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The dynamics of inter-organizational ties during crises: empirical evidence and computational analysis ☆

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Abstract

Organizations often rely on social networks in order to garner resources for survival, in particular when faced with a crisis. From a resource dependence perspective, this paper addresses two issues regarding the dynamics of inter-organizational ties during crisis situations: (a) what is the usual process organizations use, and (b) how efficient is such a process? Two real world crisis cases show that, in a crisis situation, organizations tend to follow a cascade process in which they rely on stronger ties first until there is additional resource needs before activating weaker ties. This process can go on until all the resource needs are met and the stable stage is reached. Results from a computational model simulating such a cascade process and a contrast process, the sequential/random process, show that organizations following the cascade process can exhibit much higher efficiency, though there is a decreasing effect as the severity of the crisis increases. This study has not only illustrated the real world process of organizational ties during crises empirically but also provided theoretical rationales for such inter-organizational dynamics.

Keywords: Dynamics of inter-organizational ties; Crises; Computational modeling

1. Introduction

It can be said that organizations cannot survive without resources. The importance of resources is further amplified when an organization faces a crisis [13,15]. During a

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crisis situation, an organization often has to reach beyond itself to garner sufficient resources. Organizations, therefore, exist in a world of social networks [4]. Organizations are connected by ties through which resources can flow and on which survivals depend. Though the literature of social networks has put much emphasis on the characteristics of ties [2,17], researchers have devoted much less attention to the underlying dynamics of *how* ties are used and *why* ties are used. There is also a lack of exploration into the role of resources in social networks at an organizational level.

This study intends to achieve two objectives. First, from a resource dependence perspective, we will explore the dynamics of inter-organizational relationships, in particular under crisis situations. Second, using the agent-based modeling technique, we will build a computational model to simulate the inter-organizational dynamics and measure the efficiency of such processes, thus providing insight into the rationales underneath such network dynamics. By achieving these two objectives we hope to show how simulation models can be built based on empirical cases and how simulation models in turn can provide new insights into real world case analyses. Such an approach has not been frequently attempted, yet, we believe, can be very useful for the development of organization science.

In the remaining sections of the paper, we will first examine the dynamics of organizational ties from a resource dependence perspective by analyzing two crisis cases, the Hurricane Andrew disaster [23,32] and the Three Mile Island (TMI) nuclear accident [11,15,25]. From these case analyses, we will be able to construct a theoretical model underlying the dynamics of inter-organizational ties during crisis situations. We will then describe a computational model that simulates the dynamics of inter-organizational ties and a contrasting process. Based on simulation experiments, we will analyze the efficiency of these processes. Finally, we will discuss some findings observed from our analyses and point out some limitations of the study.

2. Theoretical background

2.1. Crisis

A crisis is an event that requires extra amount of resources, which, if not handled properly, can have severe consequences to the organization's survival [10]. Though there is a lack of focus on inter-organizational crisis management in the literature of organization science, crises do occur, whose impacts often go beyond the capability of a single organization. Krackhardt and Stern [13] define "crisis" as "a situation facing an organization which requires that the organization, under time constraints, engage in new, untested, unlearned behaviors in order to obtain or maintain its desired goal states." In many cases, a crisis also has severe consequences to the organization's survival if not handled properly [18].

While recognizing the importance of handling crises, the literature of organization science has focused on preventing or managing crises [24], which has largely been dominated by how to design organizations within themselves. For example, loose coupling [30], structural redundancy [27], centralization [29], and even personnel training [25] have all been suggested as ways to help organizations deal with crisis situations.

There is thus a significant lack of research in inter-organizational crisis management in the literature of organization science. It is our belief that organizational effectiveness, and ultimately survival, is not just a matter of intra-organizational design, but a matter of how to rely on each other. In those large-scale crisis situations, inter-organizational relationships, or ties, naturally become important. To address the issue of inter-organizational relationship during crises, we thus need to have a deeper and broader view of the aspects of the dynamics of organizational ties.

2.2. Dynamics of organizational ties

Though there have been a number of studies outlining the merit of inter-organizational ties during crisis situations [5,13], few have explored the dynamics of ties during crises. Ties are connections between social nodes. In this case, the social nodes are organizations, which are composed of human beings. The existence of any organization in a social system involves interactions with other organizations. Ties have dynamics, which can be shown in the following aspects: purpose, direction, content, and strength.

2.2.1. Ties have purpose

The most important purpose of inter-organizational ties is for resource access. Resources are vital to organizational survival [26,30]. Two social nodes connect to each other in the hope of expanding resource access that will be mutually beneficial [1,6]. This is true for the relationships between countries, faculty and students, and manufacturers and suppliers. Studies have also shown how people use ties for finding better jobs [16]. The decision to form ties by organizations, therefore, is ultimately about resources, whether consciously or not.

2.2.2. Ties have direction

Ties are often not symmetrical. Such asymmetry may be reflected in the amount of resources a node receives compared to the other node. For example, the trade deficit between two countries reflects the non-symmetrical nature of the tie. Also, in the case of job seeking [16], job seekers usually have a greater need for resource expansion than their friends, mentors, or relatives. Such asymmetry may not last forever because of the inherent pressure for mutual benefit. Within any short period of time, however, non-symmetry of ties does exist.

2.2.3. Ties have content

The different types of content often reflect the different resource needs of organizations. This is especially true given that today's organizations have to handle complex tasks that require multiple resource supplies and various interpersonal as well as inter-organizational interactions. Depending on whether ties are intra-organizational or inter-organizational, content of ties can also be different [13]. In this paper we mainly look at how information and resources flow across organizational boundaries.

2.2.4. Ties have strength

The strength of a tie is often reflected by the quantity and content of contacts [8]. Although the common definition of a tie's strength is based on its frequency of contact over a long period of time, there is no consensus among social network researchers regarding the exact threshold that differentiates a strong tie from a weak tie [14]. In this paper, following previous definitions, we refer to a close and frequent connection over a stable period as an indication of a strong tie. Thus, a weak tie should have a distant connection with less interaction. We further refer to the actual contacts during a specific period of time as the activation or usage of ties.

2.3. Prior research

To address the dynamics of organizational ties from a resource dependence perspective, we briefly review two trends of research that this study will build on. The first trend is represented by research mainly from a social network perspective, which intends to explore structures embedded in various relationships [4]. While social network analysis has been proven effective in describing the status of inter-personal connections and the influence of such connections to some interesting organizational outcomes [3,12], there is a significant lack of emphasis on organizational level relationships. In addition, many studies have either ignored the dynamic change of social networks over time or disregarded the resource dependence perspective for explanation of observed relationships.

The second trend is represented by research from a resource dependence perspective, which intends to explore various relationships from the viewpoint of resource expansion and control [26]. While studies from a resource dependence perspective have provided the underlying driving force for relationships within and across organizations, they often remain at a descriptive level with a focus on static relationships between resources and some limited organizational outcome such as power. Many studies also lack a consistent and accurate methodological framework for analyzing relationships among people or organizations.

Although studies from both trends of research have made their significant contributions to the understanding of organizational relationships, they are often limited by the lack of concern for a dynamic relationship and the linkage between network and resource dependence perspectives, which we believe are important to a better understanding of the dynamics of inter-organizational ties. To examine how and why organizations expand their relationships in a crisis situation, it is necessary to combine both social network and resource dependence perspectives. While a few studies have started to integrate the social network approach with a resource dependence perspective [16,22,34], the dynamic aspect of relationships at an organizational level, in particular in a crisis situation, is often not included. It is thus the objective of this research to examine the dynamics of organizational ties with focus on the above-discussed aspects of ties from a resource dependence perspective.

3. Two real world crisis cases

We now look at two real world cases, the Hurricane Andrew incident and the TMI incident, to examine the dynamics of inter-organizational ties during crisis.

3.1. Data

We will use information on the Hurricane Andrew crisis collected from the *New York Times* (NT) and the *Washington Post* (WP) newspapers between August 24 and September 9, 1992, which covers the crisis between August 23 and September 8, 1992. The focus of this study will be on the crisis around the Florida area, rather than Louisiana, because the former has attracted more attention than the latter, thus providing more information on issues of interest. The information used in this study is represented by relevant sentences and paragraphs (in their original forms) from the two newspapers.

We will use information on the TMI crisis as reported by Lagadec [15]. Lagadec is one of the first researchers that has thoroughly described and examined the incident. We have also compared the description of the incident from Lagadec [15] with those from other books [11,25]. We found that they are all very consistent regarding the details of the event, though their perspectives may vary. The information used in this study is represented by relevant sentences and paragraphs (in their original forms) from Lagadec [15].

3.2. Method

Ties between two organizations can be shown through relations such as materials supplying/receiving, help supplying/receiving, information supplying/receiving, etc. A node can be an organization, a group of organizations, a representative from an organization, or a group of individuals. In this case analysis we will first find what organizations are involved. We will then look for two major indicators that reflect a change in characteristics for both the node and the tie.

The first indicator will be references indicating that there is a problem for the node to provide resources. Such references can be contained in information regarding things like food or shelter shortage, budget constraint, lack of control, etc.

The second indicator will be references to ties being activated or put in use. Such references can exist in information regarding whether an organization asks for help from another organization, whether an organization agrees to help another organization, whether there is supposed linkage between two or more organizations, etc.

From the two indicators we will be able to examine how and when organizations activate ties during a time of crisis. A detailed coding scheme for the content analysis used in this study is listed in Appendix A.

For example, the following are excerpts from two actual newspapers that reported the Hurricane Andrew incident on August 27, 1992.

> Hale, who warned that more people may die from inept relief efforts than from the storm, blamed the American Red Cross for not establishing more shelters. She said there had been "problems," which she did not specify, with the National Guard, and there was virtually no compliance by federal agencies with the established relief plan [32: 8/28/1992-A1].

"Fundamentally, it's Dade County on its own," Hale said [32: 8/28/1992-A1].

Dade County officials in Florida said the Federal Government has not yet responded to urgent requests for a water purification system, for example, but federal officials complained that they needed a request from the Governor [23: 8/28/1992-A10].

Gov. Lawton Chiles also pleaded for more federal help and better coordination of rescue efforts [32: 8/28/1992-A1].

From the excerpts we can see that: (1) there were signs of major problems for the organizations connected to provide sufficient resources to mitigate the crisis; (2) there were uses of ties among the Dade County residents, the Dade County Management, the Dade County Emergency Agency, the American Red Cross, the Florida National Guard, and the Florida state government; and (3) there was mention of ties with the federal government, but the ties were not fully activated.

The two crisis cases have been coded independently by two research assistants who had no prior knowledge of the theory or the cases, based on the coding scheme attached in Appendix A for the two key indicators. Raw information of the cases and their coded indicators can also be obtained from the author upon request. After the initial coding, comparisons between the two coders were conducted. Of all the indicators for all the relationships over the two crisis periods, there was an 80% agreement. The remaining differences were then resolved jointly by the author and the two research assistants after more careful reading of the relevant information.

