Real-time Decision Making in Urgent Events: Modeling Options for Action

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ABSTRACT

Decision making in extreme events presents a difficult challenge to emergency managers who are legally responsible for protecting life, property, and maintaining continuity of operations for their respective organizations or communities. Prior research has identified the benefits of gaining situation awareness in rapidly changing disaster contexts, but situation awareness is not always sufficient. We have investigated "option awareness" and the decision space to provide cognitive support for emergency managers to simulate computationally possible outcomes of different options before they make a decision. Employing a user-centered design process, we developed a computational model that rapidly generates ranges of likely outcomes for different options and displays them visually through a prototype decision-space interface that allows rapid comparison of the options. Feedback from emergency managers suggests that decision spaces may enable emergency managers to consider a wider range of options for decisions and may facilitate more targeted, effective decision making under uncertain conditions.

Keywords

Decision making, decision space, option awareness, situation awareness, emergency response, exploratory modeling, Bayesian modeling.

INTRODUCTION

Decision making in extreme events presents a difficult challenge to emergency managers who are legally responsible for protecting life, property, and maintaining continuity of operations for their respective organizations or communities. The challenge escalates with the degree of uncertainty that characterizes rapidly evolving threats, and the dynamic interaction among the participating organizations that are seeking to respond to this threat in a context of limited resources, known constraints, and potential risk. It represents a "wicked" policy problem (Churchman, 1968), given multiple actors, changing operational conditions, and uncertain outcomes.

Prior research has addressed this problem through exploring ways to provide "situation awareness," which was defined by Endsley (1988) as the perception and comprehension of the elements of an environment within a volume of time and space and the projection of the state of the environment into the near future. Gaining situation awareness involves identifying the current conditions that confront the emergency managers: what risks threaten, what damage has occurred, what weather or other conditions would affect response, and what resources are available (Comfort, Dunn, Johnson and Skertich, 2004).

There is broad agreement that having situation awareness is essential to emergency response decision-making (e.g., Johnson, Zagorecki, Gelman, and Comfort, 2011; G. A. Klein, 1999[1]). In a study of firefighters, G.A. Klein (1999) chronicles occasions in which firefighters matched the specific characteristics of unfolding emergencies to patterns that they recognized from prior fires, then remembered what had worked in a similar situation in the past. Next they ran a mental simulation to determine if the earlier approach would work in the current situation. If the simulation outcome was successful, they immediately put that decision choice into action without pausing to consider other options. Thus, for emergencies that are similar to previous events or are non-complex in nature, Klein's "recognition-primed decision making" (RPD) moves directly from situation awareness to the decision, with little intermediate deliberation.

While situation awareness is a necessary prerequisite for decision-making in emergency response, it is not always sufficient. Hall, Hellar, and McNeese (2007) recognized that RPD may break down under unfamiliar or complex events, with the result that there is a gap between the decision maker's knowledge of the situation, as presented in a "situation space," and their understanding of the potential options and consequences of those options, as presented in a "decision space." Understanding the situation space yields situation awareness, and understanding the decision space yields option awareness (Drury, G. L. Klein, Pfaff and More, 2009; G. L. Klein, Drury and Pfaff, 2011).

The brief moment in disaster operations when decision makers actually determine a strategy of action, or the next step in the decision process that shapes the evolving trajectory of response operations, is when the decision space can be effective (Pfaff, G. L. Klein, Drury, Moon, Liu and Entezari, 2012). Without such support, it can be difficult for emergency managers to determine quickly what options are available for action, and compare possible options in terms of potential consequences and likely outcomes.

G. L. Klein and colleagues (2011) have shown that the process of mental simulation, a key part of RPD, can be offloaded to a computer, generating a decision space that addresses more options than can be mentally simulated. This decision space can be graphically visualized, enabling the decision maker to apply their more powerful pattern recognition capabilities to multiple options in parallel. Providing decision support to practicing managers at this critical stage enables them to extend their capacity for exploring options in complex operational contexts that otherwise may be limited by time and by insufficient previous experience in unusual events.

