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DEVELOPING AN AGENT-BASED SIMULATION MODEL OF THE USE OF DIFFERENT COMMUNICATION TECHNOLOGIES IN INTER-ORGANIZATIONAL DISASTER RESPONSE COORDINATION

Susan K. Aros
Deborah E. Gibbons

Graduate School of Business and Public Policy
Naval Postgraduate School
555 Dyer Road
Monterey, CA, 93943, USA

ABSTRACT

Our research focuses on communications among a variety of organizations that coordinate their rapid responses to catastrophic disasters. Within the context of FEMA's National Response Coordination Center, we constructed an agent-based simulation model of the inter-organizational communications happening via their Web-based Emergency Operations Center, email, phone calls, and face-to-face conversations as the support requests were addressed and fulfilled. We developed our model based on FEMA documentation, observations, interviews, and exercise data. In this paper we outline our model development process and provide details about our simulation model to highlight and address some of the particular challenges one faces when developing simulation models of disaster response activities. We describe what specific aspects of communication media and situational factors our model was developed to test, and also present the design and select results of our first research experiment using this model.

1 INTRODUCTION

Effective disaster response depends on coordinated efforts by a variety of organizations. Timely exchange of complete and accurate information forms a crucial foundation for all activities, as multiple organizations work together to locate needed resources and arrange for their delivery. Several communication technologies are used for inter-organizational coordination, but little is known about how the availability of communication options affects the speed of response. Our research objective was to test effects of feasible combinations of communication media options on the amount of time between initial requests from a disaster zone and the shipment of the needed resources. Our methods included observation of catastrophic disaster response exercises carried out by the United States' Federal Emergency Management Agency (FEMA) and subsequent development of an agent-based simulation model to represent the communication patterns and types of resource requirements that we observed. Our model explored the use of distinct communication media to facilitate information exchange relevant to fulfilling requests for assistance, such as a web-based centralized information system, email, phone calls, or face-to-face (F2F) conversations. Our practical goal was to identify which combinations of communication media could best support rapid, accurate fulfillment of disaster response requests that are routed through a large coordination center.

A few agent-based simulation models have investigated ways to improve disaster response operations, and several have been applied to network-based coordination in other settings. For example, agent-based modeling has been combined with discrete event simulation to analyze communication through various media and subnetworks related to the emergency plan for nuclear facilities (Ruiz-Martin et al. 2016). Wang et al. (2012) used agent-based simulation to explore different response protocols in the routing of emergency vehicles to hospitals following a mass-casualty incident. Hawe et al. (2012) surveyed agent-based simulation modeling for large-scale emergency response, overviewing twelve different studies. Eight of these studies pertained to public health emergencies, and one each modeled building evacuation, an earthquake, and search and rescue. One of the studies (Saoud et al. 2006) simulated victim triage and routing to medical care to test the effects of several different variables on emergency response effectiveness including: the number of rescuers and victims, centralized vs. distributed response strategy, and the use of electronic vs. paper medical forms. The authors reported that "using electronic communication devices is better than traditional paper forms and reduces rescue delays" (Saoud et al. 2006). Our research complements prior work on disaster response coordination by focusing on complex, sometimes imperfect, communications using a variety of synchronous and asynchronous communication media.

2 DEVELOPMENT OF INITIAL MODEL

We initially observed the activities of the U.S. Defense Logistics Agency (DLA) personnel during "Ardent Sentry 14," the Department of Defense (DoD) portion of FEMA's Capstone 2014, a multi-agency catastrophic disaster response exercise. (This research was supported by DLA.) During this exercise, FEMA personnel and liaisons from many supporting organizations gathered in FEMA's NRCC to practice providing a coordinated response effort, as they do when activated for an actual emergency. Many other participants joined from their home or field locations, connecting remotely with live FEMA meetings and through other communication media. We observed the activities from DLA's Joint Logistics Operations Center, reviewed the FEMA National Incident Support Manual (FEMA 2011), and interviewed several people from DLA and FEMA. Our observations, interviews, and available FEMA documentation indicated that the flow of tasks during FEMA-coordinated disaster responses tended to be process-oriented (e.g. the flow of order processing shown in Figure 1) and hierarchical, with occasional glitches due to imprecise communication, email overload, or surges in demands on individual people. Although new information-management software (Web-based Emergency Operations Center or WebEOC, by Intermedix) had been introduced to centralize information and communication, people were still often using phone calls, in-person discussions and email to communicate. Because the overall process was formalized and centralized, we modeled the highest level of coordination—the NRCC floor during the first 72 hours after initiation of requests for help following a catastrophic, no-notice disaster.