3.3. Analyzing the Hurricane Andrew incident

In late August 1992, Hurricane Andrew hit southern Florida causing billions of dollars in damages to the social, biological, and economical environments. The impact of the crisis was unprecedented and there were many organizations around the country that became involved. In this case we will examine how organizations dealt with the crisis, with focus on the dynamics of organizational ties surrounding the crisis period from a resource perspective [23: 8/24–9/9/1992, 32: 8/24–9/9/1992].

3.3.1. Local level

We will first look at the local level for connections among organizations, where the crisis started. These organizations included the Dade County residents and the County government, which was composed of Dade County Management, Dade

County Emergency Agency, Dade County Police Department, Dade County Department of Community Services, and Dade County Department of Public Works. The contacts between Dade County residents and the County government, and the connections among the county government's departments were frequent due to their formal relations and geographical distances, thus resulting in strong ties. Insurance companies were also involved at the local level, but their contacts with local organizations were not strong in terms of frequency.

3.3.2. State level

Organizations at the local level and organizations at the state level were also connected. Organizations at the state level included the Florida State government, which was composed of the governor's office, Florida National Guard, Florida Department of Health and Rehabilitation Services, and Florida Water and Sewer Authority. The connections between the local level organizations and the state level organizations were not as strong as connections at the local level. Some other states were also involved at this level, but their connection with the local level organizations was very weak.

3.3.3. Federal level

Organizations at the local level also had connections with organizations at the federal level. Those organizations at the federal level included the executive branch of the federal government (the Bush Administration), the American Red Cross, the National Hurricane Center, the US Coast Guard, and the Congress. In the executive branch of the federal government, there were also organizations like the White House, the Department of Defense, the Department of Transportation, the US Public Health Services, and the Federal Emergency Management Agency (FEMA). The connections from organizations at the local level to organizations at the federal level were weak due to an infrequent use of the connections. An exception to this is the American Red Cross, which maintained local branches in the South Florida area. The connections between the local level organizations and Congress were even weaker due to rare use of direct connections between the two.

Thus, the strength of connections among local, state, and federal level organizations varied from strong to weak [23: 8/24–9/9/1992, 32: 8/24–9/9/1992].

3.3.4. Stage 1

On August 23, the day immediately prior to Hurricane Andrew hitting southern Florida, Dade County residents and the County's government were responsible for hurricane preparations. When Hurricane Andrew arrived, Dade County was faced with a crisis. In the beginning local organizations relied on their strong ties by building temporary shelters, evacuating residents, and maintaining public order. The potential impact of the crisis and the fear of insufficient resources, however, were soon recognized at the local level. The county's Emergency Management Agency warned of a shortage of resources.

The tie with the state government was mentioned, but not activated, when the governor declared southern Florida in a state of emergency and alerted the National

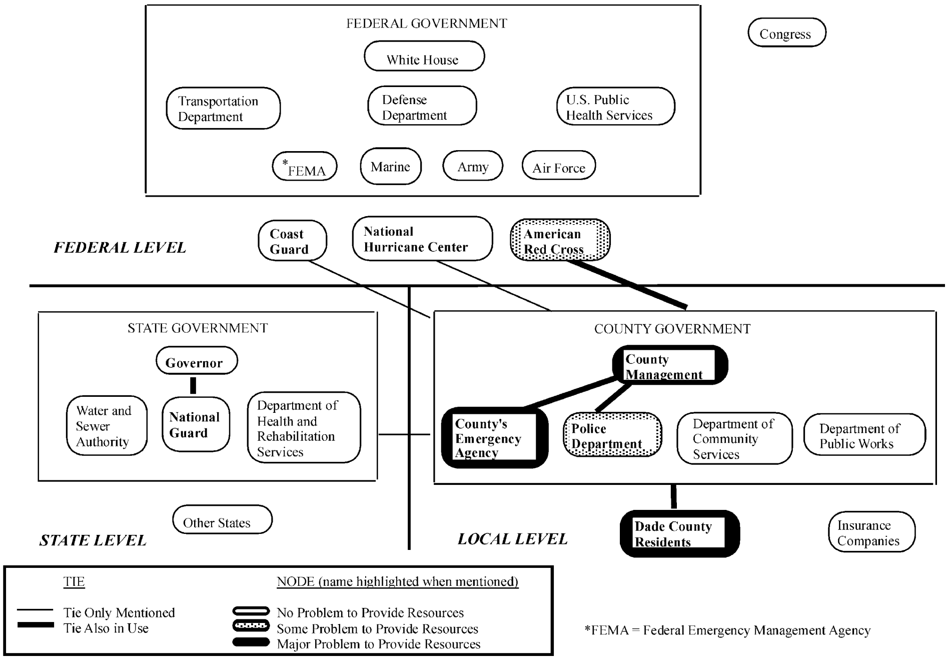

Fig. 1. Reported dynamics of organizational ties in the Hurricane Andrew incident on August 23, 1992.

Guard. The tie with the American Red Cross began to be used when requests went out asking people with first aid experience to come to shelters to help the elderly. However, still very few weaker ties were activated. This stage can be summarized in Fig. 1.

3.3.5. Stage 2

Ties with the Florida state government were then introduced through visits by the governor and some initial National Guard troops. Ties with the National Hurricane Center in Florida and the Coast Guards were introduced. There was also a sign that a tie with the federal government existed through the President Bush's visit, although the tie was not activated at this time. This stage can be summarized in Fig. 2.

3.3.6. Stage 3

From August 25 to 27, the second, third, and fourth days of Hurricane Andrew, the tie with the Florida state government was more intensively used as 3000 Florida National Guard troops were called in, and the Florida Department of Health and Rehabilitation Services also provided help. However, as thousands of people remained without adequate shelter, food, water, and other necessary supplies, it became obvious that the resources needed to overcome the disaster were still beyond the state and local government's capabilities.

The Florida state government and the Dade County government requested urgent help from the federal government. The ties with the federal government were acti-

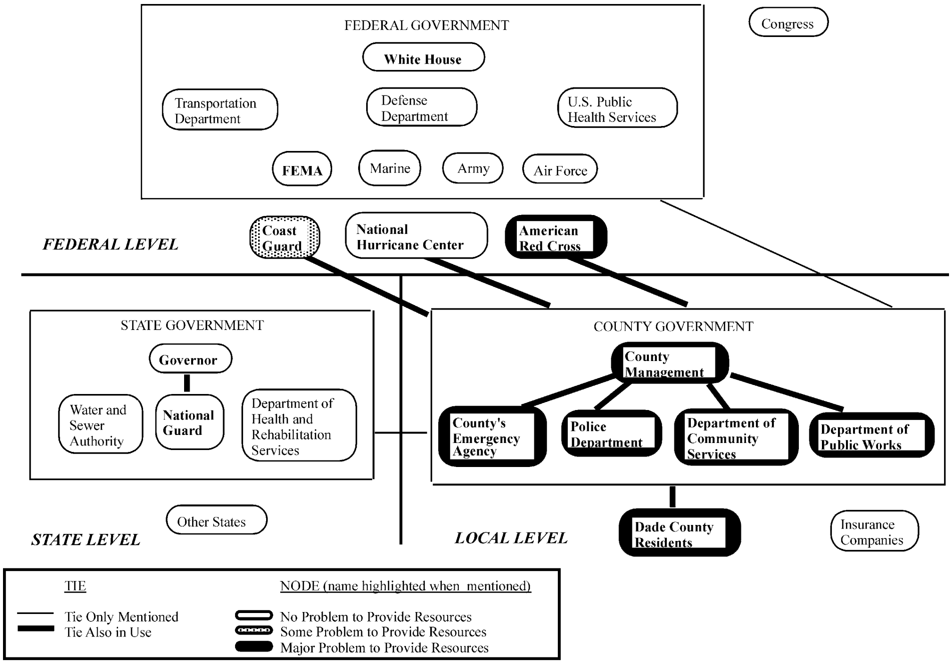

Fig. 2. Reported dynamics of organizational ties in the Hurricane Andrew incident on August 24, 1992.

vated through the US Public Health Service's preliminary offer of medical services and the promise of military help from the White House. Other ties, such as those with insurance companies, were also activated. This stage can be summarized in Fig. 3.

3.3.7. Stage 4

From August 28 to September 8, as the resources needed for the crisis were beyond the reach of the local government and the state government, it became more obvious that the state and local governments could no longer rely on the strong ties between themselves. Many problems persist in aspects like providing food and shelter for numerous homeless residents and raising funds for the wide-scale reconstruction. Ties with the federal government were further intensified through military help and financial help. Ties with FEMA were also slowly intensified.

Due to the increasing need for more resources, the ties with the federal government and other organizations were further intensified as a result. Any weaker ties that could bring possible resources were needed. As the impact of Hurricane Andrew showed no signs of decreasing, it became evident that more resources would be necessary. The federal government could no longer provide sufficient resources for the crisis relief and began to activate ties with the Congress to solicit more aid to the disaster area. This stage can be summarized in Fig. 4.

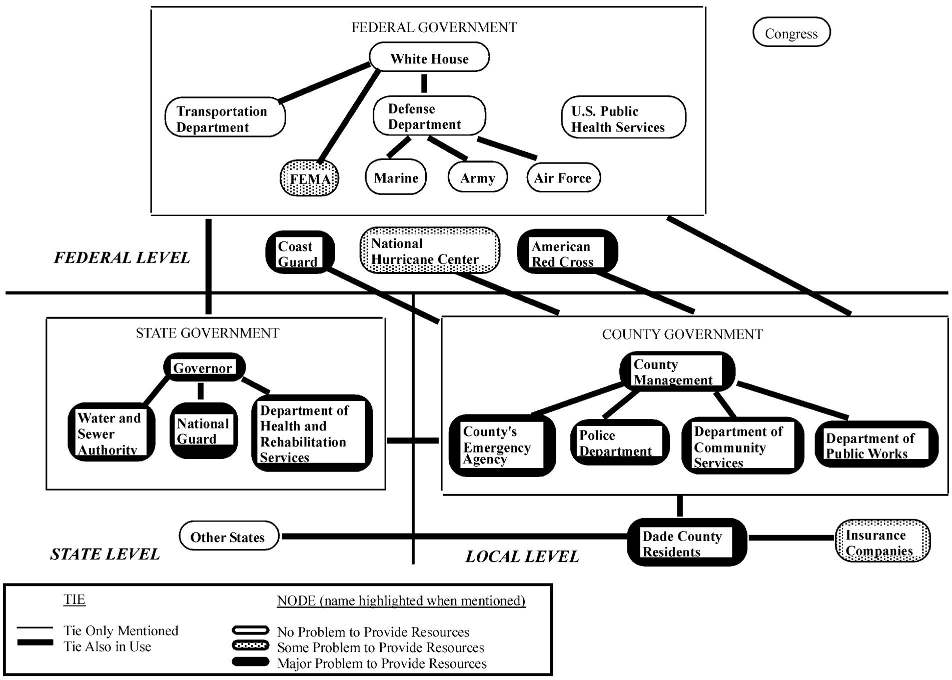

Fig. 3. Reported dynamics of organizational ties in the Hurricane Andrew incident from August 25 to 27, 1992.