Employing a user-centered design method, we developed a Bayesian network model to generate the decision space and a prototype graphical user interface design to depict the decision space. The objective was to provide decision support for emergency managers to determine quickly what options are available for action in an urgent situation and to compare options in order to achieve the most effective result. Based on incoming information about the situation, the model calculates which options are likely to be most effective in terms of protecting the community. This paper documents our employment of the user-centered design process, the model we developed to generate the decision space, and our prototype decision space interface design. This effort is the first time that Bayesian networks have been used via exploratory modeling to generate a decision space, and this is also the first time that we have designed a decision space in close coordination with the intended users.

DESIGNING AN APPROACH TO INCREASE OPTION AWARENESS

Laboratory testing of graphical depictions of decision spaces found that decisions were made more quickly, correctly, and with more confidence than decisions made with only situation space information (Pfaff et al., 2012). Up to approximately one-third of the research participants in these laboratory tests had emergency response experience. The laboratory experiments reported no significant difference in performance on relatively simple emergency events between participants with and without emergency response experience. The next step in exploring this process of decision-making should be to investigate the utility of decision spaces with the help of participants comprised exclusively of emergency responders. Further, we wanted to enhance the emergency response events being studied to be as realistic as possible, in contrast to the simple events used during the laboratory experimentation.

To ensure sufficient user involvement, we employed the user-centered design method (Norman and Draper, 1986), which Vredenburg, Mao, Smith, and Carey (2002) summarize as "the active involvement of users for a clear understanding of user and task requirements, iterative design and evaluation, and a multi-disciplinary approach" (p. 472). Specifically, our multi-disciplinary team achieved an understanding of user requirements through a series of interviews and accomplished two design and evaluation iterations with the help of emergency responders.

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[1] Both Gary A. Klein and Gary L. Klein are working in the decision making area. We distinguish the work of each by using their middle initials in citations.

CO-DEVELOPING A SCENARIO

We engaged the participation of a major international airport's fire and rescue department in developing a prototype tool and assessing its viability for increasing option awareness. First, we met with practicing emergency managers from the department to discuss the purpose of the study and to outline a schedule of tasks for completion. Next, in a series of six interview sessions, individual emergency managers identified the parameters for a realistic scenario involving interaction between a passenger plane and airline ground crews that potentially could escalate into urgent conditions with increasing risk to both lives and property, if not brought under control quickly. The key task was to trace possible options for action at each threshold decision point to determine the likely impact of that decision upon the consequent actors and conditions at risk. The emergency personnel validated this scenario as the type of event for which they plan and train.

The six semi-structured interview sessions included 22 personnel, or 60% of the members, from the fire and rescue department and were conducted over a period of two months. Each position within the departmental hierarchy – chief, deputy chief, lieutenant, and firefighter – was represented, with two-thirds of the lieutenants and more than half of the firefighters taking part.

	Interviewed	**Total Personnel**	**Percent Interviewed**
Chief	1	1	100
Deputy Chief	2	2	100
Lieutenant	4	6	67
Firefighter	15	28	54
Total	22	37	60

Table 1. Department Personnel Interviewed for Knowledge Elicitation

This distribution is essential in characterizing the decision process for the organization, as organizational roles, responsibilities, and perceptions of risk vary by position. Representation of each position creates a sample of organizational responsibilities and the distribution of cognitive awareness and knowledge within the department (Hutchins, 1995). Questions were designed to elicit perceptions of possible actions and their likely consequences in several areas, including the timing and process of risk recognition, organizations and personnel likely to be involved, possible strategies for collective action, intended results, obstacles, potential consequences of actions, and performance assessments. The interview protocol is included in Appendix A.

As a result of the interviews, we co-developed with our emergency responder partners a realistic and challenging scenario. The scenario starts with an aircraft tug operator who experiences a medical emergency and loses control of his tug, so that the tug collides with an aircraft full of passengers that is parked at the departure gate. The point of collision is the aircraft's wing, which contains a fuel tank that ruptures as a result of the impact. The spilled fuel becomes a fire ignition source and the subsequent flames threaten the passengers on board. The smoke travels through the jetway to the terminal, sickening people inside.