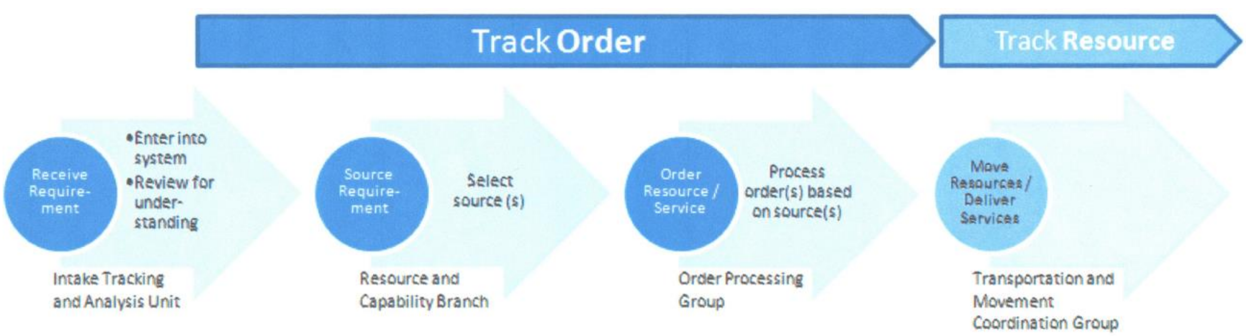

Figure 1: FEMA's Centralized Order Management and Tracking Process (FEMA 2011).

Following the completion of our initial model, we were able to observe another full-scale national disaster response exercise, this time observing within the NRCC. The intent was to validate our model and make any needed adjustments. We found instead that the communication network and handling of requests was far more complex than our initial research had indicated. The initial model focused on top-down, one-to-many information dissemination and group information sharing in meetings. While this type of information exchange does occur regularly in the NRCC, we discovered that direct interpersonal communications carries the details and facilitates the problem-solving that is necessary to meet specific needs. This discovery reinforced the necessity of direct observation or participation in actual events or activities when trying to construct realistic simulation models for aspects of disaster response operations.

3 CONCEPTUAL MODEL

In the spring of 2015 we observed FEMA's annual national catastrophic disaster response exercise from within FEMA's NRCC. We shadowed the DLA liaison to FEMA, observed processes within the NRCC and the DLA, and conversed with people from FEMA and supporting organizations. Adoption of WebEOC had progressed since the prior year's exercise, yet we observed that a number of people struggled to find relevant information within WebEOC. Representatives often needed to leave their desks to ask or answer questions, and in those moments, they might miss incoming messages or phone calls. Picking up a phone call necessarily meant delaying attention to other issues, yet trying to solve complex problems through WebEOC was frustrating, time-consuming, and often required multiple exchanges. Fulfillment of non-standard requests required iterative communications and often extensive problem-solving.

This observation of the exercise revealed that FEMA documentation was accurate from an overall process flow perspective, but the actual communications among participants were much more frequent and integral to the process than the documentation implied. In addition, the main communications of importance to the processing of the Mission Assignments (MAs, FEMA's term for the mechanism used to coordinate the response to a specific request for support) were largely informal, spontaneous phone calls, emails, and in-person conversations. Participants often required multiple communications per request/MA, and many communications were susceptible to disconnects that required follow-on discussion. This new information led us to develop a complex conceptual model of the communication network and handling of requests.

3.1 Communications Network, Avenues and Vehicles

Figure 2 provides a pictorial representation of our conceptual model of the communication network for the coordination of a large-scale disaster response at the NRCC, including primary roles, communication avenues, and communication vehicles. This figure has three main areas: the state that is requesting disaster support (top left), FEMA (top), and the supporting organizations with representatives at the NRCC which we called "brokers" (bottom). The model includes communications taking place at the NRCC, so the state is not explicitly modeled, and communications that occur between FEMA and the State are modeled as a delay. Each of the boxes in the FEMA area of Figure 2 represent a functional area, or 'role' within FEMA. These roles are modeled as single entities even though some of the roles have multiple support personnel. (In most cases a single person in each role functioned as a gatekeeper for the requests being handled in that role, so representing each role with a single person is not a stretch.) In the bottom area, two kinds of brokers are specified: Tier 1 and Tier 2. A Tier 1 broker has direct access to WebEOC while a Tier 2 broker is supporting a Tier 1 broker for at least one type of request. (MAs cannot be assigned directly to a Tier 2 broker within WebEOC.) Different disasters can have different numbers and varieties of supporting organizations present, so we modeled the number of Tier 1 and Tier 2 brokers as changeable parameters.
The arcs in the diagram represent the avenues through which communications occur, and the letters next to each arc (along with the color and type of arc) indicate which communication vehicles are used along these avenues. The numbers in parentheses identify the order in which different communication vehicles travel during the processing of requests. This is easiest to explain by describing the flow of communications and processing of the communications and activities as a request is handled.