3.4. Analyzing the Three Mile Island incident

On Wednesday, March 28, 1979, thirty-six seconds after 4:00 a.m., several water supply pumps broke down in unit no. 2 of the nuclear center at TMI, located in Middletown, just 10 miles southeast of Harrisburg, Pennsylvania. Tens of thousands of people were evacuated because of this crisis, causing millions of dollars in damage [15,25]. During that crisis numerous organizations were involved. In this case we will examine how organizations handled the crisis, once again focusing on the dynamics of organizational ties from a resource dependence perspective.

3.4.1. Local level

We first look at the connections among organizations at the local level, where the crisis started. Organizations included Metropolitan Edison (which operates the nuclear facility at TMI), the Middletown city government, and the Middletown city residents. The contacts among the three were frequent due to their close relationship and geographical proximity, and are therefore considered strongly connected.

3.4.2. State level

Organizations at the local level and organizations at the state level were also connected. At the state level was the Pennsylvania state government including the

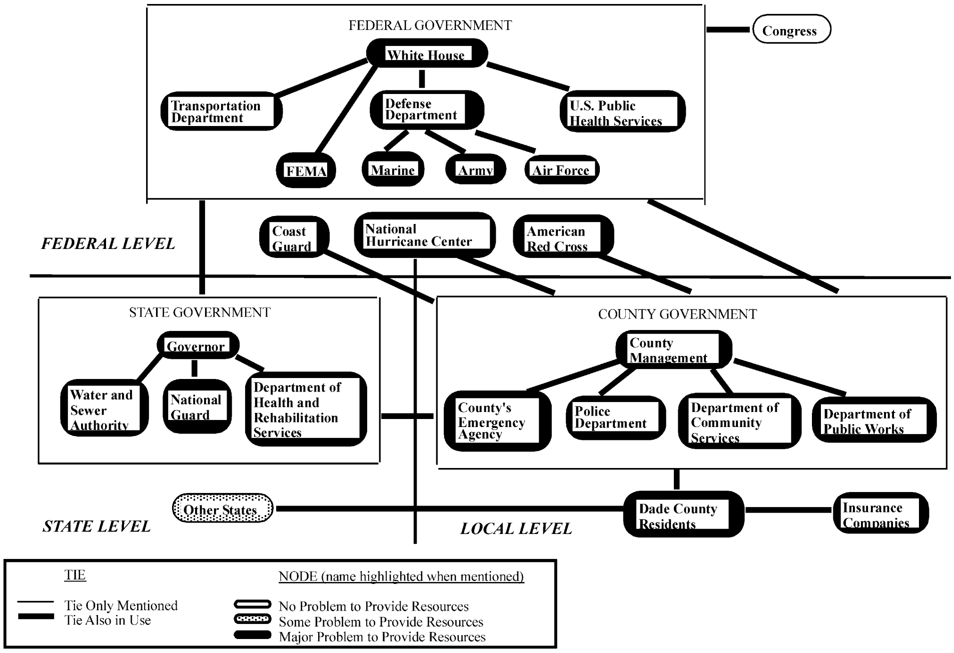

Fig. 4. Reported dynamics of organizational ties in the Hurricane Andrew incident from August 28 to September 8, 1992.

governor's office and the Pennsylvania Emergency Management Agency (PEMA). The ties between the local level organizations and the Pennsylvania state government were not as strong as the connections among the local level organizations.

3.4.3. Federal level

Further, organizations at the local level had connections with organizations at the federal level. These included the executive branch of the government (the Carter Administration), which consisted of the White House; the Nuclear Regulatory Commission (NRC); the Environmental Protection Agency (EPA); the Department of Health, Education and Welfare (DHEW); and the FEMA. Comparatively speaking, the ties between organizations at the local level and organizations at the federal level were weaker due to the infrequent or indirect contacts.

The strength of connections again ranged from strong to weak between the various local, state, and federal level organizations [15].

3.4.4. Stage 1

On March 28, the first day of the incident, several water supply pumps broke down in unit no. 2 of the nuclear center at TMI. The company operating the nuclear facility, Metropolitan Edison, initially believed that it could control the accident by itself. This can be seen by the active use of ties within the company. Soon, the company began to realize the potential severity of the crisis and informed the

Middletown city management of the incident, which then issued an alert to local residents. Residents were also informed of the crisis through the media.

Because of the catastrophic potential of the crisis, the PEMA was informed of the accident and then asked by the state government to coordinate the relief work. PEMA in turn called the rescue centers of the three counties concerned. Some initial signals were also sent to the NRC.

However, the impact of the crisis was not fully realized as the Pennsylvania lieutenant governor told a news conference that he did not believe there was any danger to the public. This stage can be summarized in Fig. 5.

3.4.5. Stage 2

From March 29 to 30, because of the explosive nature of the crisis, the state government also sought help at the federal level, in particular the NRC. However, the main contacts remained at the state level, where plans for an evacuation were being prepared. Due to the enormous resources needed for the evacuation process, however, the organizations involved were proceeding very cautiously. Finally, a small-scope evacuation was ordered for women and children within a radius of five miles. However, the actual number of people finally evacuated turned out to be huge, about 200,000 in total.

Contacts among the local level, the state level, and the federal level were then established through communication links between TMI, the governor's office, the White House, and the NRC. Other ties were also activated through help from the

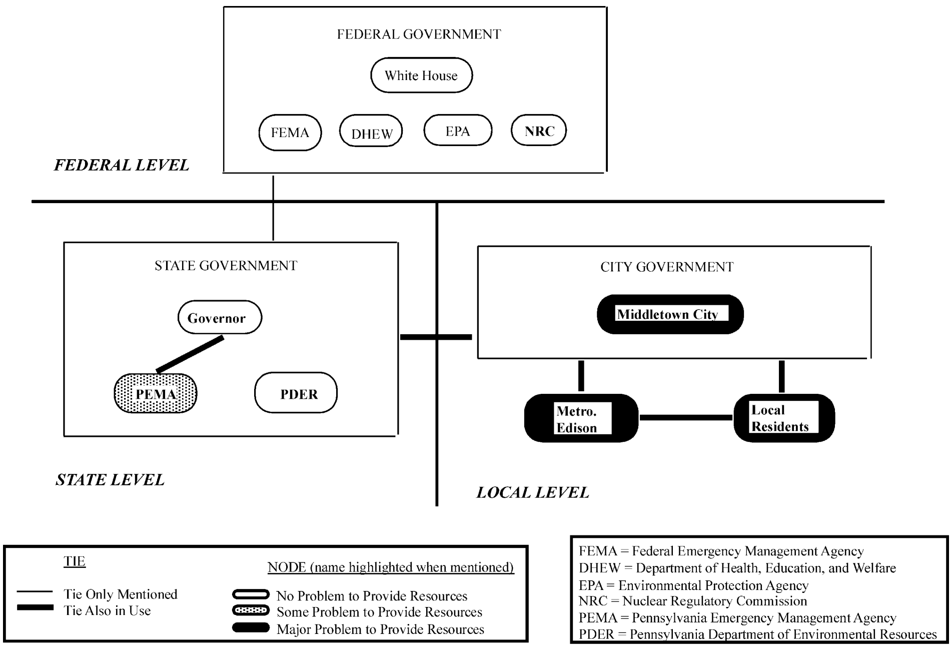

Fig. 5. Reported dynamics of organizational ties in the TMI incident on March 28, 1979.

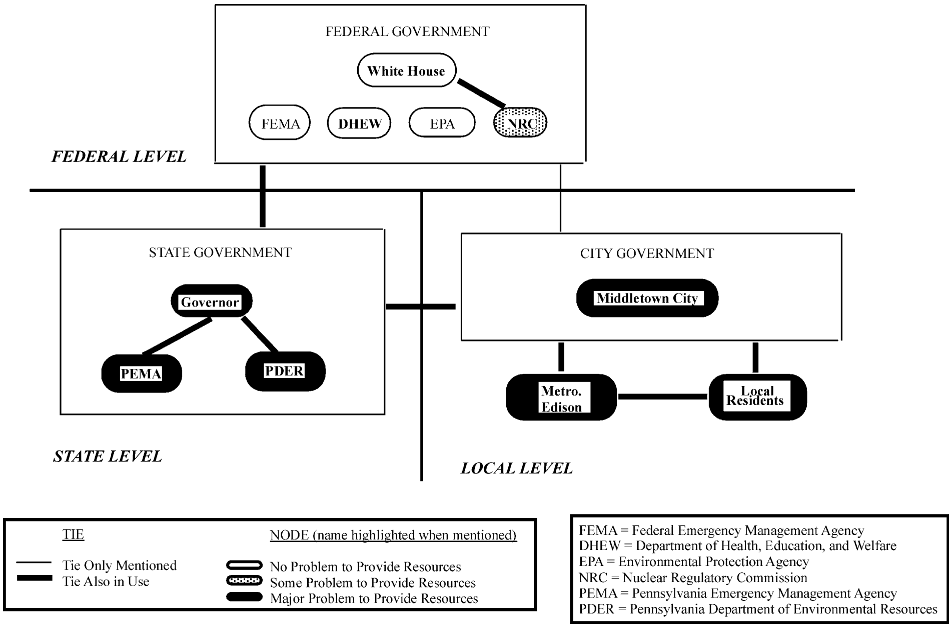

Fig. 6. Reported dynamics of organizational ties in the TMI incident from March 29 to 30, 1979.

federal Health Department (DHEM) and an expert delegate sent from the NRC to the state government. Possible declaration of a state of emergency was also considered. This stage can be summarized in Fig. 6.

3.4.6. Stage 3

From March 31 to April 1, the potential impact of the crisis increased due to the possibility of a hydrogen explosion at TMI, which would have caused enormous damage to human lives and the environment. This concern resulted in more evacuations, which in turn placed a greater demand on resources. This stepped-up activity also caught the attention of the federal government, resulting in a visit from President Carter to TMI. Fortunately, due to the effort by organizations at local, state, and federal levels, the crisis reached a stable stage, making it unnecessary to activate any more ties to provide additional resources. This stage can be summarized in Fig. 7.

3.5. Theoretical summary

The above case analyses show that when faced with a crisis that has huge resource demands, organizations tend to rely on stronger ties first and only activate relatively weaker ties when resource needs are not met. This process progresses as the crisis continues, like a cascade.

