Collaborative Evolution of a Dynamic Scenario Model for the Interaction of Critical Infrastructures

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ABSTRACT

This paper reviews current work on a model of the cascading effects of Critical Infrastructure (CI) failures during disasters. Based upon the contributions of 26 professionals, we have created a reliable model for the interaction among sixteen CIs. An internal CI model can be used as a core part of a number of larger models, each of which are tailored to a specific disaster in a specific location.

Keywords

Cross Impact Analysis, Critical Infrastructure, Collaborative Modeling, Delphi Method, Scenario Planning and Training, Emergency Management.

The white man drew a small circle in the sand and told the red man,
"This is what the Indian knows," and drawing a big circle around the
small one, "This is what the white man knows,"
The Indian took the stick and swept an immense ring around both
circles: "this is where the white man and the red man know nothing."
The People, Yes, by Carl Sandburg

INTRODUCTION

Cross-Impact Analysis (CIA, Turoff, 1972) methodology recognizes that occurrences of events are not independent. It is used to help determine how relationships between events may impact and create resulting events. Bañuls and Turoff (2011) introduced the CIA-ISM (Cross Impact Analysis and Interpretive Structural Model (Warfield, 1976) approach to generate and analyze scenarios. CIA-ISM has been adopted for use in research projects around the world in the Emergency Management field: for example, in Spain to study information technology techniques for training (Aedo et al, 2011); and in Brazil to structure the chain of events that can occur in a crisis and, based on that information, develop courses of action (Lage et al. 2013).

This paper describes a CIA-ISM application that allowed working with a large numbers of events and estimators to obtain values in the model for the interactions of failures in critical infrastructures during disasters. This research presents a major extension to a prior study (blinded 1) using CIA-ISM to estimate the interactions among critical infrastructure failures during many disasters. The resulting dynamic set of events may be incorporated as a core in a larger number of models. In order to represent the dynamic approach we present four graphical models that are incremental versions of the same working model. Each of the models includes additional information and shows the CIA-ISM capability to filter information as requested by decision makers. Moreover we demonstrate how to generate probabilistic scenarios with the analytical software tool called CIASS (Cross-Impact and Simulation Software). The remainder of the paper describes the procedures and methodology of the resulting model, then ends with reflections on the CIA-ISM methodology.

DEVELOPING THE CRITICAL INFRASTRUCTURE MODEL

Events

For this collaborative modeling process we decided to use a set of very negative events, where for each CI the event is the worst possible outcome - a complete breakdown in the structure or availability of service. The detailed 16 Critical Infrastructure events are:

1. **Fires underway:** There are major fires out of control.
2. **Water supply undrinkable:** The normal water supply is contaminated.
3. **Electrical Energy cutoff:** Electricity is unavailable except for too few portable generators.
4. **Natural Gas supply unusable:** Natural Gas is unavailable; Leaks exist in the system. Tanks of compressed gas are in very short supply.
5. **Sewage untreated:** The sewage system is not functional and has backed up in places.
6. **No Gasoline:** There is no significant store of gasoline for emergency vehicles or public vehicles.
7. **No Airports:** There are no functional local airports.
8. **Emergency Responders lacking:** Trained Emergency Responders are in short supply; many have chosen to help their families; this includes local government and utility maintenance personnel.
9. **Problem/Hazardous Materials:** Chemical Plants, locations of hazardous materials, and contaminants are unsecured and could develop further leakages.
10. **No Medical Service:** Hospitals and clinics cannot fully function; Medical supplies and prescriptions are unobtainable; there is no air rescue functioning; Inadequate maintenance and supplies for ambulances.
11. **No Information and Command System (ICS):** The Internet is not functioning. The local emergency center is cut off from most networked sources. There is no single list and map of all critical facilities in the area; the command center is understaffed and key people are missing.
12. **Community Response Lacking:** Community organizations have not been able to organize to aid response. There are few public shelters. Citizen volunteers are very few in number.
13. **Road Network clogged:** A majority of the roads is not serviceable; Solid waste and construction debris is excessive and blocking roads and rescue attempts; Government Public works and construction companies have not been able to respond to the situation nor coordinate their activities; Public transportation has shut down; some roads have become parking lots.
14. **Public Communications in difficulty:** Public Communication is unreliable; Emergency communications are not fully functional; Cell towers are out of backup energy supplies; Incompatible communication equipment in use among many different response organizations
15. **Local Government not functioning:** Local governments in the area of the disaster are not able to fully function and key people cannot be reached. No security (police, firemen, public services).
16. **Private sources not supportive:** Food shortages are occurring; People are raiding stores for supplies; There is no agreement with supermarkets, hardware stores, etc. to provide needed materials and substances; Homes, on the average, have only a few days of food and liquids; Private organizations are not contributing to the response to this disaster.