A request for support first arrives to FEMA from the state using a Resource Request Form (RRF) communication vehicle. RRFs are first received by the Resource Support Section Chief (RSSC), who then sends them on to the Operations Support Group Supervisor (OSGS). The OSGS may determine that additional information is needed from the state, or possibly from a broker, in which case the OSGS initiates a Requests for Information (RFI) communication. Once the OSGS completes the processing of the RRF (including receiving back any outstanding RFIs), the RRF is sent on to the Resources and Capabilities Branch Director (RCBD) where an MA is created. The MA is then routed through the Mission Assignment

Unit Leader (MAUL), back to the RSSC, and through the Office of the Chief Financial Officer (OCFO). Once all checks and approvals have been completed (including the approval of funding), the MA is sent to the appropriate Tier 1 broker (who will, if needed, then communicate this to a Tier 2 broker). Once a broker receives an MA, they may check with their supplier (which could just be their own organization located outside the NRCC) and will also communicate with FEMA's National Assets Unit Leader (NAUL) if more information is needed (represented as an RFI). Once all of the information pertaining to the MA's request is complete and correct, distribution orders are generated, the shipment initiated, and the MA is sent to the Transportation role to be tracked (and is deemed 'complete' relative to the scope of our model). "Complete and correct" information for an MA includes four pieces of information: (1) specific item information including all necessary details (e.g. SKU), (2) exact quantity needed, (3) the destination of the item(s), and (4) when the items are to be delivered. It can actually take several rounds of communication between a broker and the NAUL to get all of these details ironed out.

There are additional possible routes and communication vehicles as well. An increase in disaster preparedness planning has given rise to a "plan", worked out in advance between the state and FEMA, such that FEMA may create some MAs directly from the plan rather than waiting for an RRF to arrive from the state. These MAs can be fully processed, but nothing ships before the request is received from the state.

In addition to the formal MA process, Verbal Mission Assignments (VMAs) provide a way to expedite getting information about a request to a broker. When an RRF is initially received by FEMA (by the RSSC), a VMA can be communicated directly to a broker. A VMA provides an initial financial authorization as well as initial information on the request. When brokers receive VMAs, they communicate with their suppliers and the NAUL to sort out the necessary details. After everything has been clarified and agreed upon, the distribution orders can be created, the resource shipment initiated, and the information sent to the Transport group to start tracking the shipment.

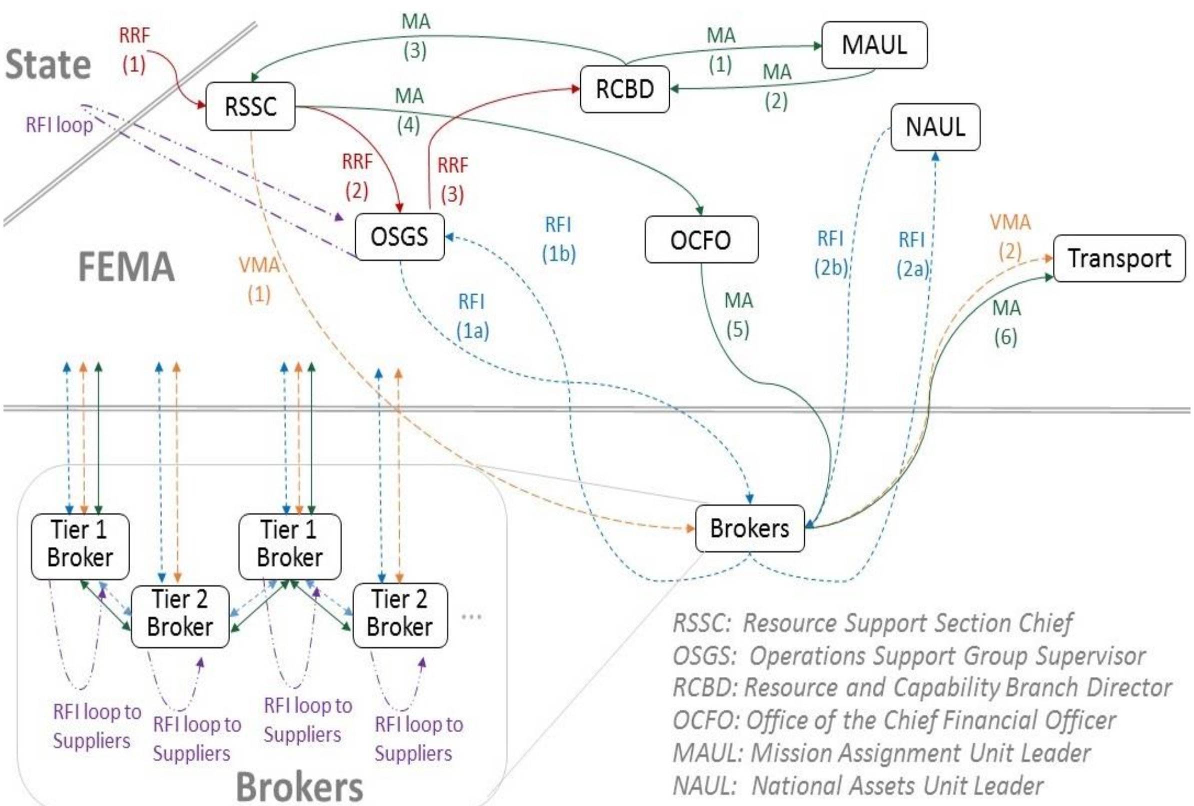

Figure 2: NRCC Communications Network (Aros and Gibbons 2018).