To further understand the dynamics of organizational ties, especially the initial reliance on stronger ties and later expansion of weaker ties, we can look into the

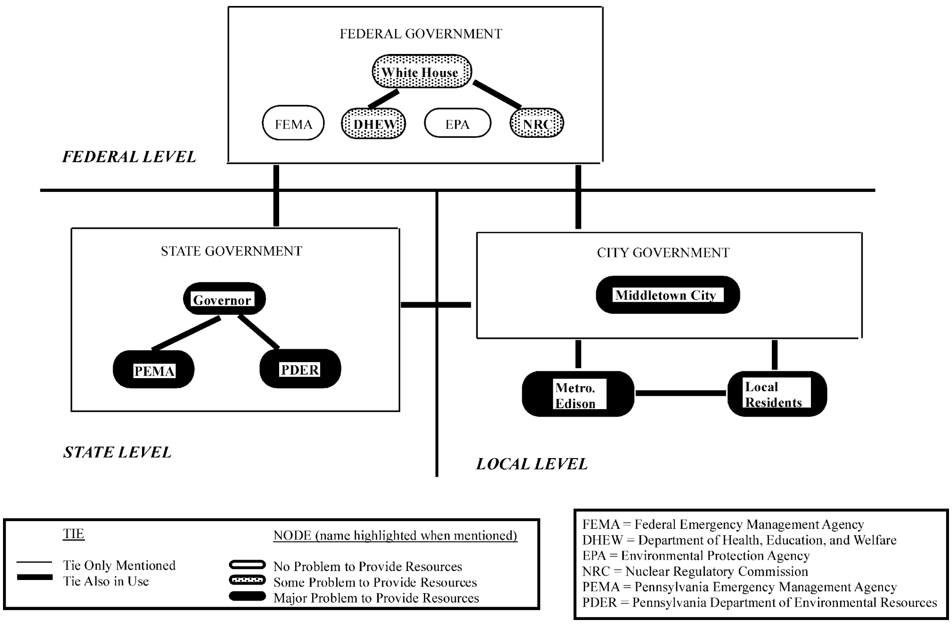

Fig. 7. Reported dynamics of organizational ties in the TMI incident from March 31 to April 1, 1979.

following aspects for some possible explanations. First, organizations' rationality is bounded [21]. Often, organizations cannot foresee all the impacts and the corresponding resource needs for a crisis situation, in particular in the early stage. Thus, organizations tend to first rely on their strong and more formal ties.

Second, organizations are fearful of uncertainty. The expansion and use of weak ties may mean a loss of authority and control to organizations involved. Thus, there is a threat-rigidity effect [29] for organizations to seek well-understood help (through strong ties) first.

Third, organizations are influenced by politics. Certain individual decision makers may not be willing to take risks or admit mistakes that will negatively affect their careers. This will also cause a delay of expanding ties.

Finally, organizations' resource capabilities are limited [26]. When the resource needs of organizations exceed their capabilities to provide sufficient resources—but only when such needs are vital to organizational survival—organizations will start to look for outside help.

Now, the remaining question is: Is this cascade process also more efficient?

4. A computer simulation model

The computer simulation model sets out to achieve two goals: simulate the dynamics of the cascade process of organizational ties based on resource needs and bounded rationality, and measure the efficiency of such a process as compared with a sequential/random process. We use the agent-based modeling technique, which will help us move beyond the limits of the conventional case analysis method. The effectiveness of employing computational methods is also noticed in a variety of studies in crisis management ranging from building models for advising governmental actions in political and military crisis situations [9] to designing training tools for managerial crisis prevention [28,31]. We believe this study, through the integration of computational modeling and organization theory, in particular social networks of organizations, can be most effective in addressing the issue of inter-organizational dynamics in crisis situations.

Because this model was based on the main stream agent-based approach and was written in Unix–C, it is readily portable to virtually all other computing environments. This will also enable the testing and extension of the model in other fields of management.

4.1. Model description

In the computational model, we model the network of organizations based on the previously literature review with the understanding that ties have purpose, direction, content, and strength. There are three key components in the computational model. The first part is the characteristics of the nodes, representing the organizations. The second part is the relationships among the nodes, and the third part is the dynamic processes of the relationships during crisis situations.

4.1.1. Modeling of the characteristics of nodes

For the computational model, a node requires several types of input resources in order to produce several other types of output resources. We also assume that in an organization, a final product (the output) usually requires larger amount of raw materials (the input). This becomes especially important in a crisis situation, as a crisis is a special event that demands more than the usual amount of input resources for the organization to survive and maintain the normal output. This was also observed in the two real world crisis cases conducted in this study. Further, one node' certain output resource can become another one's input resource, if their types match. By setting up these characteristics, we can thus create an emulated crisis setting, in which demands exceed immediate supplies.

Based on the rationale that organizations do not dramatically change their nature of operations easily, for this study, we control the number of types of resources so that the maximum number of types of input resources will be equal to that of output resources. The variable will then be about the ratio of quantity between input and output resources for each type. The following formula summarizes such modeling ideas.

$$\mathrm{IO_m} = I_\mathrm{m}/O_\mathrm{m} \tag{1}$$

where $\mathrm{IO_m}$ is the input/output quantity ratio, I_m is the maximum magnitude of input resources and O_m is the maximum magnitude of output resources for each node.

For example, each node can receive four input types of resources in order to produce another four output types of resources. We can then set the maximum amount of input resources at $I_m = 5$ units and the maximum amount of output resources at $O_m = 4$ units, which would make IO_m equal to 1.25.

4.1.2. Modeling of inter-node relationships

Besides these characteristics, nodes also have relationships among themselves. For this study, we focus on the strength of ties between each pair of nodes based on their interactions through both the contents of ties and the distance of ties. As discussed earlier, ties can have directions, so the strength of ties can also have directions.

$$S_{ij} = M_{ij}(1 - D_{ij}) \tag{2}$$

where S_{ij} is the strength of ties from node i to node j, M_{ij} is a value between 0 and 1.0 representing the degree of resource match between nodes i's output resources and node j's input resources in both type and quantity, and D_{ij} is a value between 0 and 1.0 representing the distance between nodes i and j. The introduction of the distance matrix is basically a based on the assumption that that the tie strength between two nodes can be influenced by not only the degree of resource matches but also by the physical distances between them. In real world situations, in particular in a crisis situation where the exchanges of large amount of physical resources are required, physical distance can greatly impact the interactions between organizations. This was also evidenced by the two crisis cases we have examined.

4.1.3. Modeling of the processes

Two main dynamics of inter-organizational ties will be modeled in the computational model. One relies on the cascade process and the other relies on the sequential process. Throughout the processes, amount of resources and time units are recorded to calculate the efficiency. The general algorithm for the computer simulation is as follows:

Initialization module

1. Set up a set of N nodes, each of which needs I_t types of input resources to generate O_t ($O_t = I_t = 4$) in this study) types of output resources; Each type of input resources can have a random quantity between 0 and I_m; Each type of output resources can have a random quantity between 0 and O_m.
2. Calculate the resource match matrix $\{M_{ij}\}$ for all the nodes that measures, in each pair, the extent to which one's output resources match the other's input resources in both types and quantities.
3. Set up a distance matrix $\{D_{ij}\}$ for all the nodes that allows each pair of nodes to have a random distance between 0 and 1.
4. Calculate the tie strength matrix $\{S_{ij}\}$ for all pairs of nodes, based on both the resource match matrix and the distance matrix.

Process module

5. If the *cascade process* is followed, go to 6. If the *sequential/random process* is followed, go to 9.

Cascade process

6. Select a node as the *starting node* for the cascade process. If all nodes have been selected, stop the process; otherwise, continue the process below.
7. If there is an input resource need by the starting node, search for another node with the next strongest tie and transfer resources from that node to the starting node. Record amount of resources exchanged and time units spent. Number of time units spent depends on both the resources and the distance.
8. If all resource needs are met for the starting node, restore all resources back to all the nodes for later processes and go to 6. Otherwise, go to 7.

Sequential/random process

9. Select a node as the *starting node* for the sequential/random process. If all nodes have been selected, stop the process; otherwise, continue the process below.
10. If there is an input resource need by the starting node, search for the next node and transfer resources from that node to the starting node. Record amount of resources exchanged and time units spent. Number of time units spent depends on both the resources and the distance.
11. If all resource needs are met for the starting node, restore all resources for later processes and go to 9. Otherwise, go to 10.

4.1.4. Measuring of efficiency

To measure the efficiency of each process, we keep track of both the total amount of resources accumulated by each starting node and the number of time units spent before reaching the stable stage. The formula is as follows:

$$E_i = R_i/T_i \tag{3}$$

where E_i is the efficiency of the process started with the node i, R_i is the total amount of resources accumulated by node i when all resource needs are met, and T_i is total number of time units spent in the process for node i to reach the stable stage, which also takes into consideration the distance between nodes.

4.2. Simulation experiments

We conduct three simulation experiments. In the first experiment, we set the input to output quantity ratio at 1.25 to examine both the cascade process and the sequential/random process. In the second and the third experiments, we set the input to output quantity ratio at 2.50 and 3.75 respectively, thus assuming an even greater demand for input resources. By varying the input to output ratio we can then examine how this may affect the efficiency of a process in addition to the different nature of the process. This may also indirectly reflect the severity of a crisis as we can assume that a more severe crisis may create a higher resource demand.

In each of the three experiments, the total number of nodes is 35. We conduct 40 runs for each experiment. At the beginning of each run, all resources are randomly reset according to the algorithm described earlier. For each run of the simulation, a starting node is selected and the process operates until the resource needs of the starting node are met; this procedure is repeated for each of the 35 possible starting nodes.

Table B1, Table B2 and Table B3 in Appendix B also contains sample matrices including the resource match matrix, the distance matrix, and the tie strength matrix for the inter-organizational relationships for the first run in the experiment where the input to output quantity ratio is set at 3.75.

During the experiments, we record both the resources transferred and the time spent by each node. Efficiency is calculated as the amount of resource over the number of time units. The original amount of input and output resources is randomly assigned to each node at the beginning of each run for each node. The simulation model does not track the original amount but the actually exchanged amount when calculating the efficiency of each node for resource accumulation. Given that there are 35 nodes in the network, each node will eventually be able to collect enough resources. In other words, the amount of original resources may not be as important. They are just set up to allow us to examine how each node can accumulate sufficient resources within the shortest time.

The models are written in UNIX–C language. Further coding details can be provided upon request.

4.3. Results

The results are summarized in Table 1. As we can see that when the input to output ratio is set at 1.25, we can find that those nodes following the cascade process through the decreasing order of strength of ties tend to be significantly ($p < 0.01$) more efficient when compared with those nodes that follow the sequential process regardless of the strength of ties. Characteristics of this network such as resource match matrix, distance matrix, and tie strength matrix are randomly generated based on the previous formulas, which serve as the bases for both processes.

When the input to output ratio is set at 2.50, which forces a node to obtain more resources for the same set of outputs, we can find from Table 1 that those nodes following the cascade process through the decreasing order of strength of ties still exhibit significantly ($p < 0.01$) higher efficiency as compared with those nodes that follow the sequential process regardless of the strength of ties. However, the difference of efficiency is much getting slightly smaller in this case than previously. Characteristics of this network such as resource match matrix, distance matrix, and tie strength matrix are again randomly generated based on the previous formulas, which serve the bases for both processes.

