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Information Diffusion among Agents: Implications for Humanitarian Operations

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The basis for this article is an information-processing view of the UN's cluster approach. We use agent-based modeling and simulations to show that clusters, if properly utilized, encourage better information flow and thus facilitate effective response to disasters. The article intends to turn the attention of the humanitarian community to the importance of sharing information and the role of cluster leads in facilitating humanitarian aid. Our results indicate that if cluster leads act as information hubs, information reaches its target faster, enabling a prompt humanitarian response. In addition, we show that information quality is critical for effective resource utilization—if cluster leads filter information, it moves faster. We also found evidence that the willingness to exchange information plays a larger role in transmitting information than that of an information hub, particularly during later stages of response operations.

Key words: humanitarian logistics; cluster approach; disaster response; coordination; information flows
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1. Introduction

The 2010 earthquake in Haiti killed more than 200,000 and displaced millions. Three weeks after the quake, the UN Office for the Coordination of Humanitarian Affairs (OCHA) reported 2000 organizations and agencies were operating on-site (IASC 2010). However, the plethora of actors participating in relief operations makes sharing information and coordinating relief difficult (Balcik et al. 2010). While information is a critical enabler for inter-organizational coordination (Maitland et al. 2009), a lack of coordination leads to duplication of efforts, wasted resources, and slow relief efforts (Thévenaz and Resodihardjo 2010). An examination of information-related issues among humanitarian agencies involved in the Haiti response reveals that a variety of impediments to information flow considerably hindered coordination (Altay and Labonte 2013).

Information sharing, cooperative communication, and joint knowledge creation are all identified as collaboration mechanisms (Cao and Zhang 2011). Thus, proper information collection, sharing, and processing mechanisms would lead to effective coordination and efficient operational outcomes (Loch and Terwiesch 2005). The inter-agency flow of information in humanitarian operations is closely associated with data collection, information processing, and sharing. These activities directly impact resource flows (Day et al. 2009) and coordination (Schulz and Blecken 2010). Information sharing and coordination during inter-agency response also improve the effectiveness of response (Van Wassenhove 2006). When information is dispersed across responding organizations, relief capacities strengthen as a result of coordination (Thévenaz and Resodihardjo 2010). The idea of the cluster approach (CA), the UN's humanitarian coordination and response structure, arose from this necessity to create a systemic capability to ensure a coordinated response through the facilitation of information exchange (Adinolfi et al. 2005, OCHA 2006).

Prior to the roll-out of the CA, little coordination occurred among humanitarian actors. In 2005, the humanitarian response review (HRR) identified gaps in coordination, preparedness, and response. HRR found, among other issues, problems with information exchange (no coordinating body existed) and recommended strengthening the overall response capacity by developing clusters comprised of stakeholders with a designated lead agency in gap areas like service provision (emergency telecommunications, logistics), traditional relief and assistance sectors (water/sanitation, nutrition, health, emergency shelter), and cross-cutting issues (camp coordination/management, early recovery, protection). A core activity of a cluster is indeed information management and exchange (HIME) (Jahre and Jensen 2010). Clusters facilitate information dissemination to all responding organizations (Eikenberry et al. 2007). Lead agencies are responsible for strengthening technical capacity and ensuring predictable leadership, accountability, and partnership (OCHA 2006). Implementation of the CA, however, revealed high levels of confusion among agencies regarding the roles and duties of cluster leads as well as an agency's capacity to execute designated mandates (Altay and Labonte 2011). Consequently, not all clusters were effective in coordinating response operations. In Haiti, the head of OCHA at the time, John Holmes, expressed his concern that the CA was not working as planned. He pointed out that even one month after the quake only a few clusters were fully functional as *information management focal points* among other roles (Lynch 2010). These reports indicate the need to explore the roles the lead and member agencies should play in managing and sharing information.

Galbraith's information-processing view of organizations (IPV) offers a fitting solution for disaster response scenarios. Based on IPV "the greater the task uncertainty, the greater the amount of information that must be processed among decision makers during task execution in order to achieve a given level of performance" (Galbraith 1974, p. 28). Organizations can plan ahead to respond to well-defined tasks. But if the task is not understood or its scope changes, then more information is needed during execution of the task. Incoming information needs to be processed promptly, as this can lead to changes in a task's resource allocations, schedules, and priorities.

Thus, on the basis of the IPV and coordination theory, we visualize the cluster lead as an information hub and propose three information-processing roles: facilitator (distributes information to agents regardless of relevance or quality; goal is to disperse information as fast as possible), broker (moves information based upon relevance but does not check quality), and filter (similar to broker but filters out low quality or unreliable information).

Given there are also inter-agency exchanges of information, this article investigates how information diffuses in such a cluster-oriented system and how it could be improved to enhance effectiveness of response. Our intent is not to explain coordination, but to shed light on the discussion among humanitarian practitioners on what roles the cluster lead and member agencies should play for better information flow.

We utilize agent-based modeling and simulation (ABMS) to create a theoretical space where agents roam freely and investigate the impacts of the three roles on information diffusion. We also look at the effects of trust and agencies' willingness to share information as well as the impact of information quality on task completion and resource utilization. While this article is a first attempt in exploring these issues, our results have important implications for within-cluster information sharing mechanisms, potentially leading the way to better coordination for effective response.

In the subsequent section, we develop a theoretical framework for information diffusion in the context of the humanitarian world, introduce our hypotheses, and anchor the three roles of information hub with respect to this framework. In the third section, we describe the agent-based simulation setup, and, subsequently, in section four, we discuss the experimental results and their managerial and policy implications. In section five, we discuss the limitations of our study and future research directions. Finally, section six concludes the article.