3.2 Requests

Another significant factor affecting the communications needed to fulfill a request is whether or not an advanced agreement has been put in place between a broker and FEMA for the fulfillment of a specific item or resource. This type of advanced agreement is called a Pre-Scripted Mission Assignment (PSMA) and it includes agreed-upon details about a particular resource. If a request comes in for which a PSMA is in place, fewer details need to be worked out, and the time to do so is reduced. Requests can only be initiated from the plan (i.e. have their MA created before the request arrives from the state) if they have a PSMA for the requested item, but not all requests for which a PSMA is in place will be initiated from the plan.

Many other requests that come in are for items that are more commonly needed; we model these as standard requests. And quite often in a real disaster response there are a few requests that are unusual, likely specific to a certain geographical location, population, or type of disaster. These items generally require significant additional research to determine what can be provided to meet the uncommon need, so we model these as non-standard requests. Requests also differ in terms of urgency. Three levels of urgency can be described as: Life-saving (resources need to save lives that are in imminent danger); Life-sustaining (resources needed to sustain those affected by the disaster); and High (resources to meet other urgent needs). We model life-saving requests as priority 1, life-sustaining as priority 2, and high as priority 3.

3.3 Communication Media

We modeled four different communication media: the centralized information system (representing WebEOC), direct emails, direct phone calls, and face-to-face interactions. Each of these function differently. System and email communications hand off the request to the recipient (placed in queue), and emails are read before the system is checked for new requests (as was observed). For phone calls and face-to-face communications, synchronous communication commences if the recipient is not already on a call or in a conversation (interrupting any work they may be doing) but a short delay is added for face-to-face to represent walking time. If a phone call can't be initiated, the request is added to the recipient's voicemail queue (which is attended to before the email queue). If a face-to-face recipient is in another conversation the initiator waits, but if the recipient is absent the initiator returns to their place (another brief delay) and initiates another form of communication. Each richer form of communication is modeled as having a higher probability of successfully completing and correcting each necessary piece of information for a request.

MAs are routed within the computer system and RFIs are usually conducted via email, but agents can choose to use richer communication media (escalate communications to phone calls or face-to-face) if they need a lot of additional information for a request, several communication attempts have failed to obtain the necessary details, or the request has lingered for a while.

4 COMPUTER SIMULATION MODEL

We chose to use the agent-based simulation modeling methodology because the agents in our communication network make decisions about which communication media to use to communicate about a request. We developed our model using NetLogo 5.1.0 due to its flexibility, relative ease of use, dashboard feature, and BehaviorSpace utility for the development and execution of large experiments.

We modeled each of the roles shown in Figure 2 as an agent. Each need requested by a state was modeled as a master request agent, and every communication vehicle was modeled as a request item agent. By the time a master request was fully completed (shipping had been initiated), it had associated with it 1 RRF request item, 1 MA, 0 or 1 VMAs, and possibly multiple RFIs. Along with the construction of the model, we developed a model dashboard with animation to allow a user to easily adjust many parameters of interest, and to watch as communications happen and requests are fulfilled. Two particular challenges associated with the model development were model parameterization and model verification and validation, which we address subsequently.

4.1 Model Dashboard

A snapshot of the simulation model dashboard is shown in Figure 3. People positioned in a diagonal across the middle are the FEMA roles; those in the inner circle are Tier 1 brokers; and those in the outer circle are Tier 2 brokers. A star represents an agent in a phone call, and an X represents the agent in a face-to-face interaction. Triangles are request item agents waiting to be addressed in someone's queue.