Finally, when the input to output ratio is set at 3.75, which forces a node to obtain the most resources for the same set of outputs, we can find from Table 1 again that those nodes following the cascade process through the decreasing order of strength of ties still exhibit significantly ($p < 0.01$) higher efficiency as compared with those nodes that follow the sequential process regardless of the strength of ties. However, the efficiency advantage of the cascade process becomes further smaller, though the decrease may not be statistically significant. Characteristics of this network such as resource match matrix, distance matrix, and tie strength matrix are again ran-

Table 1
The dynamics of inter-organizational ties: measures of efficiency with different input/output quantity ratios and internal mechanisms

Starting node	Ratio = 1.25		Ratio = 2.50		Ratio = 3.75	
	Cascade process	Random process	Cascade process	Random process	Cascade process	Random process
1	29.17 (3.34)	15.62 (4.84)	28.22 (2.72)	17.42 (3.50)	27.19 (2.57)	17.53 (3.25)
2	28.99 (3.49)	15.60 (5.17)	28.25 (2.79)	17.14 (4.38)	27.49 (2.88)	17.57 (4.17)
3	28.12 (3.73)	16.57 (5.88)	27.74 (3.19)	17.03 (4.64)	26.37 (2.71)	17.35 (3.80)
4	28.13 (3.50)	15.30 (4.50)	27.92 (2.99)	16.92 (3.72)	26.32 (3.24)	17.51 (3.79)
5	29.24 (2.63)	15.81 (3.91)	28.73 (2.82)	17.16 (3.19)	27.74 (2.85)	17.70 (2.99)
6	27.17 (3.43)	15.89 (5.90)	26.81 (3.67)	17.51 (4.03)	25.90 (3.38)	17.84 (3.84)
7	27.65 (3.13)	16.81 (6.46)	27.03 (3.51)	17.87 (5.23)	26.91 (3.57)	17.86 (4.45)
8	26.68 (3.74)	14.61 (5.25)	26.55 (4.08)	16.25 (4.18)	26.04 (3.66)	16.58 (3.30)
9	25.76 (3.88)	14.57 (5.30)	27.02 (3.20)	15.87 (4.51)	26.57 (3.49)	16.36 (4.01)
10	25.91 (3.61)	16.30 (4.61)	25.81 (4.04)	17.58 (3.91)	25.46 (3.71)	17.44 (3.03)
11	25.25 (4.79)	14.97 (4.45)	25.64 (4.10)	16.92 (4.08)	24.99 (3.45)	17.14 (3.53)
12	25.81 (3.97)	15.54 (3.62)	25.74 (4.19)	17.13 (3.16)	25.37 (3.69)	17.51 (3.30)
13	26.87 (4.40)	15.20 (4.03)	25.38 (4.32)	17.01 (3.19)	24.46 (4.53)	16.86 (2.30)
14	25.82 (3.62)	16.36 (4.46)	24.88 (4.21)	17.48 (4.57)	24.35 (4.86)	17.75 (4.49)
15	24.98 (3.92)	15.51 (4.55)	23.72 (3.73)	16.64 (3.60)	24.11 (3.21)	17.06 (3.23)
16	26.24 (4.36)	14.91 (4.68)	25.93 (3.98)	16.97 (4.01)	25.20 (4.00)	17.35 (3.73)
17	23.42 (5.17)	14.84 (4.47)	22.95 (3.91)	16.27 (3.95)	24.12 (4.10)	16.59 (3.13)
18	24.33 (4.83)	15.64 (4.95)	24.03 (4.53)	16.95 (4.57)	23.29 (4.90)	17.32 (4.28)
19	23.19 (4.83)	14.71 (4.25)	22.50 (4.95)	16.51 (3.88)	23.54 (5.02)	17.10 (3.73)
20	24.42 (5.56)	16.18 (5.69)	23.38 (4.90)	16.86 (3.37)	21.88 (4.96)	17.48 (3.48)
21	25.33 (4.39)	15.32 (4.59)	23.11 (4.16)	16.01 (2.81)	23.11 (4.04)	16.93 (3.01)
22	24.05 (4.51)	15.74 (4.38)	22.95 (4.89)	17.51 (3.71)	22.46 (4.87)	17.39 (2.59)
23	23.82 (4.19)	14.42 (4.19)	23.10 (4.60)	15.65 (3.28)	21.71 (4.91)	16.27 (2.78)
24	22.53 (6.06)	16.36 (4.54)	22.29 (4.91)	17.79 (4.25)	21.95 (4.87)	18.34 (4.23)
25	22.20 (5.41)	15.22 (5.46)	21.95 (4.92)	16.78 (4.21)	22.58 (5.01)	17.17 (3.46)
26	21.41 (4.68)	15.84 (5.42)	21.52 (5.28)	16.97 (4.29)	21.88 (4.96)	17.36 (3.70)
27	21.92 (4.67)	16.02 (4.97)	21.72 (5.19)	17.29 (4.48)	22.18 (4.95)	17.88 (4.08)
28	21.37 (5.89)	15.14 (4.92)	21.47 (6.07)	16.61 (3.63)	21.94 (5.50)	17.17 (3.23)
29	20.03 (5.60)	14.88 (5.11)	20.44 (4.40)	16.03 (3.63)	21.11 (4.73)	16.31 (3.17)
30	20.69 (5.32)	15.66 (5.51)	20.10 (4.39)	16.69 (3.53)	20.98 (4.39)	17.45 (3.26)
31	20.75 (5.10)	15.43 (3.93)	20.43 (4.84)	16.92 (3.57)	19.81 (5.23)	17.28 (2.94)
32	22.94 (5.72)	14.81 (3.88)	21.67 (4.92)	16.61 (3.90)	21.21 (5.52)	17.16 (3.74)
33	20.31 (5.00)	15.42 (5.38)	19.85 (5.14)	16.79 (3.73)	20.34 (4.71)	16.96 (2.98)
34	20.01 (5.57)	16.19 (5.61)	19.29 (5.07)	16.73 (3.72)	19.93 (5.42)	17.22 (3.90)
35	20.43 (5.74)	14.99 (5.10)	20.65 (5.52)	16.54 (4.49)	21.68 (5.52)	17.26 (4.28)
Overall	24.42 (5.33)	15.50 (4.88)	23.96 (5.11)	16.87 (3.93)	23.72 (4.88)	17.26 (3.55)

Note: Each cell contains the average efficiency based on 40 runs with the standard deviation in the parentheses.

domly generated based on the previous formulas, which serve the bases for both processes.

These results have thus provided the rationale behind organizations' dynamic relationships during crisis situations, that is, it generally can produce higher efficiency for organizations to follow the cascade process. Such advantage, however, can be gradually diminished when the severity of crisis is dramatically increased and the demand for resource is magnified. This is an interesting finding as it suggests that there is a limit to which the cascade process may be effective and that when under overwhelming resource pressures, it may matter less what particular process organizations rely on.

We must also note that not all organizations in the networks can benefit from such efficiency, even though on average a cascade process can be more efficient. Depending on the location in the network, during a particular run, some individual organizations may be even worse off with this cascade process as compared with the sequential/random process, which is not shown here. This implies that more research may be needed to explore the causal relationship between the nature of the network an organization is in and the efficiency of the process it adopts.

We have also tried setting the ratio of the number of types of input resources over output resources at greater than 1, similar to that of the input to output quantity ratio. What we have found is that the decrease of the efficiency advantage of the cascade process over the random/sequential process becomes faster. This phenomenon is worth further exploration as it suggests that organizations may lose the benefit of the cascade process when the severity of the crisis demands the dramatic increase of both the type and the amount of resources.

5. Discussion and conclusion

5.1. Main contributions

This study has examined the dynamics of inter-organizational ties during crisis situations. Our study has demonstrated that organizational relationships are affected by both tie and node characteristics. Resources are vital to organizational survivals and the dynamics of organizational ties can be better understood from a resource dependence perspective and bounded rationality basis. While our analyses of two major crisis cases have revealed the cascade process of ties, our computer simulation model has further demonstrated the efficiency of such a process by illustrating the dynamic relationship between the resource demand and the inter-organizational process. Although we have focused our study on crisis situations, we believe findings from this study can also be applied to non-crisis situations, as organizations in non-crisis situations also need resources and do so through networks of organizations. Indeed, the distinction between a crisis situation and a non-crisis situation may not be that clear-cut if we consider them from a resource dependence perspective.

The study has made a significant contribution to the field by providing not only empirical analyses but also computational modeling into the important issue of dynamics of inter-organizational ties, thus enabling us to understand fully the rationales behind such processes. While the computational model is simplified, it is effective in emulating key characteristics of real world social networks and providing theoretical insights.

5.2. Discussion of findings

The analysis in our study has also supported our previously listed rationales for the dynamics of ties, in particular, the initial reliance on stronger ties and later expansion of weaker ties. The first rationale states that organizations' bounded rationality will inhibit organizations' ability to foresee the impact of the crisis and the need for resources, thus organizations tend to first rely on their strong and more formal ties. For example, in the Hurricane Andrew incident, Governor Chiles of Florida admitted that at the early stage of the Hurricane Andrew crisis, he "didn't think it was necessary" to call for federal help [32: 8/29/1992-A8]. Similar things also happened in the TMI crisis.

The second rationale states that organizations tend to hold on to their familiar structures and methods because organizations are fearful of uncertainty and loss of control. Such behaviors are shown in both the Hurricane Andrew crisis and the TMI crisis as organizations were very reluctant to expose themselves to the outside world.

The third rationale states that because of politics in organizations, certain decision makers often do not want to take risks or admit mistakes that can negatively affect their careers. For example, one of the major criticisms of the handling of the TMI crisis was that organizations involved tried to cover up the incident as much as possible instead of introduce weaker ties [15]. Also, in the Hurricane Andrew crisis, politics played at both the state and federal levels were widely documented.

The fourth and final rationale states that due to organizations' limited resource capability, organizations will start to look for outside help only when they cannot provide sufficient resources that are vital to organizations' survival. Such dynamics are the essence of the cascade process of ties and are clearly illustrated in both crisis cases.

There are two specific phenomena in the crisis cases that we think are worth further discussion. One thing to notice is that even though decisions, information, and materials flowed through organizational ties, the data do not indicate that decision powers always moved to upper levels as crises progressed. As a matter of fact, in both cases, major decision powers remained at the state level. Relevant to this phenomenon, researchers have found that when faced with a crisis, organizations tend to expand their resource access structures but still maintain their hierarchical command structures as in the two cases we examined here [5]. Hierarchical structures have difficulty in forming ties with other hierarchical structures at the command level, but they can usually exchange resources at a lower lateral level.

The second thing to notice is that the duration of time that organizations relied on their stronger ties varied at different stages across the two crises. Understanding this may require further knowledge of not only the difference of the resources needed by the organization and the resources the organization has had, but also the urgency for resources by the organization and the geographic distance between the resource provider and the resource receiver.

5.3. Main implications, limitations, and future directions

This study also has rich practical implications to organizational managers. It shows that organizations can benefit from strategic networking when the environment becomes critical and when the resource demand is large, such as in a crisis situation. In this paper, the cascade process is modeled such that it is more based on the learning mechanism than on rigid standard operating procedures (SOPs). The dynamics of the tie strength actually embeds the knowledge of past interactions, which future interactions may depend on. Our study therefore also suggests when a crisis occurs, it may be beneficial for organizations to rely more on learning mechanisms rather than on pre-established SOPs. This is because SOPs may sometimes become the cause for crises as the complexity of the task coupled with the uncertainty of the environment may become too much for SOPs to handle.