DESIGNING THE MODEL

The interviews were transcribed verbatim and coded to identify the key parameters for building a Bayesian Network (BN; Pearl 1988). Such a network is based on Bayes' theorem, which can be seen as a way of understanding how the probability of an outcome is affected by actions and new information (Hartigan, 1983). The BN model was designed to capture the critical information regarding the scenario and to use that information to identify options for action, specifying the likely consequences of each option for other actors or conditions in the operational environment. The model uses a set of assumptions regarding the likely consequences that is based upon the judgment of experienced decision makers (Saaty, 1990). Using this method, weights are assigned to the outcomes for each option, based on a utility function of perceived effectiveness in bringing the incident under control with the least loss in lives, property, and continuity of operations.

A BN encodes probabilistic relationships among a set of variables and is especially suitable for reasoning under uncertainty. A BN consists of two parts: qualitative and quantitative. The qualitative part is defined by a directed acyclic graph (DAG) that encodes direct dependencies between variables or, more accurately, encodes conditional independencies. The quantitative part is defined by a local conditional probability distribution for each of the nodes, where the distribution is conditioned on the state of its parents. Several additional follow-up interviews elicited data on the probabilities that linked the various decision and chance nodes. The one exception is the specification of the root nodes, which simply have prior distributions associated with them. Together these local probability distributions define a joint distribution over all the variables.

Influence diagrams (Howard and Matheson, 1981) are a generalization of Bayesian networks in that they can contain additional types of variables. Chance nodes designate variables that could occur in random events; decision nodes provide a range of decision options; and utility nodes are used to evaluate the selected decisions. Together the three types of nodes make it possible to calculate the top-ranked decisions, given a set of real-time observations (of chance nodes). To translate the interviews into an influence diagram, we identified decision points, chance nodes, and utility nodes and modeled them using the GeNIe 2.0 (Graphical Network Interface) software program.[2] Figure 1 below shows the influence diagram used for the scenario devised by the airport personnel in which a tug operator accidently crashes into the wing of an aircraft parked at the departure gate, fully loaded with passengers, and causes a fuel leak. The model contains 6 decision nodes, 14 chance nodes, and five utility nodes (more accurately, they are cost nodes). These nodes are described below.

The decision nodes relevant to the scenario are determining the type of response (aircraft-centric, terminal-centric, or both aircraft and terminal), whether fire ignition sources have to be eliminated, whether the HAZMAT has to be contained, and if the passengers, tug operator, and terminal have to be evacuated (with the evacuation strategy consisting of three separate yes-or-no decisions). Each decision consists of a choice among a set of two, three, or four alternatives, for example, whether to eliminate ignition sources is a binary choice. We define an *option* to be the selected combination of choices for each of the six decision nodes, which makes a total of 3x4x3x2x2x2=288 options. The choices and options were constructed based on the interviews performed with the airport personnel; that is, the model encodes what the airport personnel perceived to be decision points, which are specific to the airport scenario. An example of one option is to pursue an aircraft-centric response, eliminate fire ignition sources, contain the HAZMAT (spilled fuel, in this case), do not evacuate the passengers, evacuate the tug operator, and do not evacuate the terminal. Clearly, evaluating this number of options is more than can be mentally simulated.

The chance nodes model the uncertainty in the world, such as the likelihood of passenger casualties. Based on observations, for example, responders received via a call from someone who witnessed the tug crash, the probability of passengers in danger will be updated accordingly.

Finally, there are four intermediate utility nodes that take inputs from the decision and chance nodes: operational costs, business continuity, property damage, and casualties. The states (or probability distributions) of decision nodes and chance nodes affect the utility nodes, even indirectly. For example, if the probability of passengers in danger increases, the expected number of casualties increases. The four intermediate utility nodes are combined into one final overall utility node that is used to score each evaluation of each option.