Participants

The development of this cross impact model involved a total of 20 initial estimators of the relationships. An additional six experts were called upon to comment on relationships for which the initial 20 estimators had disagreement. Some of the initial estimators also took part in that phase. Of the 26 total participants, 69% were male and 31% were female. The participants were highly educated, with 73% holding or currently pursuing doctoral degrees. On average, the participants had over 11 years experience in academia, 14 years experience in management, over 10 years experience as first responders and/or in EM planning, almost 10 years in medical EM, and over 14 years in engineering. Many participants had years of experience in a variety of roles.

Process

For each assumption (the 16 positive outcomes that were the reverse of the negative events), we asked the participants to assess the impacts of that positive assumption on the other 15 negative events. If agreement on a relationship existing or not was equal to or greater than 2/3 of the total used the voted probability values. If the agreement on the vote was less than 2/3 we considered it to be a severe disagreement. There were 93 severe disagreements in the initial round of this Delphi process. We went back to the contributors and a few additional professionals and asked them to specifically comment and explain why they felt there was or was not a relationship.

Table 1: Initial results for estimates made by 20 contributors.

Relationship types	**Number**
Complete Agreement	10
Majority agreement => 2/3 of votes	95
Majority for no relationship	42
Severe Disagreements < 2/3 of votes	93
Total	**240**

There were 13 respondents for this phase and an average of nine comments each for the 93 disagreements. In eliciting comments we expressed a need to identify the specific causation relationship. The result was a 40 page document of all the comments for the 93 items; email the first author for a copy. Since the larger values have the most influence, we use ISM by first taking the largest C_{ij}, convert them to a direct graph with values of 1, all the remaining being 0. Our study resulted in the following distribution of the 240 relationships among our 16 critical infrastructures (Table 1).

Previous Delphis dealing with complex problems requiring many respondents of different types suggest that as you add more contributors, the number of disagreements or differences of viewpoints increases (Linstone and Turoff, 2011). This often occurs when one tries to take single predictions and examine the interaction possibilities between them such as in a prior study of the Steel and Ferroalloy industry (Goldstein 1975) and the investigation of the ethical, social, and legal implications of biomedical research (Goldschmidt 1996). With the resolutions of the 93 severe disagreements, we obtained a new result for which we took the largest relationships in turn to come up with the first four models developed by applying CIA-ISM.

EVOLUTION OF THE DYNAMIC SCENARIO MODEL

The CIA produces a set of coefficients called C_{ij} which express the degree of influence of the j-th event on the i-th event. This can be represented as a directed graph made up of all the C_{ij} vectors between the j and i event directed to event i. Each C_{ij} is between minus infinity and plus infinity and the larger the value the greater is the influence of the j-th event on the i-th event occurring or not occurring (if negative). We assumed all events to be “bad” except for the j-th event and asked about the impact of the non occurrence of a critical infrastructure failure (inverse of the i-th event) which caused all the derived C_{ij}s to be positive. (In the case of a bad event (i) not occurring, other events will either stay the same or get better).

In table 2 the numerical evolution of the dynamic scenario model can be found. Note only the 2^{nd}, 3^{rd}, and 4^{th} models use the same 6 of the 93 severe disagreements (SD). Since the larger values have the most influence, we use the method of ISM in the following way. We start taking the largest C_{ij}’s and convert them to a direct graph with values of 1 and all the remaining being 0.

Table 2: Models based upon the resolution of the 93 disagreements
(A=Complete agreement; R=Majority agreement; SD Severe Disagreement resolved)

Model	C_{ij} Value	% of C_{ij} distribution	Percentile	A	R	SD resolved	Total C_{ij}	No impact $C_{ij}=0$
1	2.86	5%	95%	4	6	0	10	39
2	2.52	12%	88%	4	14	6	24	39
3	2.29	15%	85%	5	19	6	30	39
4	2.07	20%	80%	6	28	6	40	39

(A=Complete agreement; R=Majority agreement; SD Severe Disagreement resolved)

Whenever there is a link such that event j influences event i and there is also a link such that the j event influences event i (bi-directional influence), the ISM method creates a mini scenario combining the i-th and j-th event into a single event. As we take more C_{ij} values we can often establish more combinations of mini scenarios that should be treated as a collection of mini scenarios, each of which can be treated as a single event. This reduces the complexity of the initial set of events to a set of macro events, which provides useful insights into what are the fundamental relationships in the set of scenario events. The following graph gives the number of C_{ij}'s from zero to the highest values.

