.

The aforementioned research has demonstrated that RBC and its E-CARGO model have been a practical unified model for solving the M-M assignment social computing problem. Essentially, this kind of refugee resettlement problem is a M-M assignment problem [49] between the countries where the refugees are located and the host countries. Hence, we decide to apply RBC and its E-CARGO model to solve the RSP. Still, considering that the rapid increase in the number of refugees may reduce the agent's stability, traditional RBC and GRA cannot directly solve this problem. For this concern, we extend the RBC process with the innovative agent stability evaluation method and formalize the RSP by RS.

VII. Conclusion

This article proposes a novel modeling method for the RS problem.

We first formalized the RSP with the condensed E-CARGO model, i.e., RS. Since the increase in the number of refugees may bring conflicts, such as religious conflicts, we introduce the agent stability evaluation method as a feedback mechanism for RS while optimally resettling refugees. With this innovative modeling method, the RSP can be swiftly solved with the PuLP package of Python. Finally, 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 leaders in the world even though there is not a central organization to determine the ideal refugee resettlement presented by our simulations.

From this article, further investigations on RS may be conducted in the following directions.

1) When quantifying the impact of climate on the RSP, this article used the SPEI index. Albeit the larger the value of SPEI, the greater the rainfall in the area, excessive rainfall may cause floods. As such, the threshold of SPEI may require deeper consideration.
2) A tradeoff between the preferences of the host countries and the suffering countries can be introduced for more reliable refugee resettlement programs.
3) We may study a more complicated agent loss coefficient φ to express the national stability of the host countries.

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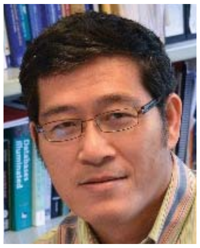
Qian Jiang (Graduate Student Member, IEEE) was born in January 1997. He received the B.S. degree in network engineering and the M.S. degree in computer science and technology from the School of Computer Science and Technology, Guangdong University of Technology, Guangzhou, China, in 2018 and 2021, respectively. He is currently pursuing the Ph.D. degree in intelligent science and system at the Institute of Systems Engineering, Macau University of Science and Technology, Macao, China.

He has reported a conference paper as the first author in the Chinese CSCW 2019. He has also published a paper in *International Journal of Cooperative Information Systems* in 2020. His research interests include human–machine systems, computational social simulation, and scheduling and optimization.

Mr. Jiang has served as a reviewer for IEEE TRANSACTIONS ON COMPUTATIONAL SOCIAL SYSTEMS.



Haibin Zhu (Senior Member, IEEE) received the B.S. degree in computer engineering from the Institute of Engineering and Technology, Zhengzhou, China, in 1983, and the M.S. and Ph.D. degrees in computer science from the National University of Defense Technology (NUDT), Changsha, China, in 1988 and 1997, respectively.

He was a Visiting Professor and a Special Lecturer with the College of Computing Sciences, New Jersey Institute of Technology, USA, from 1999 to 2002, and a Lecturer, an Associate Professor, and a Full Professor with NUDT, from 1988 to 2000. He has accomplished (published or in press) over 200 research works, including 30 IEEE TRANSACTIONS articles, six books, five book chapters, three journal issues, and three conference proceedings. He is currently a Full Professor and the Coordinator of the Computer Science Program, and the Founding Director of the Collaborative Systems Laboratory, Nipissing University, Canada. His research interests include collaboration theory, technologies, systems, and applications, human–machine systems, computational social simulation, collective intelligence, multiagent systems, software engineering, and distributed intelligent systems.

