Simulation Study on the Core-structure Industrial Cluster Innovation Network: Relationship between Structure and Performance

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Abstract—Taken complex adaptive systems (CAS) theory into cluster innovation research, this investigation focuses on the agents of cluster innovation network. And it uses network structure variables and innovation agents’ behavior to study the relationship between cluster innovation network structure and innovation capability based on CAS’s echo model and the reverse simulation method. After summarize the CAS simulation research framework and process, this investigation builds cluster innovation network structure influencing innovation capability model by analyzing the interaction between environment, agents, resource and knowledge. Through CAS multi-agent simulation method combining with the case of Zhongguancun cluster innovation network, the results show that innovation agents in order to adapt environment to adjust their behavior constantly, generate interaction, and change innovative mechanisms, that influences cluster innovation network innovation capability. Moreover, under some structural qualification, innovation capability could be enhanced with the cluster innovation network structure’s variables of mean minimal path length decreasing, aggregation coefficient increasing and degree distribution increasing.

Keywords—Complex Adaptive System; Cluster Innovation Network; Innovation Capability; Multi-Agent Simulation

I. INTRODUCTION

In high-technology industries, cluster firms overcome the difficulties of limited resources and innovation bottleneck by joining resource-knowledge clusters and localized resource-knowledge networks. In recent years, innovation network has become increasingly important in political and economic agendas in industrialized countries (Gils and Zwart, 2004). It is widely accepted that the industrial cluster has a tremendous role in promoting the development of all sectors of society on the regional economy.

Scholars acknowledge that small and medium enterprises (SMEs) with competition and collaboration relationship could get competitive advantage by specialization. As clusters of firms located in northern and north-eastern Italy (the third Italy District) representative, SMEs concentrate in a particular region (Mohannak, 2007). It endorses the SMEs’ contribution about industrial cluster formation and development. However, it also brings a misunderstanding, that researches are not only concern about the industrial cluster of SMEs but also neglect of large firms. New industrial district theory cannot cover all types of industrial cluster, besides the ‘the third Italy District’, there are three additional types of industrial cluster, with quite disparate firm configurations, internal versus external orientations and governance structures (Markusen, 1996). Existing literatures suggest that sizeable firm which is a core node of innovation network plays a dominant role in core-structure cluster. [1]

Core-structure industrial cluster innovation network has become an important organizational form of industrial cluster innovation network. The exploration of evolution and innovation mechanism contributes to the development of the network. So it is important to understand evolution and innovation mechanism of core-structure industrial cluster innovation network because of its important theoretical and practical value to innovation system establishment within industrial cluster. Core-structure industrial cluster innovation network and focal firm theory come from the moderate form of hierarchy industrial districts idea (Boari and Lipparini, 1999). It is emphasized that the industrial cluster firms heterogeneity in position, task and interaction. It also indicates sizeable firm as the core of industrial cluster innovation network should do: i. - increase business communication with other firms to share business ideas; ii.- invest and lead partner, which capability of supporting the inter-firms trust and mutually beneficial; iii.- import of advanced technology and select superior quality partners [2]. Malipiero and other scholars certified the process of knowledge creating and disseminating on the Italian packaging equipment industry cluster, and results show the focal firms play a technology gatekeeper role in the process of technology and knowledge introduction from external to internal [3]. Another view focuses on resource utilization and knowledge dissemination issues, pointed out two learning paths of focal firms. Moreover, focal firms could organize innovation activities more efficiently by cooperating with intermediate level suppliers [4].

In this paper, we argue that the innovation of focal firms is a complex process with four mechanisms of resource utilization and knowledge dissemination. Taken complex adaptive system theory into this research could focus on the agents (mainly refer focal firm, suppliers and other affiliations) of core-structure industrial cluster innovation network, and the agents’ behavior how to change the network’s structure to influence the network’s innovation. A
model is built in this paper for studying the innovation effect and mechanism, besides AnyLogic6.0 is used to simulate this process.