Our ISM modeling starts with the largest absolute values and works down. The desirable stopping point depends on the use one wants to make of the model. Here we illustrate for potential cutting points.

The four faint vertical lines represent the point where each model starts using the C_{ij} from the left end to the right line. The farthest line to the right is model 1, then moving left models 2, 3, and 4. That is, each evolutionary model *n* includes all the C_{ij}'s of the previous model *n*-1 plus an increment of at least one additional C_{ij}.

There are 201 C_{ij} values greater than zero out of the 240 possible relationships among the 16 Critical Infrastructure Failures. We could create 201 different graphical models to illustrate the dynamic evolution of the scenario. We carry the process in this case to a fourth model that shows the ultimate dominance of one crucial event that one should always try to insure does not occur.

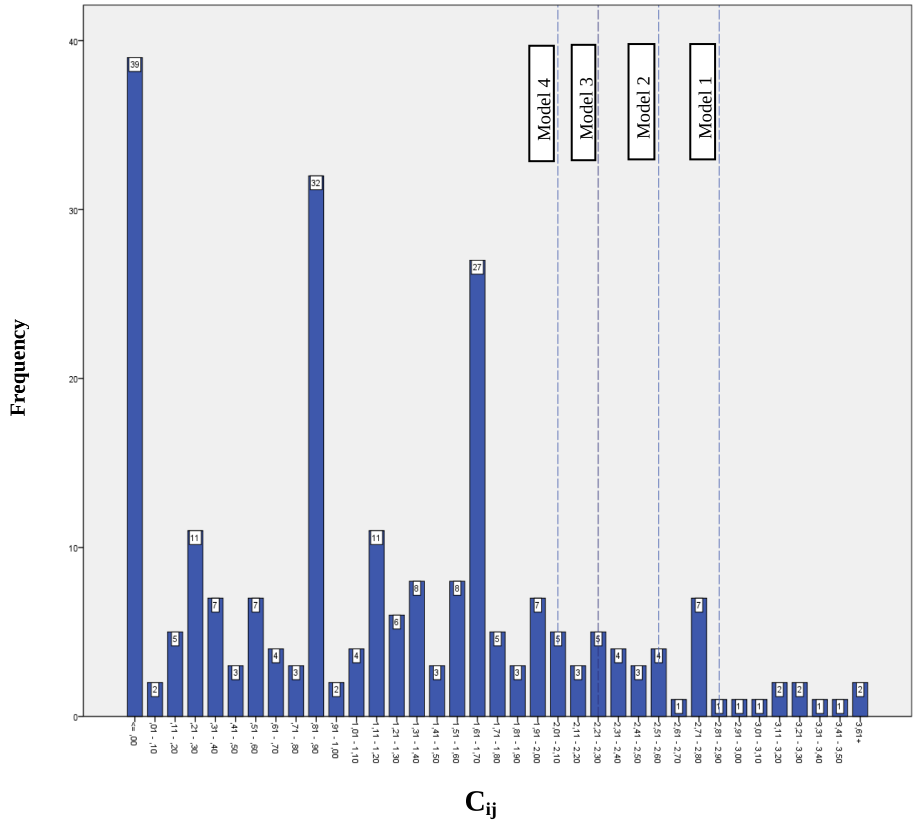


Figure 1: C_{ij} Histogram after Solving Severe Disagreements

Model 1

The first model uses only the 10 largest C_{ij} values and represents approximately 5% of all the non-zero C_{ij} values. It did not use any of the resolved severe disagreements. We have two cases of two events being condensed into one macro event or mini scenario. The shading indicates the macro event or mini scenario. Only the largest 10 links were used in this model and we had two clusters. If there is no command and control system then the pubic community is in difficulty, or vice versa. The two cannot be separated. The second combined event is a lack of emergency responders and medical problems. Since the primary goal of emergency managers is usually reducing deaths, this is not a surprise either. Only half the CIs have been connected in this model