Dr. Zhu is a Fellow of the Institute of Cognitive Informatics and Cognitive Computing (ICIC), a Senior Member of ACM, a Full Member of Sigma Xi, and a Life Member of Chinese Association of Science and Technology, USA (CAST-USA). He has been serving as an Associate Vice President (AVP), Systems Science and Engineering (SSE), the Co-Chair of the Technical Committee of Distributed Intelligent Systems of the SSE Technical Activity Committee, the Conferences and Meetings Committee, and the Electronic Communications Subcommittee of IEEE Systems, Man and Cybernetics (SMC) Society, and an Associate Editor (AE) of IEEE TRANSACTIONS ON SYSTEMS, MAN, AND CYBERNETICS: SYSTEMS, IEEE TRANSACTIONS ON COMPUTATIONAL SOCIAL SYSTEMS, *IEEE SMC Magazine*, and *IEEE Canada Review*. He has been an active organizer for the Annual IEEE International Conference on SMC since 2003, a Registration Co-Chair in 2021, a Co-Chair in 2020, a Poster Co-Chair in 2020, a Special Session Chair in 2019, a Tutorial Chair in 2018, an Area Co-Chair in 2017, a Social Media Co-Chair in 2015, a Web Co-Chair in 2015, a Session Chair from 2003 to 2020, and a Special Session Organizer from 2003 to 2020. He was a Program Co-Chair for the 13th International Conference on Computer Science and Information Technology, October 14–16, 2020, Online (ICCSIT2020), the 10th International Conference on Pervasive and Parallel Computing, Communication, and Sensors, November 3–5, 2020, Online (PECCS2020), the Publication Chair for the 1st IEEE International Conference of Human-Machine Systems, September 7–9, 2020 (Online), and the Program Chair for 16th IEEE International Conference on Networking, Sensing and Control, Banff, AB, Canada, May 8–11, 2019. He is a PC Chair for 24th IEEE International Conference on Computer Supported Cooperative Work in Design, Dalian, China, May 6–8, 2020, and was a PC Chair for 17th IEEE International Conference on Computer Supported Cooperative Work in Design, Whistler, BC, Canada, June 27–29, 2013. He also served as a PC member for 100+ academic conferences. He has offered over 70 invited talks, including keynote and plenary speeches on related topics internationally, e.g., Australia, Canada, China, Germany, Hong Kong, Macau, Singapore, Turkey, the U.K., and the USA. His research has been being sponsored by NSERC, IBM, DNDC, DRDC, and OPIC. He is a receipt of the Meritorious Service Award from the IEEE SMC Society in 2018, the Chancellor's Award for Excellence in research in 2011 and Two Research Achievement Awards from Nipissing University (2006 and 2012), the IBM Eclipse Innovation Grant Awards (2004 and 2005), the Best Paper Award from the 11th ISPE International Conference on Concurrent Engineering (ISPE/CE2004), the Educator's Fellowship of OOPSLA'03, a 2nd class National Award for Education Achievement (1997), and three 1st Class Ministerial Research Achievement Awards from China (1997, 1994, and 1991).

Yan Qiao (Senior Member, IEEE) received the B.S. degree in industrial engineering and the Ph.D. degree in mechanical engineering from the Guangdong University of Technology, Guangzhou, China, in 2009 and 2015, respectively.

From September 2014 to September 2015, he was a visiting student with the Department of Electrical and Computer Engineering, New Jersey Institute of Technology, Newark, NJ, USA. From January 2016 to December 2017, he was a Postdoctoral Research Associate with the Institute of Systems Engineering, Macau University of Science and Technology, Macao, China. Since January 2018, he has been an Assistant Professor with the Institute of Systems Engineering, Macau University of Science and Technology. He has over 80 publications, including one book chapter and 30+ regular articles in IEEE TRANSACTIONS. His research interests include scheduling and optimization, semiconductor manufacturing systems, and smart manufacturing.

Dr. Qiao was a recipient of the QSI Best Application Paper Award Finalist of the 2011 IEEE International Conference on Automation Science and Engineering, the Best Student Paper Award of the 2012 IEEE International Conference on Networking, Sensing and Control, the Best Conference Paper Award Finalist of the 2016 IEEE International Conference on Automation Science and Engineering, the Best Student Paper Award Finalist of the 2020 IEEE International Conference on Automation Science and Engineering, and the 2021 Hsue-Shen Tsien Paper Award of IEEE/CAA JOURNAL OF AUTOMATICA SINICA. He has served as a reviewer for a number of journals.

Dongning Liu (Member, IEEE) was born in January 1979. He received the Ph.D. degree in logic with Sun Yat-Sen University, Guangzhou, China, in 2007.

He is currently a Full Professor of the Guangdong University of Technology in China. He is also responsible for teaching artificial intelligent logic and discrete math with the School of Computer Science and Technology. He is engaged in education and technology transfer on collaborative computing. He is a Vice Dean of the School of Computer Science and Technology. He was a Postdoctoral Fellow in math with Sun Yat-Sen University from 2007 to 2009. He was a Visiting Professor with Nipissing University, North Bay, Canada, from 2015 to 2016. He has authored or coauthored more than 50 articles on computer magazines and international conferences.

Prof. Liu is a reviewer for IEEE TRANSACTIONS ON SYSTEMS, MAN, AND CYBERNETICS: SYSTEMS, IEEE TRANSACTIONS ON COMPUTATIONAL SOCIAL SYSTEMS, IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY, and so on. He is a member of the IEEE SMC Society and serves as a TC Member of the Technical Committee of Distributed Intelligent Systems, a Senior Member of the CCF Society, and the Vice Secretary-General and a Standing Committee Member of the Technical Committee on Cooperative Computing of China Computer Federation.

Baoying Huang (Graduate Student Member, IEEE) received the B.S. degree in network engineering and the M.S. degree in computer science and technology from the School of Computer Science and Technology, Guangdong University of Technology, Guangzhou, China in 2016 and 2019, respectively. She is currently pursuing the Ph.D. degree in intelligent science and system at the Institute of Systems Engineering, Macau University of Science and Technology, Macau, China.

She has published two regular articles in IEEE TRANSACTIONS ON AUTOMATION SCIENCE AND ENGINEERING and IEEE TRANSACTIONS ON COMPUTATIONAL SOCIAL SYSTEMS. She has served as a reviewer for a number of journals and conferences. Her research interests include scheduling and optimization, human–machine systems, computational social simulation, and semiconductor manufacturing systems.