II. COMPLEXITY RESEARCH FRAME

Complexity theory is being widely used in industrial cluster innovation network issues. Previous studies showed that: Firstly, ensure innovation network has superior network structure (such as appropriate mean path length, uniform degree distribution and moderate aggregation coefficient reflected in) that can improve innovative capability is important to build a powerful innovation network [5-7]. Secondly, innovation network structure is a non-static concept, because it is not only a dynamic growing process of the various elements engage in complex activities in network, but also the interaction process of internal-external environment. Moreover, network structure influences knowledge transferring and resource utilizing deeply in this process [8-10]. Thirdly, the positive relationship between the network structure and its performance is emphasized in previous literature, but several micro-social processes that might account for differences in managerial performance are neglected. Economic sociology and social network analysis (SNA) method could be used to research innovation network structure and its performance issue. Currently, the innovation capability of innovation network tends to rely on a few sizeable firms. The network with focal firm has already highlighted [11, 12]. At last, with network scale, density, concentration, and heterogeneity as variables of social network, SNA could apply to our research. We also collect data through a questionnaire survey, and use ordinary least-squares regression method to verify the conclusion [6, 12, 13].

Using complexity theory, the mechanism of the core-structure industrial cluster innovation network influences performance could resolve into two parts. One is the changing of network structure affects resource utilizing and knowledge disseminating. Another is agents’ co-option and performance. Besides combining complex adaptive systems, complex network with system dynamics provide a new approach. By conditions triggering, the stimulus-response model is suitable for analyzing the relationship between network variables and innovation mechanism. Complex network theory plays a role in the selection of micro and macro structural variables. System dynamics provides causality analyzing and bidirectional feedback mechanism to research ‘network-elements-mechanism’ of the transmission process as Fig. 1 shows.

Two concepts need to highlight in the framework. Firstly, innovation resource defined in this article could share and recycle, which contains both of material and immateriality style. In order to enhance and strengthen innovation, agents of the core-structure industrial cluster innovation network use resource by independent and cooperative mechanism. Its characteristics are: (1) Innovation resource is the resource which agents develop and utilize through innovation technology. (2) It supports innovation activities and enhances innovation performance. (3) It can be shared and used simultaneously by multiple agents. Secondly, innovation knowledge is defined as valuable experience and technological achievements that the agents obtained in order to meet demand of technical innovation. It is the product of intellectual innovation which could be shared and disseminated in the network. Its characteristics are: (1) Stochastic generating and fast updating. (2) Disseminate by attaching to the carrier. (3) Be inherited and renew.

In summary, the structure of core-structure industrial cluster innovation network as a complex system determines the innovative mechanism and behavior of agents. The structure also influences the dissemination effect of innovative knowledge and utilization of innovation resource. This paper seeks to explore the action of structure of the core-structure industrial cluster innovation network to mechanism through combining CAS theory and system dynamics. And it uses mean minimal path length (MMPL), aggregation coefficient (AC) and degree distribution (DD) to research structural changes.

III. INNOVATION MECHANISM

A. Environment

As Manhattan matrix, innovation environment surrounded by the regular structural framework is a relatively limited three-dimensional structure, it is described by length of shorter mean minimal path, AC, and degree distribution. Based complexity theory and multi-agent analysis, let \( t = 1, 2, \ldots \) denotes innovation time step. And \( (x_i, y_i, z_i) \) represents the location of each agent \( i \) (focal firm or supplier) in the core-structure industrial cluster innovation network as a node, and structural properties could be denoted by dataset \( \{ d_{ij}, k^n_i, p_i \} \). \( d_{ij} \) represents the relative distance from the agent to origin, \( k^n_i \) represents the number of other agents directly connected to the focal firm, \( n \) is the number of all the agents, and \( p_i \) represents degree distribution of agent \( i \). By using the geometric mean method with a variance, we could estimate the shortest distance between two agents (also each couple nodes in the network):

\[
d_{ij} = \sqrt{(d_{ij} + d_{ij})^2 + (d_{ij} - d_{ij})^2}/2
\]

Then length of shorter mean minimal path \( l \):

\[
l = \frac{1}{n(n + 1)/2} \sum_{i<j} d_{ij}
\]

Aggregation coefficient C:
\[
C = \frac{2n}{k_i(k_i - 1)}
\]

Degree distribution \( p(i) \):
\[
p(i) \propto k^{-\gamma}
\]

Now innovation environment could be demonstrated.