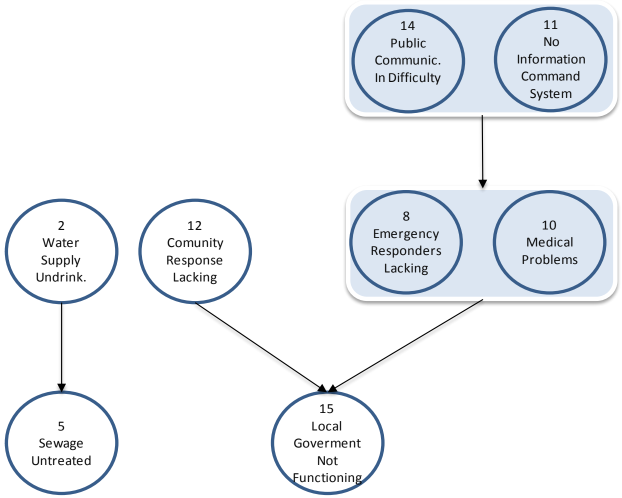


Figure 2: Model 1 – Digraph for Cij > 2.86

In the above there are two mini scenarios with two events each (shaded). What this means is that there is no sense in considering the two events in a mini-scenario as separate events as they will act together with respect to the outcome. Both events in the mini-scenario will either occur or not occur together. If one occurs, the other will occur.

Model 2

This model is based upon 24 C_{ij}s. This is the first model that includes all of the events.

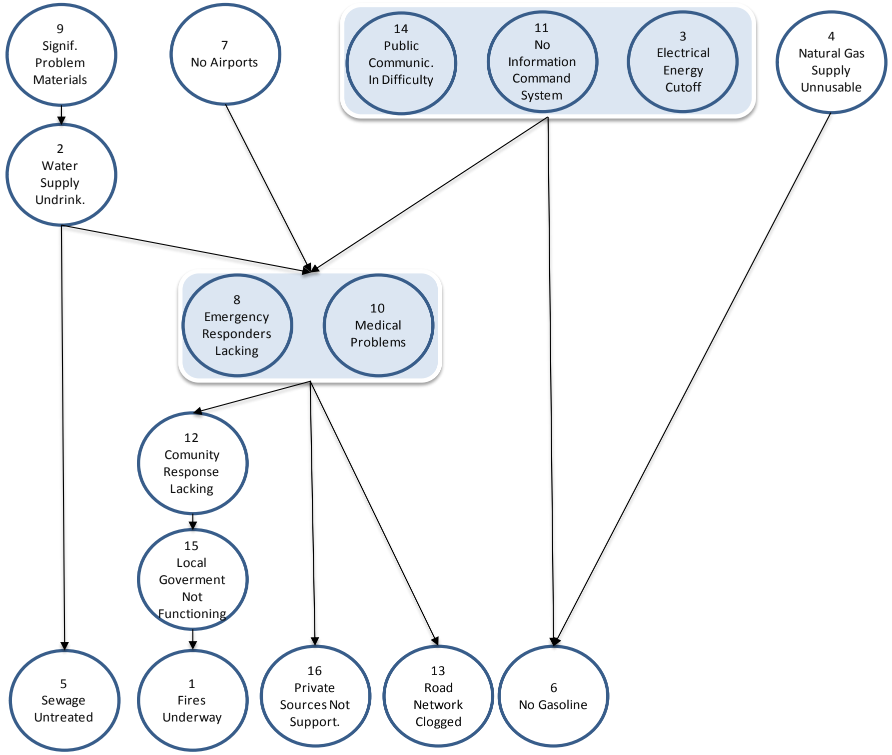


Figure 3: Model 2 – Digraph for C_{ij} > 2.52

We now see a mini-scenario made up of three of the original 16 events. It is the preferred model to get an insight into the strongest relationships because every event or mini scenario has at least one link to other nodes and every one of the 16 events is present. Six of the resolved severe disagreements are present in this diagram. Now all 16 events are part of the diagram using the 24 largest C_{ij} values. One cluster has been expanded to three events and the third entry is a lack of electricity. Since most places in the US do not require electric generators for cell towers this is not a surprise. In Katrina half hour batteries were the only back-up for cell/communication towers.

Model 3

This is now the result of 30 links.