2. A Theoretical Framework for Information Diffusion

The complex and dynamic nature of disaster response can be identified by the large number of dissimilar factors and components in the environment which are in a continual state of change (Duncan 1979). IPV suggests lateral coordination (i.e., decentralization) when tasks are significantly diverse, the work environment is rapidly changing, units are interdependent, efforts are process-focused, and prompt delivery is critical (Galbraith 1995). In the wake of disaster, uncertainty is high, as is the need for quality information. Efficient exchange of information may actually reduce uncertainty in the decision-making process (Schweitzer et al. 2002). Therefore, organizations operating in complex environments must adopt lateral coordination mechanisms that would enhance their information-processing capabilities and/or reduce the need to process information (Galbraith 1974). In IPV, an organization's structure links its units by providing the channels of communication through which information flows and facilitates effective coordination among its units (Duncan 1979). The latter becomes particularly important when the units are loosely interdependent. These units can be grouped around tasks or products using three basic types of lateral processes: voluntary groups, formal groups, and formal groups with an integrator as lead (Galbraith 1995). In the humanitarian world, clusters provide such a platform for lateral coordination among peer agencies (Simatupang and Sridharan 2002).

IPV argues that the integrator role is the most difficult to execute because it introduces confusion over roles and responsibilities in addition to an element of conflict (Galbraith 1995). This does explain some of the initial complaints about clusters mentioned in the previous section. Although there are many other factors affecting coordination within clusters, our position is that efficient diffusion of relevant and reliable information leads to a better response. On the basis of evidence from humanitarian operations and crisis management (HOCM) literature, we posit that information quality, willingness of agencies to exchange information, and the information-processing role cluster leads play directly affect information diffusion among members (Figure 1). In the following subsections, we explain the components of our proposed framework and introduce our hypotheses.

2.1. Information Quality

We define quality information as correct and relevant. In the humanitarian context, lateral coordination facilitates sharing information about the needs of the affected population, availability of resources, and the overall disaster situation (Zhang et al. 2002). Due to the sudden nature of disasters, information comes from a multitude of sources, changes constantly, may not be immediately available, or may be unreliable (Altay and Green 2006). It is the lack of comprehensive and cross-functional information rather than the absence of information that affects disaster response operations the most (Altay 2008). Senior UN staff members have acknowledged that "just as the uncoordinated arrival of relief supplies can clog a country's logistics and distribution system, the onslaught of unwanted, inappropriate and unpackaged information can impede decision making and rapid response to an emergency" (IRIN 2002). Consequently, we propose the following:

Hypothesis 1. *Better information quality will improve diffusion of information and lead to a superior response.*

2.2. Willingness to Exchange Information

Since nongovernmental organizations (NGOs) compete on donor funding, media attention, and local resources, they are often unwilling to share information, which creates serious barriers to effective response (Bharosa et al. 2010, Wakolbinger and Toyasaki 2011). An attitude of guardedness about information sharing prevails as individual groups seek to ensure the "niche" value of information for their organizations (Perry 2007). Based on a series of interviews with Hurricane Katrina relief agencies, Day et al. (2009) identified unreliable data and the unwillingness of agencies to share information along with the low priority of information as impediments to information flow. Separately, serious delays have been found in "compiling and sharing comprehensive data on the number, location, and activities of humanitarian organizations, and on sectorial needs, coverage and gaps. Delays can be attributed, in large part, to a lack of willingness by agencies to prioritize reporting on activities, particularly in the initial stages of the response" (IASC 2010, p. 24). Consequently, we posit the following:

Hypothesis 2. *As humanitarian agencies are more willing to exchange information, diffusion among them improves.*

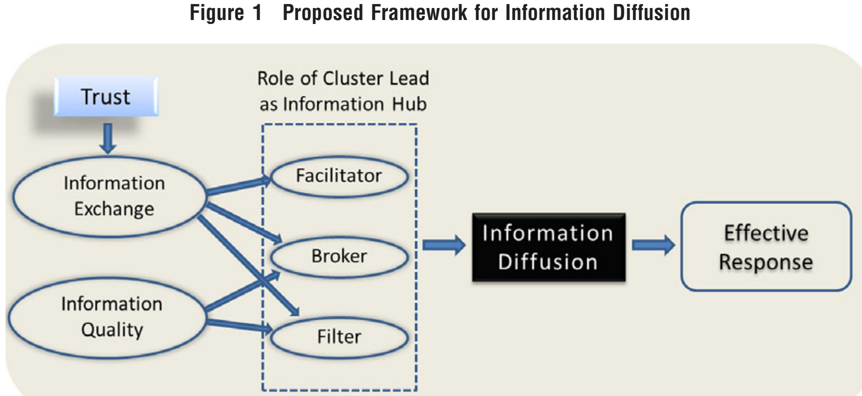
An agency's willingness to exchange information will depend on whether it has a trusted relationship with its counterparts (Thompson 1991). The speed with which agencies build a trust-based relationship and start sharing information is also important. An agency may build trust quickly or it may be skeptical, gaining trust slowly (Ebrahim-Khanjari et al. 2012). Hence, we suggest the following:

Hypothesis 3. *The faster the agencies build trust, the better the information diffusion.*

2.3. Role of Cluster Lead as Information Hub

After a disaster, information comes from all directions and in all forms. Therefore, Brown (1966)