The empirical part of the study relied heavily on the content analysis of two cases. The quantification in the analysis has only limited categories. The few categories can help us get a robust picture of the dynamics of organizational ties. Such categorization, however, may not be sufficient if we try to differentiate the impact of different contents of ties. The fact that both crisis cases involved governments at different levels in the United States may also pose a legal constraint to the dynamics of organizational ties in this study. We may need to conduct further research to find out if and how such legal constraint may influence the dynamics of organizational ties.

This study has again demonstrated that computer modeling can be a natural and effective method for studying dynamic social networks [33]. The computational model in this study has followed the tradition of agent-based computer modeling [7,19,20]. The model can be applicable to a wide range of situations related to inter-organizational relationships, and are not just limited to crises. For example, we can extend the model to the study of strategic networks where resource accumulations are also important. The current simulation results, however, also need to be viewed with a clear understanding of the model settings and the boundary conditions. For this study, we have also tested several different formulas of the strength of ties for the computational model such as using additive rather than the multiplicative rules for combining resource match and distance. The final results are similar.

There are several directions we would like to pursue further in our future research. First, we would like to look into more sources for the two cases we have examined, even though we have obtained archival data from two different sources for each crisis case. We would be most interested in talking to people directly involved in the two incidents, therefore minimizing the bias of observations. Second, we would like to examine different crisis cases to test the "cascade process of ties". In particular, we would like to examine crisis cases that contain fewer legal constraints. Third, we would like to see how power and politics may influence the dynamics of organizational ties. Fourth, we would like to have a better grasp of the contents of ties and different types of resources. Fifth, we would like to examine the dynamics of organizational ties during the period immediately following the crisis. Sixth, we would like to explore what might happen to organizations if all ties have been activated and resources are still inadequate. Seventh, we would also like to look at whether integrated crisis management systems form during each crisis situation and the formation mechanism if any. Finally, we would like to expand the computational model to include more realistic characteristics of organizations, thus providing more sophisticated theoretical insights.

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Appendix A. General rules for case analysis

Step A. Pick up nodes involved in the case

(A1) From available sources, find out what organizations were mentioned during the whole process of the crisis. For example, in the Hurricane Andrew case, the Dade County Management, the Federal Emergency Management Agency, etc., were mentioned by the NT, so they are nodes in the case. A node can be an organization, a group of organizations, a representative from an organization, or a group of individuals.
(A2) Group the organizations according to whether they belonged to another larger organization. For example, in the Hurricane Andrew crisis, organizations like Dade County Management, Dade County Emergency Agency, Dade County Police Department, Dade County Community Services Department, and Dade County Public Works Department, belonged to the Dade County government, so they can be circled (grouped) together.
(A3) Find out relative frequencies of long-term relationships among the organizations, or groups of organizations, i.e., whether they have frequent contacts or rare contacts providing or receiving materials, money, information, etc. The frequency is relative when categorizing strong or weak ties. For example, in the Hurricane Andrew crisis the contacts between the Dade County Management and the Dade County Emergency Agency were more frequent than the contacts between the Dade County Emergency Agency and the Florida state government.

Step B. Find out the starting node of the crisis

(B1) Find out the cause of the crisis, beginning immediately before the crisis. For example, the Hurricane Andrew crisis was due to an unprecedented hurricane hitting southern Florida.
(B2) Point out where the crisis occurred. For example, in the Hurricane Andrew crisis, the crisis started with the Dade County residents.

Step C. Find out nodes mentioned in the sources

(C1) Find out nodes mentioned in the sources that are related to the case.
(C2) Categorize nodes into respective levels: local, state, or federal.

Step D. Find out problems related to providing resources

(D1) Look for the indicator: was there any problem for the node or the ties connected to the node to provide resources? Find out the impact of the crisis and the resource demand caused by the crisis.
(D2) If there was a problem, was the problem a small one or a major one? A small problem would be that resources could still be provided with some difficulty. A major problem would be the inability to provide adequate resources, either due to overpowering of the resource demand, or capability of the nodes or ties (such as severe budget constraint). One needs to look for such signs as: was any concern voiced or a cry for help? Was there any mention or description of inadequate supply? For example, at one point in the Hurricane Andrew crisis (August 27, 1992), as reported by the NT and the WP on August 28, we can see that (1) ties were used among the Dade County Management, the Dade County Emergency Agency, the American Red Cross, the Florida National Guard, and the Florida state government; and (2) there were major problems for the organizations to provide sufficient resources to mitigate the crisis.

Step E. Find out whether ties were activated to provide resources

(E1) Look for the indicator: was the tie to provide resources only being mentioned or already in use.
(E2) If a relationship was mentioned for the first time between two organizations for providing resources, then the tie was activated. Point out the nodes connected to the tie.
(E3) If the ties were mentioned again, then the use of the tie was intensified. Accumulate the use of ties. Once activated a tie is regarded as being in use unless the data sources say otherwise.
(E4) Point out the nodes connected to the tie. Ties between two organizations can be shown through relations such as materials supplying/receiving, help supplying/receiving, information supplying/receiving, etc. For example, following the example in Step D, we can also see that there was mention of the ties with the federal government, but the ties are not fully in use.

Step F. Check the availability of sources

(F1) If this is the last day of the crisis or the end of the sources, stop coding.
(F2) Otherwise, go back to Step C for information on the next day of the crisis.

Appendix B. Matrices of network characteristics (Tables 2–4)

Table 2
A resource match matrix for run #1 with input/output quantity ratio set at 3.75

Node	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35
1	.00	.49	.35	.33	.38	.47	.19	.45	.21	.27	.15	.39	.33	.42	.35	.40	.57	.08	.37	.43	.39	.46	.38	.48	.33	.46	.19	.41	.29	.44	.39	.33	.44	.31	.20
2	.02	.00	.07	.10	.08	.16	.08	.10	.11	.09	.09	.08	.13	.10	.08	.14	.17	.08	.16	.12	.12	.20	.06	.13	.16	.14	.05	.13	.15	.12	.17	.09	.13	.13	.12
3	.02	.10	.00	.09	.08	.15	.06	.11	.03	.06	.01	.10	.06	.10	.09	.11	.13	.00	.10	.11	.11	.14	.09	.14	.08	.14	.02	.08	.07	.10	.10	.04	.09	.07	.04
4	.28	.61	.37	.00	.37	.41	.14	.45	.37	.40	.35	.39	.49	.43	.39	.39	.57	.18	.29	.45	.49	.38	.36	.45	.32	.50	.33	.52	.35	.43	.32	.43	.46	.44	.24
5	.06	.26	.15	.12	.00	.18	.09	.18	.14	.13	.12	.14	.18	.16	.13	.16	.25	.09	.17	.17	.17	.21	.13	.16	.18	.18	.10	.19	.17	.19	.18	.17	.20	.16	.13
6	.05	.34	.16	.11	.13	.00	.10	.21	.24	.14	.22	.15	.24	.17	.13	.21	.30	.18	.23	.16	.22	.29	.12	.15	.27	.20	.11	.27	.25	.18	.26	.22	.21	.22	.22
7	.11	.48	.26	.32	.32	.40	.00	.29	.20	.32	.16	.22	.39	.32	.27	.30	.48	.11	.37	.37	.25	.41	.20	.38	.33	.36	.21	.26	.34	.40	.34	.31	.43	.34	.25
8	.13	.41	.28	.31	.37	.36	.27	.00	.17	.32	.10	.16	.36	.39	.35	.36	.44	.06	.32	.34	.21	.38	.15	.35	.35	.38	.28	.18	.34	.37	.35	.35	.38	.34	.32
9	.27	.37	.33	.31	.35	.34	.06	.41	.00	.32	.15	.40	.32	.38	.36	.28	.43	.00	.13	.38	.41	.19	.38	.43	.10	.44	.27	.37	.14	.37	.14	.31	.36	.28	.05
10	.12	.57	.41	.25	.31	.55	.26	.57	.34	.00	.31	.40	.47	.45	.33	.51	.66	.25	.47	.39	.53	.55	.31	.36	.42	.55	.28	.51	.41	.42	.47	.49	.53	.44	.34
11	.12	.33	.24	.30	.35	.34	.26	.22	.10	.29	.00	.14	.30	.36	.33	.33	.38	.00	.28	.33	.17	.33	.13	.34	.28	.36	.25	.11	.28	.34	.30	.29	.34	.29	.26
12	.07	.35	.25	.12	.20	.33	.08	.39	.28	.11	.25	.00	.21	.30	.23	.36	.45	.18	.27	.20	.39	.43	.32	.27	.33	.35	.09	.46	.25	.19	.38	.25	.23	.22	.21
13	.21	.63	.50	.42	.56	.59	.32	.57	.33	.41	.23	.44	.00	.64	.54	.61	.78	.13	.48	.51	.49	.63	.43	.57	.53	.64	.37	.50	.47	.54	.58	.55	.58	.48	.42
14	.06	.26	.15	.11	.14	.18	.08	.20	.16	.12	.14	.15	.18	.00	.13	.17	.26	.11	.17	.15	.18	.23	.13	.15	.19	.19	.10	.22	.18	.17	.19	.18	.19	.17	.14
15	.19	.46	.34	.20	.34	.27	.10	.40	.25	.24	.23	.35	.34	.36	.00	.25	.48	.13	.21	.31	.31	.28	.33	.28	.24	.32	.26	.40	.24	.38	.24	.38	.40	.28	.18
16	.09	.33	.21	.22	.24	.31	.13	.29	.14	.19	.11	.25	.23	.26	.21	.00	.37	.06	.24	.28	.25	.31	.22	.29	.22	.30	.13	.24	.20	.30	.24	.22	.29	.21	.14
17	.30	.72	.54	.41	.45	.68	.25	.71	.46	.51	.42	.57	.63	.64	.54	.67	.00	.25	.49	.57	.76	.58	.50	.59	.45	.77	.42	.73	.46	.54	.52	.61	.66	.60	.34
18	.29	.53	.42	.39	.44	.49	.12	.54	.29	.38	.24	.51	.41	.51	.47	.45	.62	.00	.27	.49	.55	.38	.50	.57	.26	.58	.30	.55	.27	.46	.32	.39	.46	.38	.14
19	.21	.56	.37	.37	.45	.40	.23	.38	.20	.39	.16	.33	.46	.43	.35	.30	.57	.08	.00	.46	.28	.34	.31	.44	.28	.40	.32	.33	.32	.53	.29	.41	.55	.37	.22
20	.09	.26	.24	.22	.27	.35	.10	.35	.10	.15	.05	.33	.16	.31	.26	.30	.39	.00	.22	.00	.30	.32	.33	.36	.19	.34	.09	.29	.14	.28	.26	.19	.27	.16	.08
21	.13	.33	.29	.18	.28	.26	.09	.35	.16	.19	.13	.31	.24	.29	.22	.22	.39	.07	.18	.26	.00	.24	.28	.26	.18	.28	.18	.29	.17	.31	.19	.30	.32	.20	.12
22	.10	.46	.34	.15	.21	.38	.20	.43	.31	.28	.29	.28	.41	.34	.23	.38	.51	.25	.36	.27	.40	.00	.20	.20	.33	.39	.26	.41	.34	.31	.35	.45	.43	.37	.30
23	.08	.26	.19	.21	.23	.29	.12	.25	.07	.17	.04	.23	.18	.23	.20	.20	.31	.00	.20	.26	.20	.25	.00	.29	.15	.27	.11	.17	.14	.28	.18	.17	.26	.16	.08
24	.20	.62	.48	.26	.38	.51	.23	.61	.36	.38	.33	.47	.53	.52	.37	.49	.71	.25	.42	.42	.55	.48	.38	.00	.38	.55	.37	.57	.40	.49	.42	.57	.61	.46	.32
25	.01	.24	.05	.08	.05	.12	.09	.06	.16	.10	.15	.02	.17	.07	.05	.12	.16	.13	.18	.10	.09	.19	.00	.08	.00	.10	.06	.13	.19	.10	.18	.11	.13	.16	.17
26	.16	.48	.39	.26	.37	.42	.13	.51	.27	.23	.23	.44	.32	.43	.34	.41	.59	.13	.32	.36	.43	.45	.43	.41	.34	.00	.20	.50	.29	.39	.39	.38	.42	.30	.21
27	.16	.53	.36	.37	.41	.46	.24	.42	.21	.36	.16	.34	.43	.41	.34	.35	.58	.09	.38	.44	.33	.44	.31	.46	.33	.44	.00	.34	.34	.49	.36	.39	.51	.37	.24
28	.20	.63	.53	.49	.61	.56	.34	.47	.33	.39	.19	.37	.45	.62	.58	.58	.67	.09	.57	.58	.43	.59	.36	.55	.60	.59	.30	.00	.49	.57	.59	.51	.59	.49	.41
29	.11	.24	.24	.18	.25	.25	.07	.31	.08	.15	.05	.28	.17	.25	.20	.19	.32	.00	.14	.24	.23	.21	.27	.26	.11	.26	.13	.22	.00	.27	.15	.21	.26	.14	.05
30	.09	.37	.21	.20	.22	.25	.13	.24	.18	.20	.15	.19	.27	.23	.18	.21	.35	.11	.24	.26	.20	.27	.17	.24	.23	.24	.16	.24	.23	.00	.23	.25	.30	.23	.18
31	.07	.32	.18	.19	.20	.25	.13	.22	.14	.18	.11	.17	.23	.21	.17	.20	.31	.08	.23	.25	.19	.26	.15	.24	.21	.24	.13	.20	.20	.26	.00	.20	.27	.20	.15
32	.08	.29	.19	.18	.21	.26	.11	.26	.13	.17	.10	.22	.21	.23	.18	.21	.32	.06	.20	.24	.21	.26	.20	.24	.19	.25	.12	.22	.18	.26	.21	.00	.26	.18	.13
33	.06	.28	.14	.16	.16	.16	.12	.13	.11	.17	.09	.08	.21	.15	.12	.13	.23	.07	.18	.21	.10	.17	.08	.17	.16	.15	.12	.12	.18	.23	.15	.18	.00	.18	.13
34	.09	.57	.28	.27	.27	.47	.22	.40	.33	.28	.29	.30	.42	.35	.28	.43	.58	.25	.47	.36	.42	.58	.24	.37	.45	.44	.18	.46	.44	.37	.49	.35	.41	.00	.36
35	.12	.35	.22	.30	.30	.27	.20	.18	.07	.30	.03	.13	.32	.25	.22	.17	.33	.00	.25	.33	.10	.20	.13	.32	.17	.23	.20	.10	.22	.38	.17	.25	.38	.25	.00