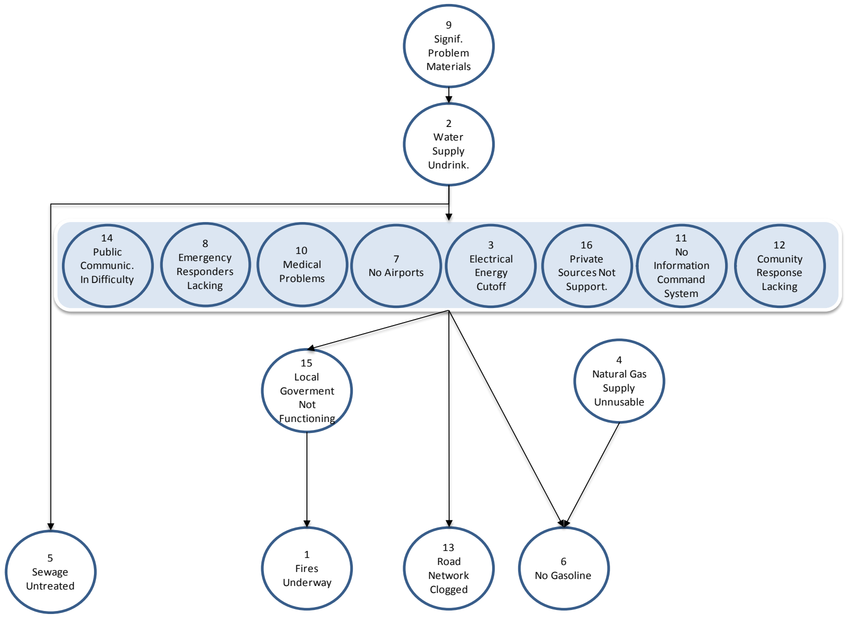


Figure 4: Model 3 – Digraph for Cij > 2.29

This next model has eight events condensed into one event and is interesting because the lack of drinking water becomes the factor that makes these eight events become one event.

Model 4

Model 4 is even more condensed with 40 links producing a merger of 11 of the 16 events into one mini-scenario.