B. Agent

The agent in the core-structure industrial cluster innovation network has some attribute be denoted by dataset \( \{ \theta_{i,t}, \mu_{i,t}, V_{i,t} \} \). Among them, \( \theta_{i,t} ( \theta_{i,t} \in [0,1] ) \) represents if agent \( i \) contact with the other at the moment \( t \). While the value equals 1, there is cooperation between two agents. On the contrary, there is no contact. And \( \mu_{i,t} ( \mu_{i,t} \in [0,1] ) \) represents the moment \( t \)'s innovative resource utilization of agent \( i \). The higher the value is, the higher the utilization. \( V_{i,t} ( V_{i,t} \in [0,1] ) \) represents the moment \( t \)'s innovative knowledge dissemination effect of agent \( i \). The higher the value is, the better the effect. Moreover, independent and cooperative utilizing as two styles of resource utilization with sharing and hypotactic disseminating as two styles of knowledge dissemination decides the innovation mechanism of agents.

- **Independent (I)** – refers to agent develops and utilizes resource independently for innovative benefits. Under mechanism I, agent will accumulate some resource of technology as the foundation of innovation, also select resource which be used for current activities from its own resource and strengthen the resource in a special warehouse. The utilization of selected resource will get promoting due to being valued, on the contrary utilization of not being selected resource will be reduced accordingly. While the utilization of some resource value reduces to 0, this resource will be lost. This reflects the reality of resource selectivity, the agent rather chooses high utilization and the benefits resources to develop and use of. Fig. 2 shows the I mechanism.

- **Cooperative (C)** – refers to the innovation activity that agent utilizes resource cooperating with other agents. Due to complementarity of innovative technology and resource, agent selects the other who has higher resource utilization to cooperate first. Of course, agent could give up the cooperation and change the CValue to false. This situation often occurs when most agents have better utilization than focal firms. The two collaborative agents select resource from their own resource library, and put them into the cooperative innovation common library. The resources’ utilization will be enhanced when they are put into the common library, but the remaining resource without investment maybe cause utilization decreasing due to neglect. If agents cooperate successfully for many times, they will combine into a fixed network until a low utilization emerging. Fig. 3 shows the C mechanism.

- **Sharing (S)** – refers to agents open their knowledge about innovation and transfer into innovation achievement by collaborating with other agents. Each agent has its own innovative knowledge library which storages the knowledge accumulated by agent from real innovative activities as experience. Agent could decide to share its knowledge or not, and it usually choose another more knowledge storage one to share both of their innovative knowledge and study. The agents willing to share create innovative knowledge-sharing channels between them (industrial innovation network connections). Innovative knowledge sharing process is as follows: agents, respectively, extract knowledge from their own library to share, this innovative knowledge be put into the sharing knowledge library. The principle of the process is first choosing knowledge related to innovation activities closely. The key of sharing process is innovative knowledge dissemination effect, which is used to measure the efficiency of knowledge dissemination after successful absorption and receiving, and the ability of anti-jamming in the process of innovative knowledge dissemination. Fig. 4 shows the S mechanism.

- **Hypotactic (H)** – refers to the agent knowledge dissemination after successful absorption and receiving, and the ability of anti-jamming in the process of innovative knowledge dissemination. Fig. 5 shows the H mechanism.
Hypotactic ($H$) – refers to the style of agents subordinate to focal firms gain innovative benefits transformed by innovative knowledge disseminating from focal firms. Focal frims create channels of innovative knowledge dissemination (industrial innovation network connections) through business merging and collaborating. The process is as follows: focal firms select innovative knowledge from their own base and spread to subordinates. The innovative knowledge selected relating to innovative actives is put into subordinate agent’s base. The transforming benefits of hypotactic agents are decided by the efficiency of dissemination. Fig. 5 shows the $H$ mechanism.

Thus, $a_{ij}$ represents the mechanism, and bases resource utilization and knowledge dissemination perspective $a_{i} \in \{‘IS’, ‘CS’, ‘IH’, ‘CH’ \}$, that means Independent-Sharing, Cooperative-Sharing, Independent-Hypotactic and Cooperative-Hypotactic.