Figure 1 Proposed Framework for Information Diffusion



suggests standards for HIME to regulate the flow of information across organizational boundaries. While cluster members may agree to share information, without standardization and shared HIME strategies most attempts to coordinate will fail (Maitland et al. 2009). Galbraith (1974) argues that the role of an integrator proves particularly useful in implementing shared HIME strategies when organizational units are different from one another in terms of structure, goals, and orientation (as humanitarian actors usually are). This role is a good fit for cluster leads in the CA. An effective integrator should be a trusted partner that possesses wide contacts in the cluster, understands the goals and orientations of different groups, and exerts influence based on its expertise rather than through a formal command and control mechanism (Lawrence and Lorsch 1967). Consequently, an agency placed in the information flow pattern of the organization acting as a clearinghouse should command the "integration, evaluation, and comparison of various kinds of information coming to the organization" (Brown 1966, p. 326). NGOs and local groups may not have the capacity and capability to process this information overload. On the other hand, UN agencies such as the World Food Program may either have these capabilities to handle large amounts of information or have access to the necessary resources to develop them. Thus, we postulate the following hypothesis:

HYPOTHESIS 4. *The lead agency of a cluster acting as an information hub will improve diffusion of information.*

The three roles we identified (facilitator, broker, and filter) are derived from Brown (1966), and they become particularly critical when an organization's information systems get overloaded and inputs constantly change. Individual units may respond to these dynamic situations by omitting information, delaying response, taking *ad hoc* decisions, and filtering incoming information (Meier 1963). Thus, the information hub should take on roles that combat such misguided responses.

First, the cluster lead may act as a *facilitator*. In this role, information is collected and swiftly made available to all humanitarian agencies without any filtering and regardless of relevancy. Consequently, while the agencies' willingness to exchange information may affect the ease of information gathering, quality would be unaffected since filtering has not yet occurred.

Second, the cluster lead may act as an *information broker*. This role improves upon the facilitator role by sending information exactly where it is needed. The broker should have prior knowledge of who needs what type of information and send only relevant information to an agency. While only certain humanitarian agencies take part in disaster relief, the UN agencies are active in most. They provide the continuity and organizational memory needed for effective coordination. As the CA becomes widely implemented, cluster leads will be able to establish tighter relationships with participating agencies and better understand their information needs. Without a broker, information is less likely to find a relevant target and inevitably delay effective response.

Third, the cluster lead may act as an *information filter*. This role not only passes relevant information to agencies but also checks its reliability. Based on his experience with the US Military, Weeks (2007) suggests that creating a central collection point for filtering and disseminating information should improve humanitarian aid. As such, the information hub acts as a clearinghouse, processing and sifting through information and discarding inaccurate, malevolent, or simply useless pieces. Since the facilitator role is the basic information hub without any capability of processing information, one would expect that brokered and filtered information should improve information diffusion and therefore effectiveness of response. Consequently, we suggest the following:

HYPOTHESIS 5. *The information hub's assumption of a filter role will result in better information diffusion and response than when it assumes a broker role.*

3. Methodology

We utilize ABMS to investigate the impact of the above-mentioned factors on information diffusion. Although developing analytical models is a possible methodological approach, without access to data on information diffusion, they cannot go beyond elaborate simulation models. In addition, such analytical models often require restrictive assumptions. While traditional differential equation models (DEM) can capture the aggregate-level interactions of the system's constituent units, non-linear discontinuous behavior of individual entities is difficult to model using DEM. Aggregate-level differential equations also tend to smooth out fluctuations observed at the individual level, and the complexity of equations increases drastically as the complexity of behavior increases (Bonabeau 2002). On the other hand, in ABMS the behavior of the system emerges out of interactions among the individual constituents of the system, which in turn change their behavior in response to system changes. Because of its dynamic and microscopic nature, ABMS captures the emergence of overall behavior of the system using a bottom-up approach and provides more meaningful insights than a top-down approach. This is particularly useful when agents are autonomous (Macal and North 2009). In our context, agencies involved in a disaster are independent entities that determine actions based on their interactions. Thus, ABMS fits naturally to be a suitable approach for exploring the complex behaviors of these entities during disasters.

Since ABMS accounts for individual entities, aggregation of information is easy to attain, but additional insights may be obtained from disaggregate-level data, making ABMS a valuable modeling tool despite its inherent computational cost. Also, ABMS offers significant flexibility in changing levels of description and aggregation by grouping and subgrouping agents and in terms of complexity by varying agents' behavior, ability to learn and evolve, and rules of interactions. Humanitarian relief agencies act autonomously, but collectively form a "complex adaptive system" (North and Macal 2007, p. 11), and the emerging behavior is the focal point of analysis.

3.1. Agent-Based Model and Simulation Setup

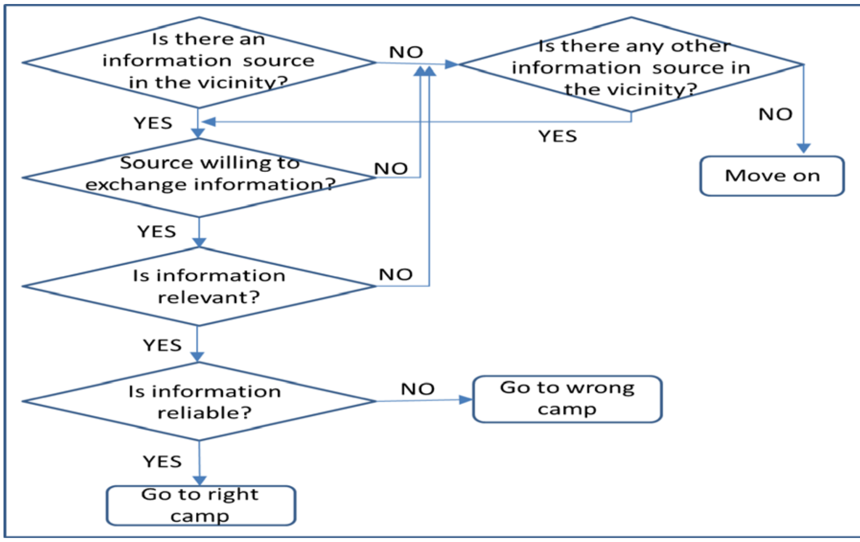
We consider a theoretical cluster of humanitarian agencies in a generic location where the agents can freely move anywhere. The cluster consists of four distinct sets of agents: hub, seekers of similar type, seekers of different type, and injectors. The *hub* is a single agent (representing the cluster lead) and assumes one of the three previously discussed roles. The humanitarian agencies, including international nongovernmental organizations (INGO)s, NGOs and other humanitarian actors, look for information to carry out their operations and are modeled as *seekers* (who receive and act upon information). It is reasonable to expect that humanitarian actors will go to the cluster lead for information (e.g., visiting the cluster web site, going to cluster meetings, or contacting the lead agency directly). While the humanitarian agencies can receive information from direct interactions with the cluster lead (hub), their peer agencies (seekers of same type), and other agencies (seekers of different type), it is also possible to obtain information from interactions with other sources, including media reports, donors, beneficiaries, local government, and other cluster leads. These sources outside of the cluster act as alternative carriers of information, and we use four *injectors* to simulate their role in our experiments.