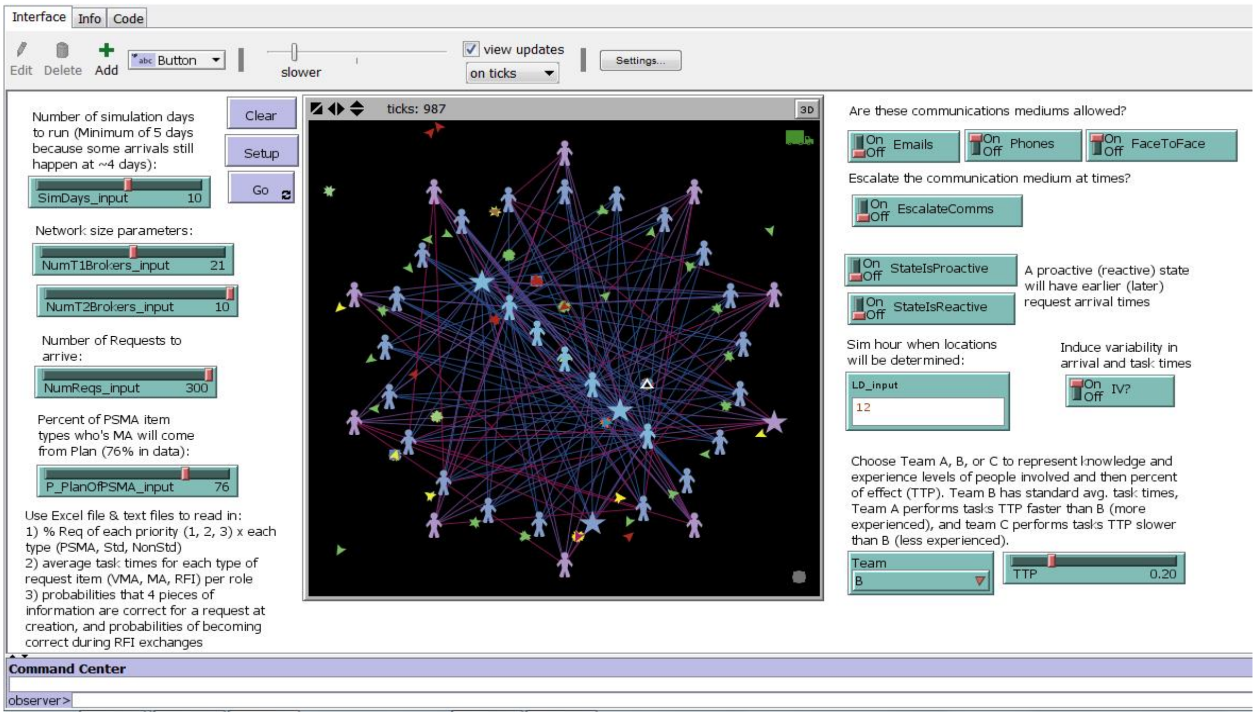

Figure 3: NetLogo Simulation Model Dashboard.

The dashboard also allows for the easy manipulation of different model parameters of interest. The number of each type of broker can be selected here, which determines the total network size. The number of requests, and the percent of requests that will be initiated from the plan (percent of all PSMA requests) can be controlled to simulate different sizes of disasters and different levels of advanced planning. Each different communication medium (outside of the CIS) can be allowed or not allowed, as can the escalation of communications. The state can be either proactive (sending RRFs sooner) or reactive (sending RRFs later), relative to the default timing of RRF arrivals. The time at which the possible delivery locations have been decided upon (response staging locations that can receive the delivery of requested items) can be changed. And the relative skill level of the personnel at the NRCC can be varied to see the effects of more or less training (represented as shorter or longer task times).

4.2 Model Parameterization

When coding a simulation model representing an aspect of disaster response operations, choosing the right value for the various parameters in the model becomes a significant challenge. The primary reason for this is the stark scarcity of data for many aspects of disaster response operations. Our primary source of numerical data was the exercise data that was available from WebEOC following the exercise we observed, which consisted of MA information. Combing through the MA information yielded data for several aspects of our model. To estimate parameter values for all of the model parameters for which we did not have numerical data we developed good estimates of parameter values based on a combination of our observations, conversations with subject matter experts, and educated guesses.

4.2.1 Parameterization from Exercise Data

Most MAs from the exercise contained a single resource request; however, some had multiple requests 'bundled' within them which were referred to as Mission Assignment Task Orders (MATO). We analyzed the MA request data two ways: with each MA counting as one request, and with each MATO/MA counting as one request which give two different counts of requests. We used this information to determine the range of possible requests allowed in the model (100 to 300).

Most of the MA data from the exercise also had information about whether or not a PSMA had been used, whether or not the MA was initiated from the plan, when the MA was created relative to the time of the simulated disaster onset, and the urgency of the request. We used this data to determine the values used for the percent of overall requests that were PSMA requests and the percent of those that were initiated from the plan. (We had to estimate the percent of non-PSMA requests that were non-standard vs. standard; we assumed 3% of all requests were non-standard.) We also used this data to determine the proportion of requests assigned each priority level, and also to distribute the arrival of these over the first 96+ hours post-disaster.

The MA data also allowed us to determine how many support agencies were assigned MAs, informing the range of Tier 1 brokers we allowed in the model (12 to 30). The number of MAs assigned to each broker varied significantly, with a few brokers receiving many of the MAs while many other brokers received few MAs; we distributed request assignments across brokers accordingly. (Since, by definition, Tier 2 brokers do not receive MAs within WebEOC, we had no actual data regarding numbers of Tier 2 brokers or the number of requests that would be assigned to each, so we had to estimate the range of Tier 2 brokers to use (5 to 10) and the varying number of requests assigned to each.)

4.2.2 Parameterization Estimation

For a number of parameters in the model there was no available data to directly determine the correct parameter values. For these parameters we had to develop values based on a combination of our observations during the exercise, conversations with subject matter experts, and educated guesses. These parameters primarily consisted of task times, probabilities that each piece of information was correct when the request 'arrived' (was created), and the probability that each piece of information became complete and correct after being worked on or communicated about.

We developed initial estimates of task times for each role by taking into consideration what type of work was being performed by that role and recalling our observations during the exercise. For example, if the role was primarily performing data entry, such as when the RCBD is converting an RRF to an MA, task times are shorter and more consistent across the different request types (PSMA, Standard and Non-Standard); in contrast, where conversations must be conducted to iron out the details of a request or research must be performed to determine how a request could be fulfilled, task times are quite different for the different types of requests. Once these estimates were developed, we discussed them with personnel involved in both the response exercise and actual disaster responses.