The model itself is constructed before, and not during, an actual event. During an actual event, only observations are instantiated in the model that, in general, affect the likelihood of the different outcomes and could require selecting a different option to minimize the cost. How each observation changes the likelihood of outcomes is quantified when the Bayesian network is constructed. When time is short, the model can quickly estimate the consequences of decisions. In other words, our approach allows new information (the observations) to be combined with existing knowledge (the Bayesian network) to select the decision option with the greatest probability of effectiveness, according to criteria defined by emergency managers: life safety, stabilization of the incident, continuity of operations, and preservation of property.

We now describe the procedure regarding how observations are turned into user-presentable information that serves as input to the decision maker. Given a set of observations, the model is executed 100 times for each of the 288 options. For each option, we sampled from all plausible values for the chance variables (taking into account the evidence), and repeated this process 100 times to obtain a distribution of the resulting utility values. These distributions were then ranked, ordered by distribution of outcomes with highest utility, and displayed in the user interface using box plots (Tukey, 1977). This method of exploratory modeling (Chandrasekaran, 2005) aids decision makers by constructing decision spaces for events under deep uncertainty (Bankes, 1992).

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[2] The models described in this paper were created using the GeNIe modeling environment developed by the Decision Systems Laboratory of the University of Pittsburgh and are available at http://genie.sis.pitt.edu/.