In disaster situations, different agencies may choose to respond to different needs and/or areas. We use camps to represent this reality. Each seeker's objective is to find a designated camp. This signifies task accomplishment and illustrates resource requirements because seekers that receive bad information end up wasting time (i.e., a scarce resource). We utilize four sets of 100 seekers where each seeker should receive information for one of the four camps to which it intends to respond. The hub and the injectors carry relevant information to all four camps. While the total number of seekers (400) and injectors (4) do not represent a specific scenario, their relative magnitude may characterize a generic disaster situation. Our model is not an attempt to mimic a specific scenario such as Haiti. Rather, it is an abstraction of what happens during an international humanitarian response in which the CA is activated so as to make inferences about the effectiveness of HIME.

Initially, in many situations, humanitarian agencies may not have information on where and how to respond after arriving at the disaster area. Thus, we assume that these agencies enter the disaster zone free of any information and search for information sources. Injectors bring the initial piece of information into the cluster. While larger INGOs have their own assessment teams supplying situational data, they still depend on other sources for key information such as location of resources, transportation options and schedules, supply conditions, and needs of the affected population. This search process in the simulation model does not involve physical movement; rather it utilizes precious resources (represented here by time). At the initial phase of a response, chaos prevails and clear communication channels may not be established. Searching for information without knowing the details of appropriate information sources may be represented by a random search as described above. Note that humanitarian agencies may have prior knowledge on whether/where to attend a cluster meeting and/or which peer agencies to approach for information. Thus, humanitarian agencies may be more effective in gathering information than the random search assumptions used in the simulation model, which would possibly worsen the seekers' performance. Nonetheless, considering the lack of clear communication channels due to the chaotic nature of the initial response phase, the random search assumptions are not far from reality.

Figure 2 describes the decision rules a seeker utilizes during the simulation. Each seeker searches for information sources in its vicinity (i.e., within one distance unit in all directions). Once a seeker receives information, it cannot evaluate its reliability (i.e., whether an address is correct or not) until it reaches the camp. One may argue that a humanitarian agency can update information before reaching the wrong camp and change its course. Many humanitarian agencies, however, may not have this capability, and for the sake of simplicity, we stick to the worst-case scenario where error is not detected until the destination is reached. After arriving at the wrong camp, the seeker realizes the mistake, leaves the camp, and continues to search for the correct information. Alternatively, if the seeker arrives at the correct camp, then it

Figure 2 Decision Rules Used to Model Seeker Behavior



may pass this information along to other seekers it comes across. A seeker that accomplishes its task will share only reliable, confirmed information with other seekers. The simulation continues until all seekers find their respective camps. This setup allows us to also explore resource utilization, since two types of resources—information and time—are needed to execute an assigned task. Thus, if resources are misallocated, it takes longer for the seekers to find their respective camps.

The set of probability values that is used to design the behavior of each agent can be found in Table 1. While the probability values used here are somewhat subjective, their relative orders are based in reality. For example, probability of exchange value of 1.00 for the hub denotes that the cluster lead acting as an information hub will always pass information. However, since the facilitator role does not require the cluster lead to know the intended recipient of information or whether it is reliable, the probabilities for relevance and reliability are 0.50. As the cluster lead becomes a broker, we assume it knows where information belongs, and the probability of relevance is thus 1.00. In the filter role, we assume the cluster lead can tell whether information comes from a reliable source and will share reliable information with a probability of 1.00.

Table 1 Base Probability Values Used in the Simulation Experiments

Agent type	Prob of exchange	Prob of relevance	Prob of reliability
Hub as facilitator	1.00	0.50	0.50
Hub as broker	1.00	1.00	0.50
Hub as filter	1.00	1.00	1.00
Injectors	0.50	0.50	0.50
Seekers (same type)	0.25	0.50	0.50
Seekers (different type)	0.25	0.25	0.25
Successful seekers	0.25	1.00	1.00

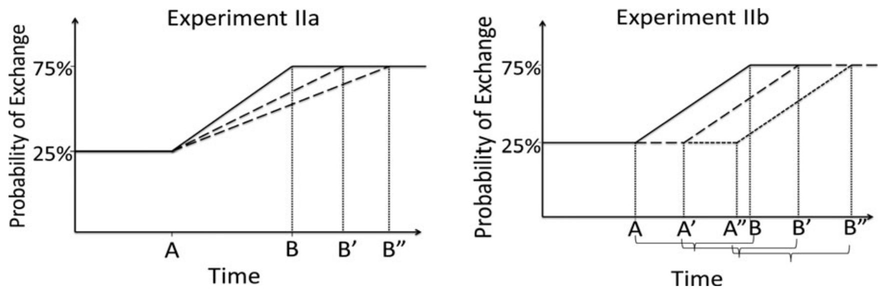
On the other hand, inherent competition resulting in potential withholding of information is characterized by the lower probability values of exchange among seekers. Seekers will be able to provide more relevant and reliable information to other seekers of the same type. Thus, the corresponding probability values are higher for the same type of seekers. For seekers successfully completing assignments, the probabilities of relevance and reliability values are set to 1.00.