Table 3
A distance matrix for run #1 with input/output quantity ratio set at 3.75

Node	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35
1	.00	.77	.09	.90	.52	.58	.07	.76	.32	.14	.04	.55	.02	.25	.28	.45	.48	.68	.20	.01	.66	.25	.70	.39	.08	.34	.01	.50	.10	.83	.98	.13	.11	.58	.02
2	.77	.00	.15	.16	.08	.90	.99	.21	.46	.05	.75	.70	.84	.19	.69	.51	.90	.22	.69	.15	.91	.59	.74	.76	.59	.23	.37	.93	.72	.01	.03	.30	.03	.17	.97
3	.09	.15	.00	.62	.59	.47	.35	.56	.52	.09	.77	.35	.79	.45	.38	.69	.18	.06	.83	.60	.16	.56	.87	.26	.30	.23	.18	.01	.24	.20	.82	.78	.89	.78	.91
4	.90	.16	.62	.00	.99	.25	.25	.54	.28	.85	.30	.62	.64	.26	.51	.84	.96	.08	.66	.55	.23	.73	.42	.48	.02	.16	.65	.02	.91	.37	.84	.20	.77	.13	.11
5	.52	.08	.59	.99	.00	.75	.37	.35	.80	.16	.20	.61	.78	.35	.38	.80	.18	.33	.88	.35	.40	.10	.07	.81	.10	.08	.48	.26	.61	.39	.14	.96	.58	.90	.09
6	.58	.90	.47	.25	.75	.00	.68	.16	.97	.55	.47	.13	.26	.59	.42	.60	.97	.21	.29	.81	.08	.63	.20	.70	.69	.52	.79	.28	1.0	.56	.88	.38	.70	.84	.47
7	.07	.99	.35	.25	.37	.68	.00	.59	.92	.15	.27	.40	.69	.73	.52	.46	.84	.93	.05	.80	.14	.33	.60	.73	.95	.32	.42	.15	.83	.72	.42	.82	.28	.81	.19
8	.76	.21	.56	.54	.35	.16	.59	.00	.97	.64	.66	.07	.07	.32	.33	.47	.52	.58	.98	.97	.41	.43	.53	.72	.56	.85	.83	.80	.31	.14	.22	.97	.97	.45	.38
9	.32	.46	.52	.28	.80	.97	.92	.97	.00	.78	.72	.18	.49	.20	.34	.66	.27	.92	.49	.11	.38	1.0	.20	.88	.48	.12	.30	1.0	.35	.37	.36	.18	.16	.18	.31
10	.14	.05	.09	.85	.16	.55	.15	.64	.78	.00	.89	.14	.79	.86	.03	.57	.09	.72	.57	.29	.57	.74	.07	.49	.22	.69	.86	.73	.41	.25	.20	.52	.06	.71	.87
11	.04	.75	.77	.30	.20	.47	.27	.66	.72	.89	.00	.42	.58	.56	.10	.75	.86	.50	.40	.65	.35	.94	.73	.96	.65	.81	.24	.22	.54	.82	.22	.75	.50	.59	.47
12	.55	.70	.35	.62	.61	.13	.40	.07	.18	.14	.42	.00	.42	.84	.18	.94	.89	.88	.32	.83	.45	.87	.44	.71	.24	.93	.10	.40	.80	.55	.12	.27	.19	.44	.50
13	.02	.84	.79	.64	.78	.26	.69	.07	.49	.79	.58	.42	.00	.92	.97	.83	.65	.23	.84	.24	.21	.26	.07	.38	.71	.47	.77	.02	.29	.73	.40	.24	.43	.63	.69
14	.25	.19	.45	.26	.35	.59	.73	.32	.20	.86	.56	.84	.92	.00	.04	.03	.48	.58	.66	.74	.29	.10	.75	.72	.58	.09	.37	.81	.92	.12	.01	.17	.18	.91	.39
15	.28	.69	.38	.51	.38	.42	.52	.33	.34	.03	.10	.18	.97	.04	.00	.16	.19	.40	.97	.92	.79	.20	.86	.94	.88	.42	.48	.87	.51	.13	.12	.31	.74	.86	.03
16	.45	.51	.69	.84	.80	.60	.46	.47	.66	.57	.75	.94	.83	.03	.16	.00	.32	.46	.91	.12	.38	.02	.64	.06	.71	.06	.45	.38	.25	.36	.34	.68	.67	.06	.05
17	.48	.90	.18	.96	.18	.97	.84	.52	.27	.09	.86	.89	.65	.48	.19	.32	.00	.60	.93	.46	.07	.80	.97	.71	.43	.79	.45	.81	.81	.76	.26	.23	.39	.15	.76
18	.68	.22	.06	.08	.33	.21	.93	.58	.92	.72	.50	.88	.23	.58	.40	.46	.60	.00	.54	.21	.98	.60	.17	.36	.36	.52	.69	.03	.18	.74	.07	.29	.9	.53	.87
19	.20	.69	.83	.66	.88	.29	.05	.98	.49	.57	.40	.32	.84	.66	.97	.91	.93	.54	.00	.50	.01	.58	.92	.79	.02	.72	.12	.77	.98	.86	.67	.64	.62	.20	.84
20	.01	.15	.60	.55	.35	.81	.80	.97	.11	.29	.65	.83	.24	.74	.92	.12	.46	.21	.50	.00	.59	.79	1.0	.94	.14	.04	.15	.68	.73	.40	.75	.02	.58	.79	.88
21	.66	.91	.16	.23	.40	.08	.14	.41	.38	.57	.35	.45	.21	.29	.79	.38	.07	.98	.01	.59	.00	.59	.31	.97	.51	.61	.98	.74	.24	.26	.23	.10	.92	.87	.23
22	.25	.59	.56	.73	.10	.63	.33	.43	1.0	.74	.94	.87	.26	.10	.20	.02	.80	.60	.58	.79	.59	.00	.64	.70	.81	.94	.22	.27	.60	.77	.93	.27	.01	.32	.53
23	.70	.74	.87	.42	.07	.20	.60	.53	.20	.07	.73	.44	.07	.75	.86	.64	.97	.17	.92	1.0	.31	.64	.00	.02	.42	.83	.42	1.0	.13	.90	.50	.26	.88	.76	.49
24	.39	.76	.26	.48	.81	.70	.73	.72	.88	.49	.96	.71	.38	.72	.94	.06	.71	.36	.79	.94	.97	.70	.02	.00	.13	.98	.10	.57	.84	.32	.20	.06	.65	.65	.79
25	.08	.59	.30	.02	.10	.69	.95	.56	.48	.22	.65	.24	.71	.58	.88	.71	.43	.36	.02	.14	.51	.81	.42	.13	.00	.43	.24	.07	.35	.51	.07	.66	.55	.61	.07
26	.34	.23	.23	.16	.08	.52	.32	.85	.12	.69	.81	.93	.47	.09	.42	.06	.79	.52	.72	.04	.61	.94	.83	.98	.43	.00	.38	.54	.59	.02	.43	.60	.27	.82	.35
27	.01	.37	.18	.65	.48	.79	.42	.83	.30	.86	.24	.10	.77	.37	.48	.45	.45	.69	.12	.15	.98	.22	.42	.10	.24	.38	.00	.28	.47	.85	.37	.03	.20	.21	.74
28	.50	.93	.01	.02	.26	.28	.15	.80	1.0	.73	.22	.40	.02	.81	.87	.38	.81	.03	.77	.68	.74	.27	1.0	.57	.07	.54	.28	.00	.77	.85	.38	.07	.27	.14	.13
29	.10	.72	.24	.91	.61	1.0	.83	.31	.35	.41	.54	.80	.29	.92	.51	.25	.81	.18	.98	.73	.24	.60	.13	.84	.35	.59	.47	.77	.00	.61	.64	.72	.78	.18	.32
30	.83	.01	.20	.37	.39	.56	.72	.14	.37	.25	.82	.55	.73	.12	.13	.36	.76	.74	.86	.40	.26	.77	.90	.32	.51	.02	.85	.85	.61	.00	.37	.07	.37	.47	.09
31	.98	.03	.82	.84	.14	.88	.42	.22	.36	.20	.22	.12	.40	.01	.12	.34	.26	.07	.67	.75	.23	.93	.50	.20	.07	.43	.37	.38	.64	.37	.00	.79	.06	.35	.13
32	.13	.30	.78	.20	.96	.38	.82	.97	.18	.52	.75	.27	.24	.17	.31	.68	.23	.29	.64	.02	.10	.27	.26	.06	.66	.60	.03	.07	.72	.07	.79	.00	.93	.14	.59
33	.11	.03	.89	.77	.58	.70	.28	.97	.16	.06	.50	.19	.43	.18	.74	.67	.39	.19	.62	.58	.92	.01	.88	.65	.55	.27	.20	.27	.78	.37	.06	.93	.00	.77	.51
34	.58	.17	.78	.13	.90	.84	.81	.45	.18	.71	.59	.44	.63	.91	.86	.06	.15	.53	.20	.79	.87	.32	.76	.65	.61	.82	.21	.14	.18	.47	.35	.14	.77	.00	.61
35	.02	.97	.91	.11	.09	.47	.19	.38	.31	.87	.47	.50	.69	.39	.03	.05	.76	.87	.84	.88	.23	.53	.49	.79	.07	.35	.74	.13	.32	.09	.13	.59	.51	.61	.00