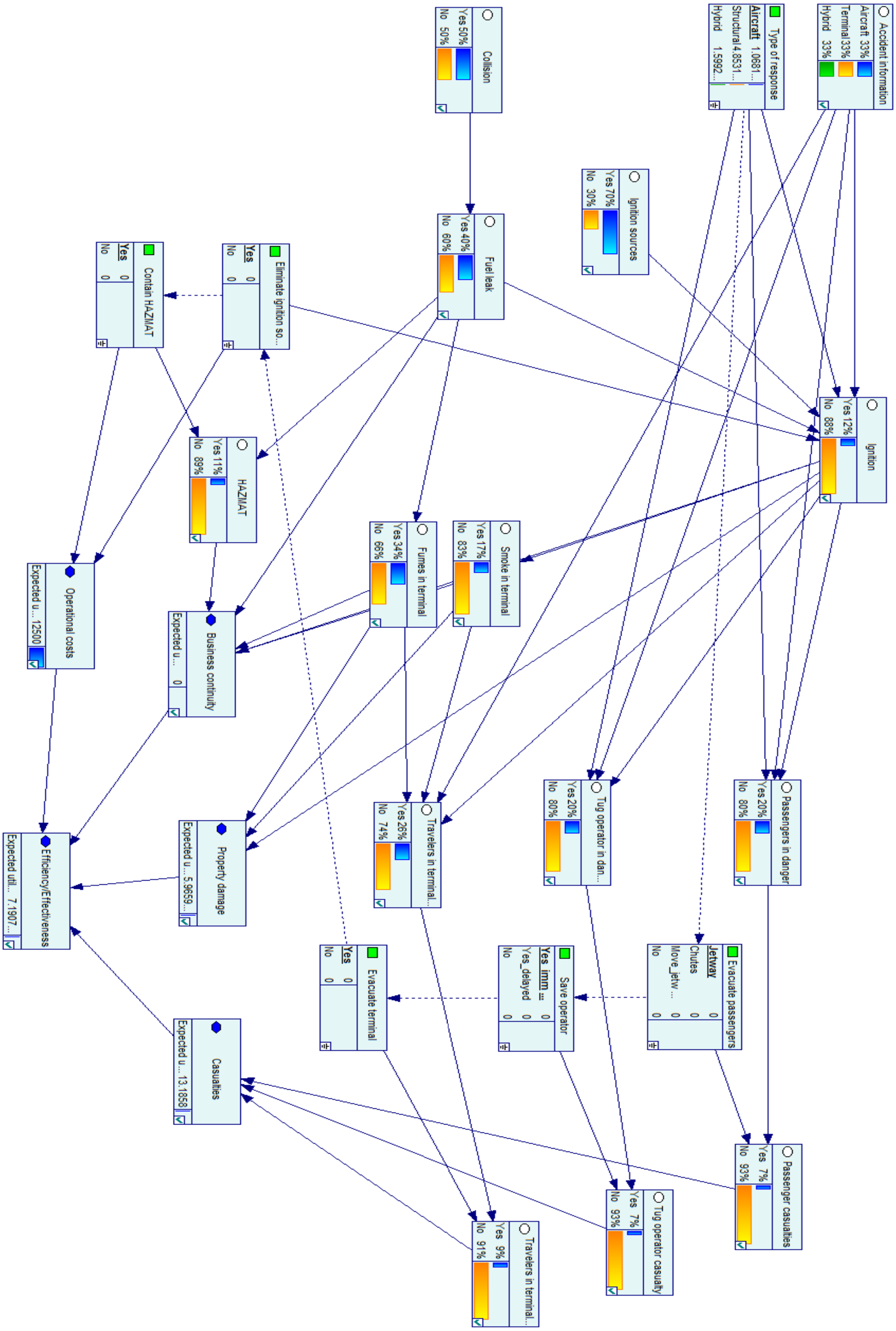

Figure 1. Influence Diagram of the Tug Operator Scenario.

We emphasize that the current model is only directly applicable to the airport scenario. While some parts of the model could apply to other scenarios as well, it would have to be expanded and generalized to be applicable to any possible event. For example, there could be other reasons that passengers need to be evacuated from an airplane that would require choosing between use of a jetway or chutes. Our model illustrates this process.

DEVELOPING THE PROTOTYPE

As conditions in the emergency change, emergency managers can update values in the model through a user interface and re-execute the exploratory modeling in real time. Results are presented in a visual format that enables fast comparison of different options in terms of likely effectiveness, given the goals and criteria previously specified for performance.

The user interface is designed to allow users to alter the observed inputs to the model's chance nodes prior to running the simulations, e.g. number of crews available, recognition of ignition sources, and observation of a fuel leak. For example, if the emergency responder using the decision space tool knows that there is no fuel leak present, then he or she can adjust the prototype's inputs quickly to reflect that fact. As a result, the dependent probabilities regarding the fuel leak are disabled and the user is given a visual cue that those probabilities are no longer influencing the modeled outcomes. The interface uses a series of incremental sliders that allow for fine-grained input of the probabilities that are used for each chance node. The sliders are organized into groups with hierarchical dependencies to clarify visually some of the relationships between inputs in the underlying model.

Because the responder may have a particular option in mind, the interface allows them to construct that option and test it against the top ten options that are generated by the model. The user is presented with a series of drop down boxes representing each decision point and the potential courses of action at each point. The user is able to alter these items to represent how they would respond to the situation. The simulation is then run and returns the top ten options with the best distribution of outcomes. These outcomes are displayed alongside the user-defined option to allow for simple, direct comparison. The user can now see how his or her defined option compares with the top ten options based on the knowledge encoded in the model. To enable more detailed comparison, clicking on one of the box plots shows the specific interactions estimated for that option.

ASSESSING THE PROTOTYPE

Consistent with our user-centered design approach, we demonstrated the prototype to rescue and fire personnel on two occasions, April 16, 2012 and June 29, 2012. After each demonstration, we invited comments and suggestions from experienced personnel regarding the functionality and utility of the prototype in providing decision support in actual operations. We incorporated feedback from departmental personnel into the model iteratively after each demonstration, adapting it to meet their needs more effectively.

Question (1 = completely disagree to 5 = completely agree)	**Mean**	**Median**	**STD**	**Min**	**Max**
It was easy to understand the box-plots once I heard the explanation.	4.08	4	1.00	2	5
It was easy to understand what the sliders meant.	3.50	4	1.09	2	5
The sliders were relevant and appropriate.	3.25	3	0.75	2	5
It was easy to understand the options' labels and pop-up information boxes.	3.92	4	0.79	2	5
I would like to incorporate my preferences into the way that "effectiveness" of each option is calculated.	3.67	4	0.89	2	5
I would be able to make more effective decisions with this tool.	3.67	4	1.07	2	5
This tool would be useful for training.	4.92	5	0.29	4	5
This tool would be useful in the EOC.	4.25	4	0.75	3	5
This tool would be useful in a large regional exercise.	4.00	4	0.74	3	5
This tool would be useful in a large regional (real) event.	3.50	3.5	1.00	2	5

Table 2. Frequency of Responses to Key Evaluative Questions[3]

[3] N=12**.** Respondents were asked to select the answer that most closely expressed their opinions. Potential answers ranged from "Completely disagree" (1) to "Completely agree" (5).