While we did not use an explicit network topology for information dissemination, we used a graduated scale in parameter settings to maintain relative propensity of exchange and levels of quality. We capture high-level interactions among the cluster lead, humanitarian agencies, and other parties with fairly accurate details. Given certain agencies' abilities to update information more efficiently, in reality the system performance would be slightly better than what we see here. Thus, the results from our simulation model serve as a lower bound on system performance. Nonetheless, our high-level model should provide meaningful insights; the assumptions are not too restrictive and realistic interactions among agents are captured with sufficient detail.

3.2. Simulation Experiments

Five sets of experiments were conducted: Experiment I focuses on the willingness of agents to exchange information, which demonstrates unintended consequences of this behavior and changes the probability of exchange for the seekers of same type and the successful seekers. The probabilities of exchange for the seekers of same type and the successful seekers have

Figure 3 Time-Based Trust-Building Process Used in Experiment II as Represented by the Probability of Information Exchange



been kept equal throughout the experiments but increased together at increments of 0.25.

Experiment II investigates the effect of trust building among agents. We assume trust emerges from subtle interactions among agents and trustworthiness changes with time (Birk 2000). We devise a rudimentary time-based trust-building process which linearly increases the probability of information exchange after a predetermined threshold, A (as shown in Figure 3). Once the agents' trust level reaches point A they slowly build trust (between points A and B). Experiment IIa investigates the effect of the trust-building rate. Point A was kept constant at time unit 30, while B, B′, and B′′ were kept at time units 60, 75, and 90, respectively. Experiment IIb examines the effect of the length of time to reach the threshold while the rate is kept constant. Explicitly, time between A and B, A′ and B′, or A″ and B″ is constant and A, A′, and A″ are 30, 45, and 60, respectively.

Experiment III investigates the impact of the three roles of information hub in information diffusion. Experiment IV explores the impact of information quality on resource utilization. Improvements in quality of information is simulated by three points in time after the disaster (initial days, middle of the process, and late in the response), where the reliability probability for seekers of the same type grows from 0.00 to 0.25 to 0.50. However, the relative magnitude of probability values among all agents is kept constant. Consequently, the probability of reliability for seekers of different types during the initial days is truncated to 0.00 as the relative difference to seekers of the same type is 0.25. Table 2 shows the information reliability probabilities used in this experiment. The exchange and relevance probabilities were kept consistent with those in Table 1. Since this experiment is about information quality, all simulation runs use only the filter role for the hub.

Experiment V focuses on robustness tests. They are useful when data on information networks and distributions of an agent's attributes are unknown or highly uncertain (Rahmandad and Sterman 2008). It is important to see how changes in probability values and number of agents influence results. We maintain

Table 2 Information Reliability Probabilities Used in Experiment IV

Agent type	Initial days	Midpoint	Late in the response
Information hub as filter	0.50	0.75	1.00
Injectors	0.25	0.50	0.75
Seekers (same type)	0.00	0.25	0.50
Seekers (different type)	0.00	0.00	0.25
Successful seekers	0.50	0.75	1.00

the relative order of these values to ascertain reality when conducting sensitivity analysis. While the magnitude of the performance measures may vary with changing parameter values, we expect the general implications in Experiments I–IV will hold true. We utilized a $3 \times 3 \times 3$ full factorial experimental design, with the number of seekers in each type (20, 60, 100), number of injectors (4, 8, 12), and probability values of exchange, relevance, and quality for the seekers (low, medium, high) being varied across three levels. The medium level has the same values as reported in Table 1, while the low and high levels are established by reducing and increasing base values by 0.15, respectively.

In all experiments, we used two performance measures: *total time* and *fixed time window seeker count* (or *seeker count* for short). The first measure, *total time* (measured in discrete time units called "ticks"), is the time it takes for all seekers to reach their designated camps. The second measure, *seeker count*, is the number of seekers that reach designated camps in a specified time window. This second measure is used to capture the efficacy of information diffusion in the early stage of response since the initial effect of the information hub and injectors will be diminished as the number of information-carrying seekers increases. Moreover, an information hub will play a critical role at the beginning of a response since initial information is expected to be of low quality. We used the first 25 ticks to check seeker count in all experiments except Experiment II (for which it was 100 ticks).

Simulation experiments were conducted using NetLogo 4.1 (Northwestern University, Evanston, IL), a multi-agent programmable modeling environment.

Each experiment set contains 30 repetitions. Each repetition utilizes a given random number seed to control variance within the sample (e.g., a simulation run compares the three roles of a cluster lead and uses the same random seed for each role).

4. Discussion of Results

Overall, experimental results indicate that an information hub makes diffusion faster. In addition, our results show that information quality is an important factor in resource utilization, and if cluster leads act as information filters, information moves faster and resources are better utilized. The evidence also suggests that willingness to exchange information has more of an impact on information diffusion than the existence of an information hub. Results also imply that the threshold for trust building is more important than the rate of trust building. Finally, our sensitivity analysis indicates that our model is robust and behaves as expected when model parameters change.