IV. RESEARCH HYPOTHESIS

As structural variables of core-structure industrial cluster innovation network, the mean minimal path length, aggregation coefficient and degree distribution are usually used in the regular rule of network’s innovation. The hypothesis for studying based on the premise of the appropriate scope. As follows:

A. Shorter MMPL Could Enhance Innovative Resource Utilization

Network’s MMPL could measure the journey that nodes link each other need to go through. In the innovation network, it means a journey of products, technologies, knowledge, and other types of information exchange between agents needs to pass through. Here MMPL more inclined to the extent of ease or hard contact, as well as the number of cost. It needs to be emphasized that: In normal case, it is generally agreed that innovation network nodes (agents) communicate each other to get resource more easily and the cost lower with the shorter MMPL in network structure. But more intense competition for resource between the nodes will occur in too shortest MMPL’s innovation network. It is not conducive to innovation resource utilization. Therefore, innovative resource could be utilized better in the innovation network with appropriate mean minimal path length.

**Hypothesis 1.** If MMPL changes influence innovative performance and the distance between focal firm and focal firm-co-opetitors decide the changes, shorter distance always accompany with higher performance in core-structure industrial cluster innovation network. So the relationship between MMPL and performance is negative correlation.

B. Higher Aggregation Coefficient Could Enhance Innovative Resource Utilization

Aggregation coefficient depicts innovation network’s linking density, while reflecting the network’s connectivity and transitivity. A higher aggregation coefficient network means higher linking density and more close links between nodes. In terms of the whole innovation network, nodes can connect to each other closely in higher aggregation coefficient network, while the scope of resource integration is expanded with links of nodes increasing and innovative resource is diffused more widely. Because each link makes network’s social relations cost increasing, thus resource integration can be implemented between multiple nodes. Compared with lower aggregation coefficient network structure, the higher one can enhance efficiency of resource integration in innovation network. Under normal circumstances, the researchers believe that high-density network structure more conducive to promoting the nodes’ communication and giving nodes greater social support. However network characteristics as high cohesion and strong relation in highest aggregation coefficient structure could cause higher homogeneity of innovative resource and lead to technology and innovative resource convergence. So while losing of diversity and heterogeneity, resource cannot expand even shrink, and also there is no competitive advantage in agents. This over-embedded resulted in innovation fatigue restrains efficiency of resource integration. Therefore, innovative resource could be utilized better in the innovation network with moderate aggregation coefficient.

**Hypothesis 2.** If AC changes influence innovative performance and the density of the network as the amount of focal firm and its co-opetitors in the region decide the changes, more concentrated density always bring about higher performance in core-structure industrial cluster innovation network. So the relationship between AC and performance is positive correlation.

C. Larger Degree Distribution Could Enhance Innovative Resource Utilization

Degree distribution reflects the number of links each node contact with others, also known as vertex degree. It is similar with the concept of network centrality. They all depict the number of links and their influence and importance. According to social capital theory, innovation network nodes’ tangible and intangible social capital depends on the number of their social links. Each link represents various acquisition channel of resource. In terms of single node, it is always tends to replicate its social ties and moves from the sparse ties area to dense for getting more social capital. The amount of links between nodes shows that determines the node’s location in network and its force. For example, compared with isolated node larger degree distribution node has the more advantage of resource acquisition. Otherwise, the node in structural hole has the greatest advantage of resource acquisition, because it can get more information and becomes the information distribution center. The intermediary nodes can contact other nodes in network and link one node with another unknown node. This activity can ensure the mobility of innovative resource and promote resource integration. Excessive large degree distribution maybe cause confusion while resource flowing. Therefore, innovative resource could be utilized better in the innovation network with uniform degree distribution.
Hypothesis 3. If DD changes influence innovative performance and the number of links between focal firm and other agents is highly correlated with DD, more links always lead to higher performance in core-structure industrial cluster innovation network. So the relationship between DD and performance is positive correlation.

V. MODELING

Core-structure industrial cluster innovation network could be viewed as a complex system, which has the following characteristics: (1) Integrity, it contains a large number of agents. (2) Relativity, agents contact each other through innovative resource and knowledge mutual transferring. (3) Hierarchy, different agent as a network node plays different role. Some agents take heart position and play an important role in the network is usually considered as focal firms, which have more special research value than general agents. (4) Similarity, more similar actions in a shared vision for enhancing innovation performance, agents adapt to the environment for survival under the changes in the environment. In addition, the overall pattern of behavior depends on the dynamic structure and the ‘structure - environment’ feedback mechanism with common evolution according to certain rules.