Following the demonstration of the prototype at the June 29, 2012 workshop, participating emergency personnel were invited to complete a questionnaire to document their assessment of the functionality of the prototype and its utility for decision making in urgent events. Table 2 summarizes the findings from key questions.

These results can be interpreted in light of usability (the first six questions) and utility (the remaining questions). In other words, what could we do to improve the prototype design, and in what situations might decision spaces be useful?

Usability

Since all mean and median usability scores were 3 or above (with 3 being neutral), the responders rated the usability of the interface positively.

The sliders garnered the lowest score, with a mean of 3.25/5.0. Some responders suggested that the sliders could be replaced with check boxes to indicate whether or not they believe a certain condition has occurred. One responder explained, “either something exists or it doesn’t. It’s very hard for an individual to put a value on an item in the heat of the moment during an incident.”

The responders were somewhat mixed on the usability of depicting the range of outcomes for each option using box plots. While the questionnaire results showed a mean score of 4.08/5.0 for ease of understanding the box plots, some responders commented that they would like an “easier-looking graph.”

Responders mentioned that they would like to be able to fine-tune the weighting of the criteria used to score the results (they agreed at a level of 3.67/5.0). Similarly, responders would like to be able to set the crew sizes dynamically. (In fact, we had planned to provide these capabilities for future versions of the decision space tool.)

Utility

The emergency responders identified three settings in which a decision space system could be useful: 1) training, 2) at the emergency operations center (EOC) level in a multi-jurisdictional incident, and 3) in highly complex environments that can be well-characterized in advance such as chemical plants or electrical generating stations.

Training

As noted above, experience is needed for rapid RPD, but it is difficult to gain experience with challenging situations when they occur only rarely. The responders stressed that training for decision-making using the decision space tool could be especially useful in such low frequency, high-stakes situations: their agreement with this view attained a mean of 4.92/5.0.

For example, one responder mentioned that only a small number of people in the world know the subtleties of fighting Marcellus shale oil fires. He explained that the finer points of Marcellus shale oil fire fighting could be reflected in different options and a model could be created to evaluate the outcomes that could result from using each of the options. The trainees could then use the resulting decision space to explore the specific conditions under which options will have better or worse outcomes, thereby learning how to account for the impact of conditions such as temperature or geography on each of the potential courses of action.

While large regional exercises are normally performed for training purposes, the questionnaire scores for this question, at a mean of 4.0/5.0, were lower than for training as a whole.

EOC

Some responders thought that decision spaces could benefit EOC personnel, particularly in the case of large-scale events such as the California wildfires that unfold over hours or days instead of minutes. The somewhat strategic nature of operations at the EOC level could provide operators with sufficient time to view decision spaces as they consider tradeoffs among a number of options. Scores for this question had a mean of 4.25/5.0.

Well-known, complex environments

While no survey question explored this scenario specifically, the responders brought up this case in our discussions. Fire fighters in jurisdictions with industrial activity understand that fires in operations such as chemical manufacturing plants or electrical power plants could be very dangerous events. Since there are usually only a few of these complex installations within a jurisdiction and the stakes are high when fires occur at these locations, the responders thought it would be well worth preparing in advance decision spaces tailored for these well-known, specialized environments.