4.1. Impact of Willingness to Exchange Information

To isolate the effect of willingness to exchange information among seekers, Experiment I was run without an information hub. If seekers do not exchange information, information can only be transmitted through injectors, and total time rises above 3700 ticks. The reduction in total time, even with 0.25 probability of exchange, is drastic—down to 160.63 ticks. Results are presented in Figure 4. An analysis of variance (ANOVA) shows that the differences in averages of total time and seeker count metrics between different exchange probabilities are statistically significant with p-values of 7.89×10^{-44} and 1.25×10^{-16}, respectively.

Clearly, these results support Hypothesis 2: as humanitarian agencies are more willing to share information, diffusion among them improves. Even a slight increase in willingness will have a significant impact on information diffusion. Figure 4 indicates that the reduction in total time slows down as exchange probability increases, while this is not true for seeker count. Information sharing is critical during the initial stages of a response, but as an increasing number of agents carry information (and information becomes easier to access), the exchange becomes less vital.

4.2. Impact of Trust on Information Exchange

Results of Experiment IIa show no statistically significant difference between different rates of trust building, while the differences in total time and seeker count for various threshold points in Experiment IIb are statistically significant only at $\alpha = 0.15$. Therefore, we only report the results of Experiment IIb in Figure 5. Due to their low statistical significance, our results do not provide support for Hypothesis 3: the faster the

Figure 4 The Impact of Willingness to Exchange Information on System Performance

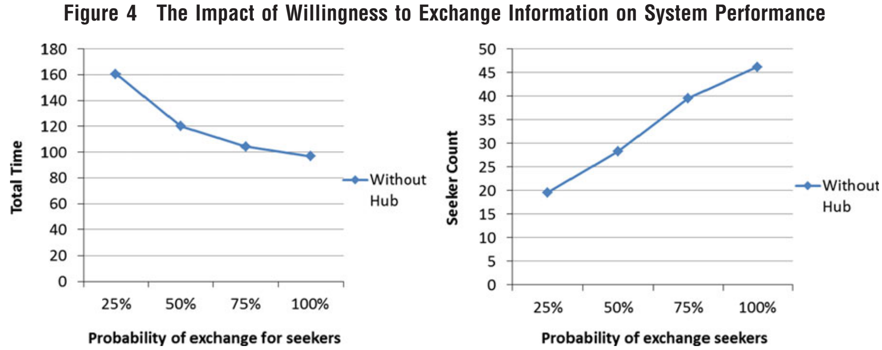
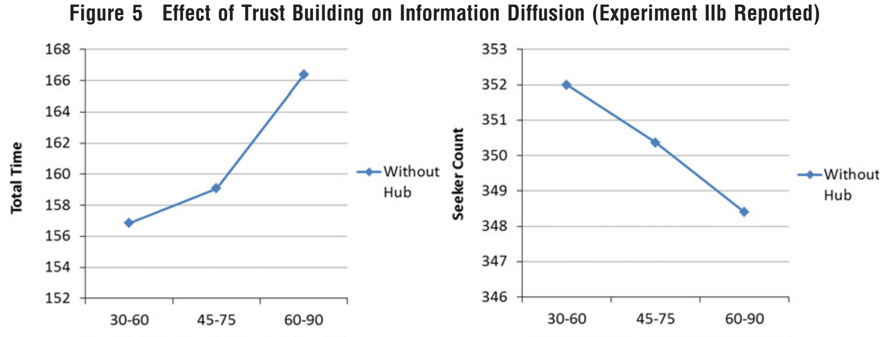


Figure 5 Effect of Trust Building on Information Diffusion (Experiment IIb Reported)



agencies build trust, the better the information diffusion.

Experimental results, however, do indicate the time it takes the agents to reach a trust threshold (point A) to be more important than the rate of trust building. Experiment I showed that information sharing is much more important at the beginning of a response operation than it is toward the end. Basically, the threshold in Experiment II is a delay in exchange probability increase. Until point A, seekers receive information either from injectors or other seekers, where exchange probability is still 0.25. Therefore, once the threshold hits 30 ticks, at least 20–25 seekers have been successful and roam the area. By the time the exchange probability reaches 0.50 or 0.75, the importance of information sharing has diminished. As a result, we do not see any significant difference in the results of different rates on increasing the probability of exchange.

4.3. Impact of Information Hub and Its Information-Processing Role

While Experiment I showed that without an information hub it takes, on average, 160.63 ticks for all seekers to find their respective camps, Experiment III examines the impact of a cluster lead as information hub. Even simply acting as a facilitator, a hub improves total time by 3.2% compared to a no-hub scenario. Comparing the filter role to facilitator, the total time improves by 5.3%. Since bad information wastes seekers' time, the filter role gives the best results.

Figure 6 shows system performance based on the two metrics we used. As in the first experiment, the impact of having an information hub is emphasized at the beginning of a response as indicated by the increase in seeker count. If the cluster lead acts as a facilitator, seekers reaching their intended destination within the first 25 ticks increases by 54.2% compared to a no-hub scenario. Changing this role from facilitator to filter improves it by an additional 46.3%.

ANOVA results show that differences in averages for total time and seeker count among the three roles are statistically significant, with p-values of 0.073255 and 4.29×10^{-10}, respectively. Similarly, two-tail t-tests (assuming unequal variances) indicate that the difference in performance with respect to total time and seeker count between the filter role with and without hub scenarios is statistically significant, with p-values of 0.00138 and 6.34×10^{-18}, respectively.

These results support Hypothesis 4—the lead agency acting as an information hub will improve diffusion—and Hypothesis 5—information hub's assumption of a filter role will result in better information diffusion and response than when it assumes a broker or a facilitator role.