A. RK-MAD model

Using AnyLogic simulation based SD and CAS, the model should be needed. The process of resource and knowledge transform innovative benefits is complex and CAS theory is suit for this research. Besides, some conduction process in the transformation should be comprehended which maybe an emergence phenomenon (Albino 2006, März 2006 and Tang 2010).

There is a nonlinear effect on the transformation which is complex process and with no quantitative analysis [14]. RK-MAD model has been built for relationship research in this investigate based resource-knowledge standpoint. In the model RK represents two dimensionality of innovative resource and knowledge, MAD is the structural variables. Two conditions should be considered before this research. Firstly, reducing innovation depreciation- agents limit to absorb the innovative resources and knowledge which negative impacts on innovation activities. Secondly, the risk is controllable- the risk in the transformation process of innovative resource and knowledge to performance is controllable. The model describes the relationship between structure and performance in core-structure industrial cluster innovation network. On the one hand, the structural changes cause agents choosing different innovative mechanism, and influence the effect of innovative resource and knowledge as R&D investment, human resource and patent transform into performance. On the other hand, innovative activities could change the behavior of agents for adapting to the environment, and also change the network structure with the innovative mechanism shifting. In this investigation, the structural changes are indicated by the changing of minimal path length, aggregation coefficient and degree distribution. Meanwhile, the performance relates to innovative mechanism and different mechanism has different effect of resource utilization and knowledge dissemination which are the two key factors. However, a recessive relationship between resource utilization and knowledge dissemination, because the purpose of utilization is better absorb knowledge for innovating and dissemination is better utilize resource for higher performance.

SD logic causality analysis on RK-MAD model reflects the whole innovation process, which is the basis of the system dynamics simulation as Fig. 6 shows.

Network structure changing could influence the performance by acting on the style and effect of resource utilization and knowledge dissemination from the perspective of structure to function. In this process, structure changing acts on the innovative mechanism which could positive impact on the performance with the MMPL shortening and aggregation coefficient-degree distribution increasing. From the perspective of function to structure, performance also could force agents into altering their behavior to adapt the environment, and this impact sometimes destroys original link or eliminate the maladjusted nodes which changes the network structure. In this process, higher performance promotes resource-knowledge sharing and the frequent interact between agents which let the MMPL become shorten, aggregation coefficient increase and degree distribution increase. These two effects exist in the system, and ultimately will help the system to reach stable equilibrium.

B. Equations

AnyLogic SD simulation requires translating RK-MAD model into mathematical expression. Referencing former literature about CAS emergence, innovation is an accumulating process with calculus [15-17].

As in

\[
\begin{align*}
\ln C_i = \ln C_{i-1} + \int \left( \alpha \sum \ln L_{i,j} + \sum \ln R_{i,j} + \sum \ln K_{i,j} \right) dt + \ln \left( \delta A + \theta D + e_i \right) dt
\end{align*}
\]

For the RK-MAD model:

- \( I_i = I_{i-1} \times (K_i + K_{i-1})^{\frac{\mu_i}{\mu_{i-1}}} \times (\eta M_i + \phi D_i) \)
- \( K_i = K_{i-1} + \phi \delta_i \)
- \( K_i = K_{i-1} + \phi \delta_i \)

\[ K_i = K_{i-1} + \phi \delta_i \]

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Where $i$ represents agent, and $t$ is innovation activities last time. $C_i$ is innovative performance at moment $t$, and $L_i$ is effect of innovative activities when agent $i$ do it at moment $t$. $\alpha$ is its coefficient. $R_i$ represents the effect of agent $i$ innovative resource transform to performance at moment $t$, and $K_i$ represents the effect of agent $i$ innovative knowledge transform to performance at moment $t$ with the influencing coefficient $\beta$ and $\gamma$. Moreover, at $t$ moment the MMPL, aggregation coefficient $A_i$ and degree distribution $D_i$ of core-structure industrial cluster innovation network has their influencing factors $\alpha$, $\delta$, $\theta$ to innovative activities as the structure changing. $\varepsilon_i$ is parameter of profit and loss and unintended effects of innovation. $R'_i$ and $K'_i$ represent the reserves of innovative resource and knowledge at moment $t$. $\xi$ is transformation rate. $I_{pt}$ is R&D investment, $N_i$ is effect of human resource and $P_{ri}$ is related to patent. $\mu$, $\eta$ and $\varphi$ represent influencing factor of above process respectively. The factors affected by structure changing subject to random distribution. $\lambda$ (0 ≤ $\lambda$ ≤ 1) represents the depreciation rate which describes the previous stage resource and knowledge successfully disseminate to a later stage. If $\lambda$ = 1, all the resource and knowledge disseminate to the next stage without loss.