Table 4
A tie strength matrix for run #1 with input/output quantity ratio set at 3.75

Node	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35
1	.00	.11	.32	.03	.18	.20	.17	.11	.14	.24	.15	.18	.32	.32	.25	.22	.30	.02	.29	.42	.13	.34	.12	.29	.30	.30	.18	.20	.26	.08	.01	.29	.39	.13	.19
2	.00	.00	.06	.08	.07	.02	.00	.08	.06	.09	.02	.02	.02	.08	.03	.07	.02	.06	.05	.11	.01	.08	.02	.03	.07	.11	.03	.01	.04	.12	.16	.06	.12	.11	.00
3	.02	.09	.00	.04	.03	.08	.04	.05	.01	.06	.00	.07	.01	.05	.05	.03	.11	.00	.02	.04	.09	.06	.01	.10	.06	.11	.02	.08	.05	.08	.02	.01	.01	.01	.00
4	.03	.51	.14	.00	.00	.31	.10	.21	.27	.06	.24	.15	.18	.32	.19	.06	.02	.16	.10	.20	.38	.10	.21	.23	.31	.42	.12	.51	.03	.27	.05	.34	.11	.38	.22
5	.03	.24	.06	.00	.00	.05	.05	.12	.03	.11	.10	.06	.04	.11	.08	.03	.20	.06	.02	.11	.10	.19	.12	.03	.16	.17	.05	.14	.07	.11	.16	.01	.08	.02	.12
6	.02	.03	.08	.08	.03	.00	.03	.17	.01	.06	.12	.13	.17	.07	.08	.08	.01	.14	.16	.03	.20	.11	.09	.04	.08	.10	.02	.20	.00	.08	.03	.13	.06	.04	.12
7	.10	.00	.17	.24	.20	.13	.00	.12	.02	.28	.12	.13	.12	.09	.13	.16	.08	.01	.36	.07	.22	.27	.08	.10	.02	.24	.12	.22	.06	.11	.20	.06	.31	.07	.20
8	.03	.32	.12	.14	.24	.30	.11	.00	.01	.11	.03	.15	.33	.26	.23	.19	.21	.02	.01	.01	.13	.21	.07	.10	.15	.06	.05	.04	.23	.32	.28	.01	.01	.19	.20
9	.19	.20	.16	.22	.07	.01	.00	.01	.00	.07	.04	.33	.16	.30	.24	.10	.31	.00	.06	.34	.25	.00	.31	.05	.05	.38	.19	.00	.09	.23	.09	.25	.30	.23	.03
10	.11	.54	.37	.04	.26	.25	.22	.20	.08	.00	.03	.34	.10	.06	.32	.22	.60	.07	.20	.28	.23	.14	.29	.18	.33	.17	.04	.14	.24	.31	.37	.24	.50	.13	.04
11	.11	.08	.06	.21	.28	.18	.19	.07	.03	.03	.00	.08	.13	.16	.30	.08	.05	.00	.17	.11	.11	.02	.04	.01	.10	.07	.19	.08	.13	.06	.23	.07	.17	.12	.14
12	.03	.11	.16	.05	.08	.29	.05	.36	.23	.10	.15	.00	.12	.05	.19	.02	.05	.02	.18	.03	.22	.06	.18	.08	.25	.02	.09	.28	.05	.08	.33	.18	.19	.13	.11
13	.21	.10	.10	.15	.12	.44	.10	.53	.17	.09	.10	.26	.00	.05	.02	.10	.27	.10	.08	.39	.39	.47	.40	.35	.15	.34	.08	.49	.34	.15	.35	.42	.33	.18	.13
14	.04	.21	.08	.08	.09	.08	.02	.13	.13	.02	.06	.02	.01	.00	.12	.17	.13	.04	.06	.04	.13	.20	.03	.04	.08	.17	.06	.04	.01	.15	.19	.15	.16	.01	.09
15	.13	.14	.21	.10	.21	.16	.05	.26	.16	.24	.20	.29	.01	.35	.00	.21	.39	.08	.01	.02	.07	.22	.05	.02	.03	.18	.14	.05	.12	.33	.21	.26	.11	.04	.18
16	.05	.16	.07	.03	.05	.12	.07	.15	.05	.08	.03	.01	.04	.25	.18	.00	.25	.03	.02	.25	.15	.30	.08	.28	.06	.28	.07	.15	.15	.19	.16	.07	.10	.20	.14
17	.15	.07	.45	.02	.37	.02	.04	.34	.34	.46	.06	.06	.22	.33	.43	.46	.00	.10	.03	.31	.71	.12	.02	.17	.26	.16	.23	.14	.09	.13	.38	.47	.40	.51	.08
18	.39	.41	.40	.36	.29	.38	.01	.23	.02	.11	.12	.06	.32	.21	[illegible]	.24	.25	.00	.13	.39	.01	.15	.41	.37	.17	.28	.09	.53	[illegible]	.12	.30	.28	.38	.18	.02
19	.17	.17	.06	.13	.05	.28	.22	.01	.10	.17	.10	.22	.07	.15	.01	.03	.04	.04	.00	.23	.28	.14	.02	.09	.28	.11	.28	.08	.01	.07	.09	.15	.21	.30	.03
20	.09	.22	.10	.10	.17	.07	.02	.01	.09	.11	.02	.06	.12	.08	.02	.26	.21	.00	.11	.00	.12	.07	.00	.02	.16	.33	.08	.09	.04	.17	.06	.18	.11	.03	.01
21	.05	.03	.24	.14	.17	.24	.07	.21	.10	.08	.09	.17	.19	.21	.05	.13	.36	.00	.18	.11	.00	.10	.20	.01	.09	.11	.00	.08	.13	.23	.15	.27	.03	.03	.09
22	.08	.19	.15	.04	.19	.14	.13	.25	.00	.07	.02	.04	.30	.30	.18	.37	.10	.10	.15	.06	.16	.00	.07	.06	.06	.02	.20	.30	.14	.07	.02	.33	.43	.25	.14
23	.02	.07	.02	.12	.21	.23	.05	.12	.06	.16	.01	.13	.17	.06	.03	.07	.01	.00	.02	.00	.14	.09	.00	.28	.09	.05	.06	.00	.12	.03	.09	.13	.03	.04	.04
24	.12	.15	.35	.13	.07	.15	.06	.17	.04	.19	.01	.14	.33	.15	.02	.46	.21	.16	.09	.03	.02	.14	.38	.00	.33	.01	.34	.24	.06	.33	.33	.54	.21	.16	.07
25	.01	.10	.04	.07	.04	.04	.00	.03	.08	.08	.05	.01	.05	.03	.01	.04	.09	.09	.17	.09	.05	.04	.00	.07	.00	.06	.05	.12	.12	.05	.17	.04	.06	.06	.16
26	.10	.37	.30	.21	.34	.20	.09	.08	.24	.07	.04	.03	.17	.39	.20	.38	.12	.06	.09	.35	.17	.03	.07	.01	.19	.00	.12	.23	.12	.39	.22	.15	.30	.05	.14
27	.16	.34	.29	.13	.21	.10	.14	.07	.15	.05	.12	.31	.10	.26	.18	.19	.32	.03	.34	.37	.01	.34	.18	.41	.25	.27	.00	.24	.18	.07	.22	.38	.41	.29	.06
28	.10	.04	.52	.48	.45	.40	.29	.09	.00	.11	.15	.22	.44	.12	.08	.36	.13	.09	.13	.18	.11	.43	.00	.24	.56	.27	.22	.00	.11	.09	.37	.47	.43	.42	.35
29	.10	.07	.18	.02	.10	.00	.01	.21	.05	.09	.02	.06	.12	.02	.10	.14	.06	.00	.00	.06	.17	.08	.23	.04	.07	.11	.07	.05	.00	.10	.05	.06	.06	.12	.04
30	.02	.37	.17	.12	.13	.11	.04	.21	.11	.15	.03	.08	.07	.20	.16	.14	.08	.03	.03	.16	.15	.06	.02	.16	.11	.24	.02	.04	.09	.00	.15	.23	.19	.12	.16
31	.00	.31	.03	.03	.17	.03	.07	.17	.09	.15	.09	.15	.14	.21	.15	.13	.23	.07	.08	.06	.14	.02	.08	.19	.19	.13	.08	.12	.07	.17	.00	.04	.25	.13	.13
32	.07	.21	.04	.14	.01	.16	.02	.01	.11	.08	.03	.16	.16	.19	.13	.07	.25	.04	.07	.23	.19	.19	.14	.23	.06	.10	.12	.20	.05	.24	.04	.00	.02	.16	.05
33	.06	.27	.01	.04	.07	.05	.08	.00	.09	.16	.05	.07	.12	.12	.03	.04	.14	.05	.07	.09	.01	.17	.01	.06	.07	.11	.10	.09	.04	.15	.14	.01	.00	.04	.07
34	.04	.47	.06	.23	.03	.08	.04	.22	.27	.08	.12	.17	.16	.03	.04	.40	.49	.12	.37	.08	.05	.40	.06	.13	.18	.08	.14	.39	.36	.19	.32	.30	.09	.00	.14
35	.11	.01	.02	.27	.27	.14	.16	.11	.05	.04	.02	.07	.10	.15	.21	.16	.08	.00	.04	.04	.08	.09	.07	.07	.15	.15	.05	.09	.15	.35	.14	.10	.19	.10	.00

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