4.4. Impact of Information Quality

The results of Experiment IV as presented in Figure 7 show that information quality is indeed critical for the

Figure 6 The Impact of Having an Information Hub on System Performance

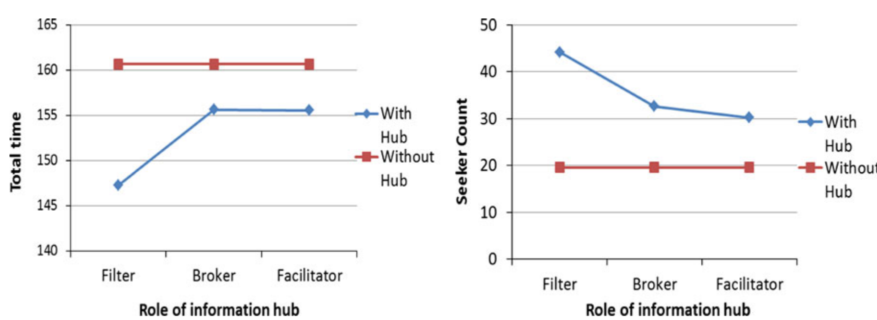
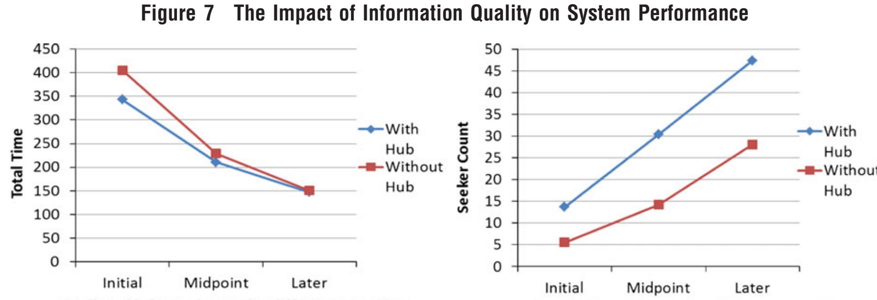


Figure 7 The Impact of Information Quality on System Performance



effectiveness of response, supporting Hypothesis 1. As expected, the effect of the filter on total time diminishes as information quality increases in the system. This implies that late in the response, as an increasing number of successful seekers are roaming around sharing quality information, the difference between having a filter and not having one diminishes. It is worthwhile to note that although the hub and no-hub results appear close in the total time graph, two-tail *t*-tests (assuming unequal variances) indicate that the difference between them are statistically significant except for late in the response (*p*-value of 0.47594).

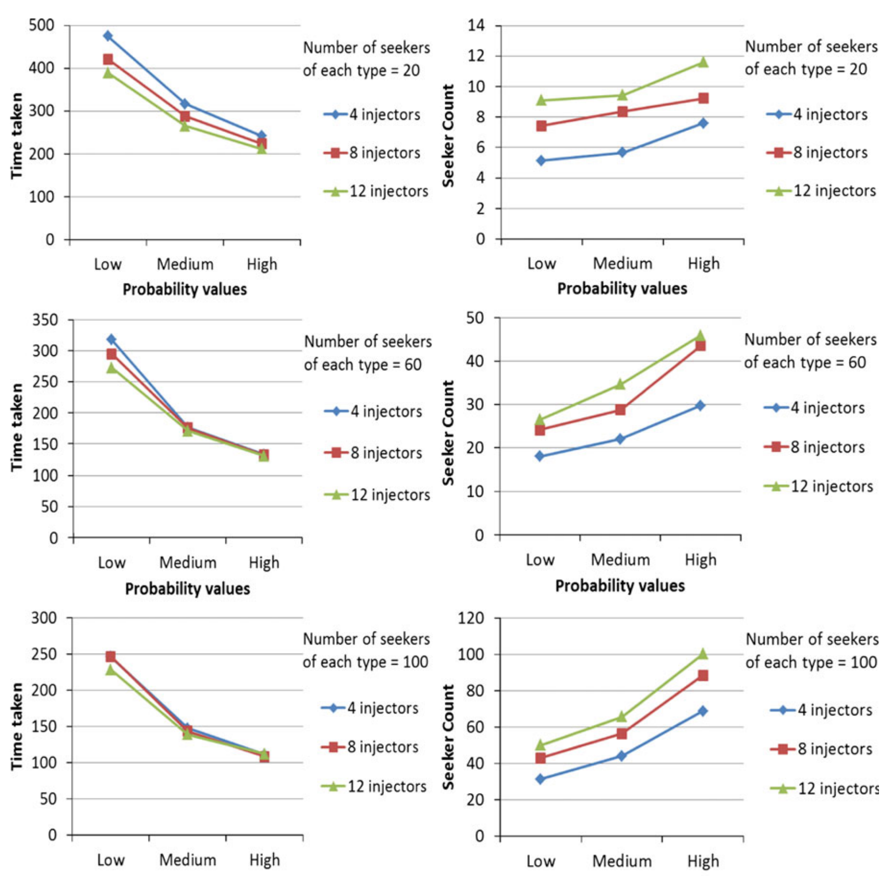
Having an information filter clearly accelerates information diffusion, especially during initial periods of response. Employing a filter from the beginning increases the number of seekers accomplishing tasks within a fixed time window as indicated by significant *p*-values for every scenario (3.19×10^{-12} for "initial," 5.36×10^{-15} for "midpoint," 1.58×10^{-10} for "later").

4.5. Robustness Tests

The robustness of ABM is tested through Experiment set V. Figure 8 shows that our model behaves as expected even when system parameters such as probabilities of exchange, relevance, reliability, number of seekers, and number of injectors are varied. The three-way ANOVA for seeker count shows significance at the $\alpha = 0.05$ level for all three factors: probability values of seekers (exchange, relevance, and quality), number of seekers, and number of injectors, and their two-way and three-way interactions. For the total time measure, all main effects and interactions (except the three-way interaction) are significant at the $\alpha = 0.05$ level.