VI. SD SIMULATION AND RESULT

The AnyLogic simulation model build as Fig. 7 shows. The MMPL, AC and DD impact on the style of resource utilization and knowledge dissemination, and their changes could affect agents’ innovative mechanism selecting. The distance between two agents decides the value of MMPL which is used to research the complex relationship and cooperative feasibility in this investigation. The density of the network is described as AC which could calculates the amount of focal firm and its co-opetitors in the region. The AC also could be used to research the complex relationship and cooperative feasibility. The number of links between focal firm and other agents is highly correlated with DD, as agents’ connection, it could reveal the complex relationship and cooperative feasibility.

![Fig. 7 AnyLogic SD simulation model](image)

With the time step size of innovative process is 20, the simulating result as Fig. 8-10 shows as follow:

The development of network’s innovative performance is from slow growth to fast growth and eventually slow growth with the decrease of MMPL. On the first step, the performance develops slowly because of the long distance of focal firm between its co-opetitors. Although that distance decreasing, communication and cooperation between focal firm and its co-opetitors is still difficult. In addition to the hard shared innovative resource and knowledge, focal firm selects independent-hypotactic mechanism. The lower transforming effect under that mechanism causes the slow growth. On the second step, the communication and cooperation between agents become easier with the decreasing distance. At that time, the good co-opetitor relationship promotes focal firm to select cooperative-sharing mechanism. The more investment and higher transforming effect cause the fast growth. However, there is a limit to the decrement of MMPL, because too shortest distance is not conducive to the performance. This phenomenon on the third step is called innovation convergence (Baumol 1986 & Busch 2005) meaning agents imitate the innovative technology of each other, which could lead agents to lose their innovative motion. So the lower transforming effect causes the slower growth. Overall, the performance is increasing with the MMPL decreasing. Therefore, the above conclusion is verified Hypothesis 1 (Fig. 8).

![Fig. 8 The relationship between MMPL and performance](image)
The trend of performance development is same as above. The differences is on the first step, less links between focal firm and other agents influence focal firm to choose independent-hypotactic mechanism. The lower innovative transforming effect causes the performance developing slowly. On the next step, innovative activities is frequently and the more links make the communication and cooperation become easier. Meanwhile, cooperative-sharing mechanism promotes the effect of resource utilization and knowledge dissemination and their transforming. The performance develops so fast. At last, too more links accelerate the competition of coopertor selecting and reduce the capability for innovation. For example, the average supply capability of supplier abates with the external relations increasing. So the performance develops slowly. The performance is increasing with the DD increasing. Therefore, the above conclusion is verified Hypothesis 3 (Fig. 10).

VII. CONCLUSION

This study puts forward simulation research frame based on system dynamic and CAS theory. In the core-structure industrial cluster innovation network, the communication and cooperation of focal firm and its co-opetitors reflects the structural changes. RK-MAD model used in AnyLogic simulation shows the negative, positive and positive relationship between the changes of structural variables (mean minimal path length, aggregation coefficient and degree distribution) and innovative performance. The varigation of innovative activities leads to different mechanism shifting and influences the transforming effect of innovative resource utilization and knowledge dissemination. At the same time, the environment of innovation also changes with agents’ activities. For surviving and developing, agents adapt to the innovative situation. Generation, extinction and other activities could cause the structure altering. To demonstrate these relationships a threshold should be emphasized in this paper. Through literature and simulation analyzing, the value of mean minimal path length, aggregation coefficient and degree distribution between 0 to 100, 0 to 20 and 0 to 80 is suit for research. Too shorter mean minimal path length, concentrated aggregation coefficient and bigger degree distribution is not conducive to higher innovative performance. In summary, the threshold is better limited in 3 to 15, 0.1 to 8.0 and 0.1 to 30. Under this situation, focal firm has a good co-opetitor relationship with other organizations.

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