When developing estimates for the probabilities of information being complete and correct initially we considered the type of request, the type of information, and where the request was generated, focusing on ensuring that the relative differences made logical sense. (We also checked with personnel involved in both the response exercise and actual disaster responses to ensure that the estimated values seemed appropriate.) For example, the probability of a non-standard request's item details being fully complete and correct in the initial request is very low (10%) while the same information for a PSMA request generated from the plan is quite high since it was based on an advanced agreement (90%). However, the likelihood of the exact quantity information initially being complete and correct in a PSMA request generated from the plan is relatively lower than the same information coming initially from the state (20% vs. 50%).

When developing estimates for the probabilities of information becoming complete and correct following being researched or discussed we again took into consideration the role that was doing the work or initiating the communication, keeping the focus on ensuring that the relative differences made logical sense (and also discussing these with knowledgeable participants). For example, the probability of item, quantity or delivery timing information becoming complete and correct after an RFI to the state is relatively low (20%) since this often consists of gathering more general information about the need, while the probability of any of this information becoming complete and correct after being processed or discussed by the primary broker or FEMA's NAUL is a fair bit higher (50%) since they are focused on finalizing the exact details pertaining to the request. The probabilities of destination information becoming complete and correct are modeled differently though, since the probability of correct destination information is zero before the primary disaster distribution staging locations have been determined, and quite high after that time (90%).

4.3 Model Verification and Validation

Verification consists of "determining that a simulation computer program performs as intended", and validation consists of "determining whether the conceptual simulation model (as opposed to the computer program) is an accurate representation of the system under study" (Kleijnen 1995). Verification and validation (V&V) of an agent-based simulation model is difficult even in the best of circumstances. Our simulation model is a representation of a real environment that does not operate continuously or regularly (and data on the output metrics was not available). This made it impossible to use the most prevalent type of model validation: empirical validation comparing the output data from the simulation model against output data from the real system. In addition, "there is no comprehensive tool set for verification and validation of agent-based simulation models", particularly due to the fact that "there is a wide variety of application domains of ABMS" (Gürcan et al. 2013). There have been several frameworks for V&V proposed across different domains; however, not all are appropriate for our situation since different domains may have a different fundamental purpose for model construction, different methodologies to guide model construction, and different intended uses of the completed model. To guide the V&V of our simulation model, we used the framework for "simulation models in operations research" presented by Kleijnan (1995).

Lacking empirical data on the time from request arrival to the requested resources being shipped, and requiring accuracy in the process model, we focused on ensuring the validity of the conceptual simulation model and the model parameters used in the computer simulation model. As described previously, we made every effort to ensure that our conceptual model aligned with the real situation being modeled. As the exercise progressed, as well as after the exercise, we continued asking questions of the exercise participants and revising our conceptual model. Where possible we based parameter values on exercise data. Where data was unavailable, we made every effort to ensure that our model parameters were realistic according to subject matter experts, and that we maintained realistic relative values when compared against related parameters in the model. Kleijnen noted that the only "perfect model would be the real system itself," and that validation needs to focus on making the model "good enough, which depends on the goal of the model" (Kleijnen 1995). Since the goal of our model was relative performance under different scenarios, rather than precise prediction of the values of the output data, we determined that all of our validation efforts ensured that our model was 'good enough' for our purpose.

Our model verification was maintained through incremental model development, where we verified the functionality of each section of added code before starting the next section. The code was heavily commented to maintain a clear understanding of what each section of code was designed to do. Animation was used to verify several aspects of the model functionality, and error checking routines were regularly employed to catch possible errors as the code grew more complex. These practices align with several of the techniques for verification mentioned by (Kleijnen 1995) including "good programming practice", "verification of intermediate simulation output", and animation.

5 INITIAL EXPERIMENT AND RESULTS

Our initial experiment asked which communication technologies are more effective additions to the centralized information system (CIS) for processing disaster response requests. Our baseline condition was use of only the CIS, assuming that all players, including every supplier and the state as well as FEMA personnel and all brokers, were able to use the CIS. We then systematically tested effects of all combinations of emails, phone calls, and F2F discussion. In cases where additional communication was allowed (not CIS only), we tested effects of escalating communications from email to phone calls or F2F discussions, or moving from phone calls to F2F discussions.

We developed a full factorial experiment to test effects of all combinations of media options and escalation of communications. We varied the network size by varying the number of Tier 1 brokers (12, 21, and 30) and Tier 2 brokers (5 and 10), the overall number of requests (100, 200, or 300), and the percentage of requests that had PSMAs in place (42%, 55% or 68% PSMAs). We ran 20 instances of every combination of input parameters, recording as our primary performance metric the average Need Flow Time (the average duration from when a need was presented by the state to FEMA through an RRF to when the shipment was initiated), within each type of request (PSMA, Standard, Non-standard). Additional metrics included Request Flow time (the average duration from when a request "arrived" to FEMA, whether in the form of an RRF or an MA created from the plan, to when the shipment was initiated) averaged within each type of request, and also averaged across all requests (denoted Request Duration). Several performance metrics were highly correlated, and we used factor analysis to identify the data structures. This produced a six-item scale (alpha = 0.91) indicating a Global Flow time which we then used as an overall performance metric.