There is empirical evidence to support implementing the responders' observations in practice. Unlike a fire in a small-to-moderate sized wood-frame structure, where fire fighters can make a decision quickly that is informed by previous experience, a major industrial fire can be so complex that "naturalistic" decision making processes (G. A. Klein, 1999) can break down. Even in time-urgent situations, previous work (Pfaff, G. L. Klein, Drury, Moon, Liu, and Entezari, 2012) has shown that it is faster to augment intuition with decision spaces that show graphical overviews depicting the tradeoffs in a number of different options simultaneously. Besides their utility for training, using such specialized decision spaces during emergency situations could help alleviate the necessity of mentally simulating many complex courses of action, thus reducing cognitive burden and speeding response during a stressful situation.

DISCUSSION

After the demonstration of the prototype, we asked the emergency responders whether, when, and where they would find such a tool useful in their decision making processes. Several responders replied that the prototype would be most useful in large, complex disaster operations with multiple organizations engaged in different types of actions at different locations simultaneously. In such dynamic, complex operations, it is difficult for individual managers to keep their focus on the whole operations environment, while they are intensively engaged in managing separate incidents. The scale of information that is needed to comprehend such large events is beyond the problem solving capacity of individuals. In such situations, a computational tool would be very useful.

We clarified during discussion that, during a real-life incident, we would also provide "situation space" tools that enable responders to have facts about what is happening as well as a depiction of the options that they could take. The responders affirmed the value of having both the situation and decision spaces.

The responders identified challenges to implementation, especially for firefighters on the ground, based on the availability of information technology. Personnel in the EOC or a mobile command center have access to computers, tablets, and other media useful for such decision support systems. Firefighters during tabletop exercises also have access. Operational access to such media, however, varies. The fire discipline is still years away from incorporating laptops in their vehicles. Several responders questioned their ability to access such media effectively during a response operation. They suggested that their option awareness could be improved by such a support system if emergency managers at the EOC were interpreting results and informing them via traditional communication links.

CONCLUSION

Based on the findings from our user-centered study, we affirmed the likely usability and utility of decision spaces for emergency managers operating in complex, urgent environments. We report the largely positive assessment from one fire and rescue department of using a computational tool to identify and compare different options for action in such complex, stressful environments. They perceive the benefits of the tool to be most useful for training emergency responders to operate effectively in complex events involving multiple organizations. Furthermore, they also acknowledged the value of the tool to assist them in exploring a wider range of options that could increase efficiency and decrease costs of operation, which are important in an era of tighter budgets and increasing demands for emergency services.

The next step in this research will be to engage a wider group of emergency managers in a training exercise in which the participants access and run the prototype model to consider options for decision in simulated emergency conditions. If validated in regular training exercises by practicing emergency managers, the prototype would make a significant contribution to increasing option awareness for decision making under urgent conditions.

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APPENDIX

Interview Protocol: Knowledge Elicitation

1. Phase 1: An aircraft incident (involving evacuation and fire)
    a. When would you recognize the risk?
        i. How would you recognize it?
    b. Who would be involved? (including other agencies)
        i. Who is affected?
        ii. What is affected?
    c. What would need to be done immediately? (goals, objectives, aspect to be addressed)
        i. Who is responsible?
    d. How would you assess its severity?
    e. What actions would you take (for each goal, objective, aspect?)?
        i. What options do you have?
        ii. What information would you need to choose among these options? (including information about the actions and outcomes of other agencies)
        iii. What obstacles would you face?
        iv. What resources would you need to carry out these actions?
            1. If you would not have access to those resources, does your decision change?
        v. What are the consequences of these actions?
            1. What could go right?
            2. What could go wrong?
            3. What would be the outcome of things going right or wrong?
            4. How would you evaluate the goodness/badness of those outcomes?
    f. Would there be other options for action? If so, what are they?
        i. What are the consequences of these actions?
            1. What could go right?
            2. What could go wrong?
    g. How do you assess your actions in progress? (performance and effectiveness)
            1. How frequently do you check your progress?

2. Phase 2: A hazardous materials release (a major fuel spill) *(same questions as above)*
3. Phase 3: A structural fire (in the terminal area) *(same questions as above)*
4. Phase 4: A complex evacuation problem (of both the terminal and the aircraft) *(same questions as above)*