Figure 8 also shows that as the probabilities increase, total time goes down and seeker count goes up. Results also validate the importance of information sharing during the initial stages of response. Information can diffuse without injectors as these probabilities increase. Therefore, the impact of the number of injectors on total time disappears. But the same is not true for seeker count. Because this metric focuses on the initial period of response, when every bit of information counts, the difference between having 4, 8, or 12 injectors is significant. Furthermore, seeker population makes a difference. As the disaster zone is attended by more agencies, the chances for them to find each other and exchange information is higher.

Figure 8 Results of Robustness Tests



4.6. Implications of Results

Our research has important managerial and policy implications. While the debate on the usefulness of the cluster system remains open, our research indicates that clusters are useful and the cluster lead plays a significant role. Cluster leads should act as "filters" at best and as "facilitators" at minimum to promote information diffusion among agencies. For cluster leads to play a facilitator role, they need to invest in information dissemination technology infrastructure (such as web pages, radio and TV announcements, and physical and virtual meetings). To act as a hub, cluster leads must be actively involved in every disaster, demonstrate ownership of operations, and establish long-term relationships with humanitarian agencies. For the filter role, lead agencies need to create and nurture organizational memory and develop an understanding of member agencies' informational capacity and operational capabilities. A certification system for humanitarian agencies that assesses their capabilities may be useful, although its implementation may prove controversial.

The second important finding is that the willingness to exchange information has a bigger impact on information diffusion than the presence of an information hub. This finding sends a profound message to the opponents of CA, suggesting that they must share more information than they currently do under the CA. Unfortunately, since humanitarian agencies compete for donations and media attention, they sometimes refrain from sharing information. Our finding presents an either/or scenario to agencies: either work with clusters or share more information with others.

Managerial implications for humanitarian agencies are simple: avoid operating in isolation by joining an appropriate cluster. Use the cluster lead as an information source but gain access to as many other sources as you can at the beginning of the response. Our experiments show that the more willing the agencies are to share information, the better the response, and trust promotes exchange. Agencies should share information and develop partnerships to build trust long before a crisis occurs. This means that if agencies recruit crews who are familiar with each other and have already established a level of trust, information diffusion would improve.

5. Limitations and Further Research

5.1. Limitations

This study is exploratory in nature. Although the agent-based simulation model provides a reasonable illustration of information diffusion dynamics among humanitarian agencies within a cluster, it does not provide a replica of reality. The benefit of an information hub is somewhat overestimated in the article, but the potential of improved diffusion is real. The model and its results provide a solid lower bound to information diffusion. Our simulation captures different major sources of information, the dynamic nature of information quality, and willingness of agencies to share information. But the model assumes that cluster leads have the capacity to act as information hubs and humanitarian actors start fresh each time they arrive to a disaster site. In reality, agencies have varying capacities and capabilities for acquiring information which may not be reflected by the random roaming idea we utilized. Thus, our model provides a "worse case" result and does not capture well the interdependent nature of humanitarian response.

5.2. Future Research Directions

Although the simplistic simulation model is still quite insightful, the precision of it could be improved. First, we could use smart agents who optimize their decisions. They would have an assigned capacity to obtain and capability to process information, learn from their mistakes, and modify their behavior. We could also increase the diversity of seeker types to represent various humanitarian actors. Second, a capacitated information hub would be more realistic. Third, utilizing social network theory, a network topology could be used to model social connectivity of agents, rather than an agent randomly roaming. Fourth, the concept of information is simplified in the article and could be improved by understanding what "quality information" specifically entails and how it initially evolves. Using different types of information (e.g., situational, beneficiary/agency needs, infrastructure status, security) and identifying their cross-correlations (e.g., x may point to the location of need, y to available transportation routes, and z to the security of these routes) would allow us to implement a collective intelligence in the model. And fifth, the rudimentary trust models we used can be replaced with more sophisticated frameworks. Research on quick response programs in commercial supply chains shows that faithful sharing of information does not necessarily happen naturally (Choi and Sethi 2010). Trust can be built between two organizations over time, but, on an interim basis, appropriate auction systems, markets, or incentive schemes must be employed.

This article also opens avenues in HOCM for future research on HIME. For example, in addition to diffusion problems, information distortion in confined areas such as refugee camps poses a serious issue for the livelihood of many people. Separately, the impact of social media, crowd-sourcing, and mobile phone technology on humanitarian information flow is not yet well understood. Lastly, effective coordination using the CA depends on inter-cluster information exchange. This was not captured here but would be of relevance for future research.

6. Conclusion

Coordination requires collecting, processing, and sharing quality information effectively. With the recent adoption of the CA, scholars and practitioners must now determine whether it has helped close the information gap in humanitarian operations. We present an information-processing view of clusters and, on the basis of this model, recommend that cluster leads take on the role of information facilitator, broker, or filter to improve information flow among humanitarian actors.

Our study shows that information diffusion within a cluster can be accomplished if agents are willing to share quality information and the cluster lead acts as a filter. Even in cases where the lead agency may not have the capacity to filter information, taking on a central role to simply facilitate information flow improves diffusion. The cluster lead's role as an information hub is especially critical during the initial phase of response. As the dust settles and a clearer picture emerges, information quality improves and the importance of an information filter diminishes. Our research also shows that the willingness of humanitarian agencies to exchange information has a larger impact on information diffusion than that from an information hub. Our information flow-based analysis hints that the CA is a step in the right direction in humanitarian response. Clearly, the CA is a work in progress and needs further refinement. However, it does seem to improve the collection, processing, and dissemination of information through generating clear lines of accountability, reporting, and pooling resources.

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