5.1 Effect of Reliance on CIS

Results indicate that exclusive reliance on a CIS for information exchange slows the fulfillment of requests, as compared with scenarios in which direct interpersonal communication was possible. We found that mean flowtimes using the CIS only were longer than mean flowtimes when any direct communication media were available, and this result was consistent across all request types: PSMA (273.87 vs. 199.52), Standard Requests (467.59 vs. 295.95), and Non-standard Requests (1542.32 vs. 1268.08). Forcing people to communicate solely through the CIS lengthened response times across scenarios, and the benefit of having at least one direct communication medium option outside the CIS transcends different network sizes and configurations, as well as different percentages of requests having PSMAs (see Figure 4). (The "Broker Network Indicator" denotes the network configuration with respect to the number of Tier 1 and Tier 2 Brokers. Networks 1 to 3 have 12, 21 and 30 Tier 1 brokers, respectively, with 5 Tier 2 brokers; networks 4 through 6 are similar but with 10 Tier 2 brokers).

5.2 Effects of Number of Interpersonal Communication Options

Having established that sole reliance on the CIS is not likely to be as effective as allowing supplemental interpersonal communication, how might the total number of available communication media options, regardless of which media they are, influence request flow times? Table 1 shows means for PSMA Need Flow Times, Standard Need Flow Times, and Non-Standard Need Flow Times given availability of zero to three direct interpersonal communication media. Subscripts in each row indicate statistical differences among means on that row. Means that have the same subscript are not statistically different from each other. Means that do not share a subscript are statistically different. Mirroring the graphs and *t*-tests presented above, given 42% PSMAs, the flow times are significantly higher when no interpersonal communication media are available (subscript a). PSMA flow times are higher with one medium (subscript b) than with two (subscript c), but for standard and non-standard requests, there is no significant change in flow times as more than one communication medium becomes available. This pattern of results is robust across increases in the proportion of requests that have PSMAs.

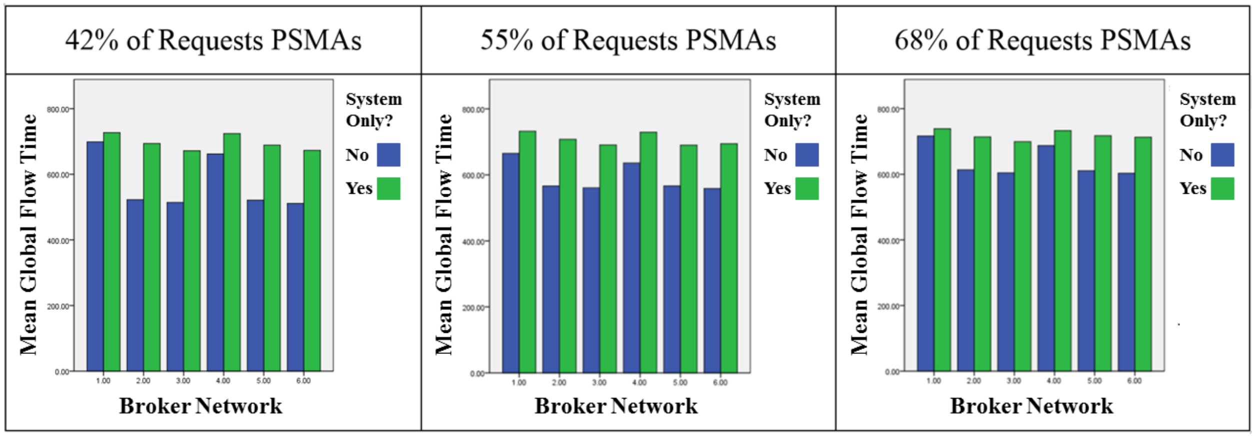

Figure 4: Mean Global Flow Time by Percent PSMAs, Broker Network and CIS Reliance.

Table 1: Mean Need Flow Times Given Availability of Zero to Three Interpersonal Communication Media, Separated by Percentage of Requests That Have PSMAs.

Given 42% PSMAs	Number of Direct Communication Media			
	0	1	2	3
PSMA Need Flow Time	288.0863_a	239.8074_b	219.4475_c	$228.1518_{b,c}$
Std Need Flow Time	516.0437_a	292.6571_b	283.8168_b	277.7026_b
NonStd Need Flow Time	1578.5160_a	1240.2071_b	1246.6716_b	1240.6580_b

Given 55% PSMAs	Number of Direct Communication Media			
	0	1	2	3
PSMA Need Flow Time	276.8619_a	202.5239_b	188.5897_c	$192.7211_{b,c}$
Std Need Flow Time	463.7952_a	283.4535_b	275.1745_b	268.7213_b
NonStd Need Flow Time	1549.8131_a	1265.8917_b	1261.0228_b	1257.2443_b

Given 68% PSMAs	Number of Direct Communication Media			
	0	1	2	3
PSMA Need Flow Time	256.6691_a	181.3944_b	166.9812_c	$172.7935_{b,c}$
Std Need Flow Time	422.9214_a	328.5300_b	320.2099_b	316.9584_b
NonStd Need Flow Time	1498.6237_a	1301.0236_b	1299.3615_b	1289.2204_b

Note: Values in the same row and sub-table not sharing the same subscript are significantly different at $p < .01$ in the two-sided test of equality for column means. Tests assume equal variances. Tests are adjusted for all pairwise comparisons within a row of each innermost sub-table using the Bonferroni correction.

5.3 Direct Effects of Specific Communication Media

Across all levels of PSMA requests, controlling for number of requests and numbers of Tier 1 and Tier 2 brokers, we found that the use of email reduced flow times for all four outcome measures (see Aros & Gibbons 2018). For example, allowing people to supplement the online system with email reduced the average time to complete a standard request by 79 minutes. Phones and F2F options were helpful for all except PSMA requests, and they were particularly valuable for non-standard requests.

5.4 Effects of Communication Options in Combination

For PSMA and standard requests, singular use of email or joint use of email and F2F conversations to supplement the online system produced the fastest mean flow times. For non-standard requests, F2F conversations lowered flow times slightly (see Table 2).

Table 2: Effects of Combinations of Communication Options on Need Flow Times for Different Percentage of Requests Using PSMAs.

Flow times from initial processing of state's request to ship time given 42%, *55%*, and **68%** PSMAs						PSMA Need Flow Time	Std Need Flow Time	NonStd Need Flow Time
F2F?	0	Phone?	0	Email?	0	288.09 *276.86* **256.67**	516.04 *463.80* **422.92**	1578.52 *1549.81* **1498.62**
					1	173.84 *148.77* **135.58**	254.92 *252.07* **288.96**	1242.14 *1278.23* **1293.88**
			1	Email?	0	260.98 *218.03* **195.65**	316.65 *304.75* **356.14**	1230.32 *1258.82* **1305.52**
					1	214.97 *183.79* **165.27**	285.12 *275.76* **323.09**	1236.52 *1277.54* **1296.64**
	1	Phone?	0	Email?	0	284.60 *240.77* **212.96**	306.41 *293.54* **340.50**	1248.17 *1260.63* **1303.68**
					1	174.13 *150.38* **136.75**	255.66 *249.26* **285.12**	1250.37 *1246.56* **1294.42**
			1	Email?	0	269.25 *231.60* **198.92**	310.67 *300.50* **352.42**	1253.12 *1258.97* **1307.02**
					1	228.15 *192.72* **172.79**	277.70 *268.72* **316.96**	1240.66 *1257.24* **1289.22**

6 DISCUSSION AND ONGOING RESEARCH

Our agent-based simulation model represents an inter-organizational communication network working together to quickly respond to critical needs following a catastrophic disaster. We developed our model based on activities and communications observed at FEMA's National Response Coordination Center. In this paper we have presented details of the model and model development, especially addressing some of the most challenging aspects of simulation model development for disaster response: data availability and model validation. We presented our initial experiment, key results pertaining to the benefit of direct communication media options, and the robustness of these results across scenarios and levels of advanced planning (seen in different percentages of requests having PSMAs developed in advance of the disaster). These results indicate that at least one alternative communication channel should be provided to supplement the web-based information hub when multiple organizations need to coordinate their response efforts. The ability to discuss complex and non-standard requirements is particularly crucial.

Our ongoing work continues experimentation with this model, exploring the impact of different experience levels among responders. We are testing all combinations of communication options given fixed networks, representing levels of user experience by varying the time it takes them to complete tasks and conversations in 10% increments. Results will be included in our conference presentation. The model could also be used to seek ideal communication media for other emergency situations. For example, Spain's Nuclear Emergency Plan includes communication via phones, fax, internet, police systems, face to face, and several other media (Ruiz-Martin et al. 2015). Our simulation model could contribute to understanding which communication channels are most important to support an efficient response. Finally, our future work will simulate international disaster response coordination networks, allowing for more varied disaster scenarios and communication media options such as radio systems and video conferencing.

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AUTHOR BIOGRAPHIES

DEBORAH E. GIBBONS holds a Ph.D. in Organizational Behavior and Theory, with a minor in statistics, from Carnegie Mellon University. As an associate professor at the Naval Postgraduate School, she integrates social psychological principles with data analysis and system modeling. She has developed agent-based simulation models that apply to diffusion of innovations, public health crises, and collaboration within organizations. Her email address is degibbon@nps.edu.

DR. SUSAN K. AROS is an Assistant Professor at the Naval Postgraduate School. She holds a Ph.D. in Information, Risk, and Operations Management from the University of Texas at Austin. Her research interests include disaster planning and response operations, healthcare operations, and production management. She utilizes simulation (DES and ABS) and optimization modeling methodologies. Her email address is skaros@nps.edu.