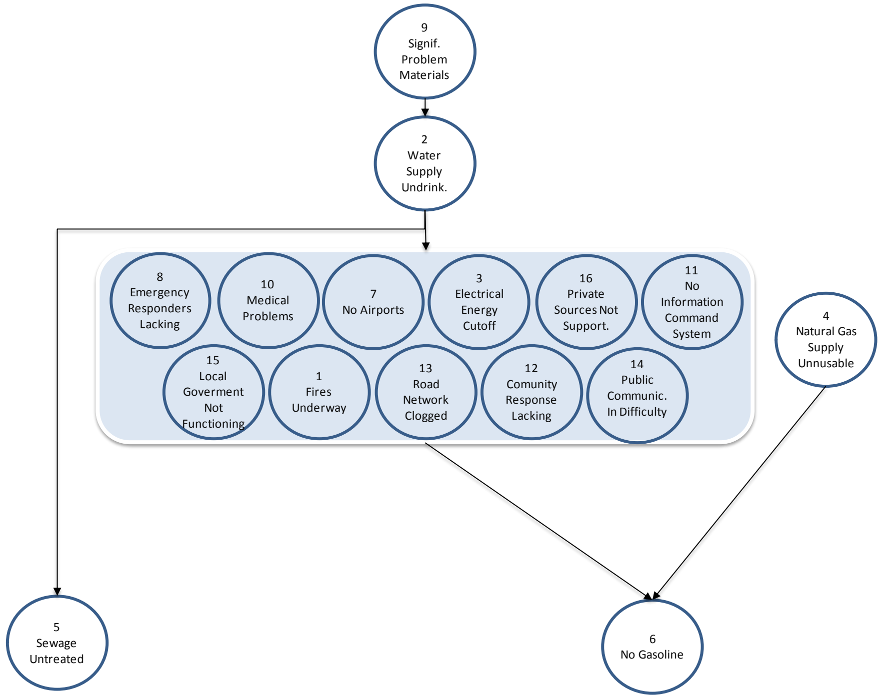


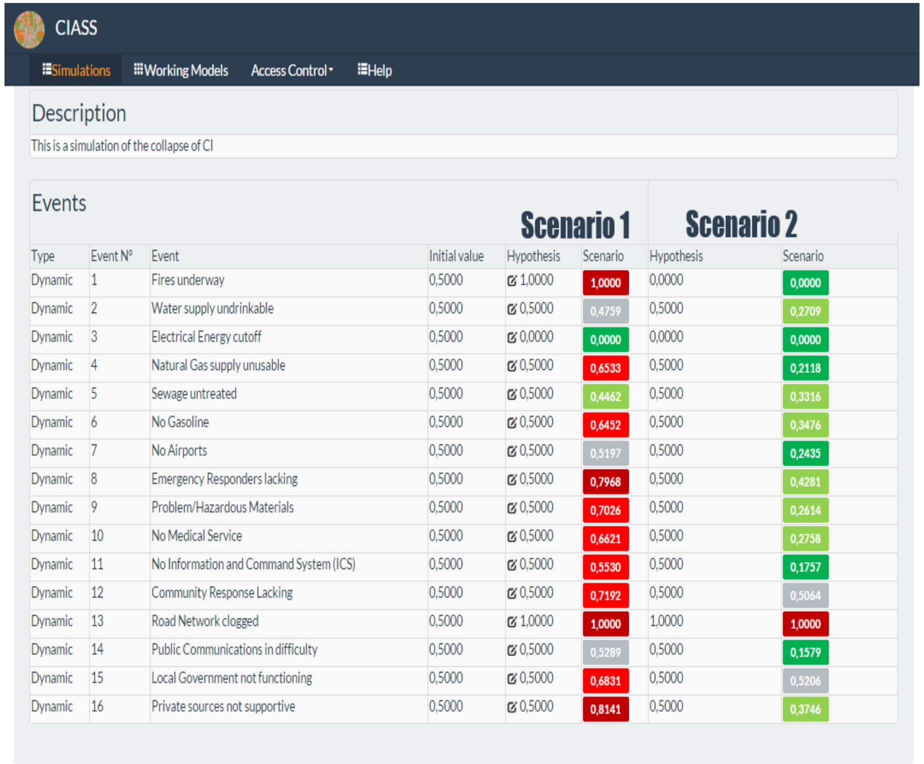
Figure 5: Model 4 – Digraph for C_{ij} > 2.07

It very strongly shows that the single condition of a lack of drinking water is a bad enough condition to cause everything else to fail. There was some of this happening in the Haiti disaster. Level 4 of the structural model is much too condensed to provide much insight into mitigation options and one must really go back to Model 2 to begin asking where mitigation considerations might be most effective. However, if one goes back to the full model we have developed software to be able to change the initial .5 probability on one or more of the 16 Critical Infrastructure events and see the impact on any of the others.

The total calculation for decision support

We have shown four different models to illustrate the evolution of the most reliable scenario attending to the relationships between events. Nevertheless the potential number of scenarios are 16!= 20.922.789.888.000. We have developed software (Cross-Impact Analysis and Simulation Software – CIASS) to allow a person to simulate any scenario by taking any of the events and changing the initial probability from .5 to any value that they want, to see the impact on all the other events (Figure 6). This represents 16 non linear equations where the value of given probabilities is determined by the values of the other 15 probabilities. In this caption a comparison between two hypothetical scenarios is shown.

In scenario 1 we assume that there are fires underway and road network clogged but there is no problem with energy cutoff. In the interface above (Figure 6) you can see that a change made to the hypothesized events 1 (fires underway =1), 13 (roads clogged =1) and 9 (road network clogged =0) impacts other events, thus resulting in higher probabilities of failure and turning reddish. That is, we have a very bad scenario with a potential collapse of other critical infrastructures events (in dark red). In scenario 2 we change the hypothesis about fires underway (we assume that there are no fires so hypothesis =0) and we can see the impact on the rest of the critical infrastructures: a lot of events turn to shades of green that means that the control of fires has a big positive impact. This expands to the right so you can develop a whole set of changes and see the impact they have. The resulting calculation below uses all the impacts and is not restricted to the earlier four graphical models, providing a visualization of the most significant relationships.



Type	Event Nº	Event	Initial value	Hypothesis	Scenario	Hypothesis	Scenario
Dynamic	1	Fires underway	0,5000	1,0000	1,0000	0,0000	0,0000
Dynamic	2	Water supply undrinkable	0,5000	0,5000	0,4759	0,5000	0,2709
Dynamic	3	Electrical Energy cutoff	0,5000	0,0000	0,0000	0,0000	0,0000
Dynamic	4	Natural Gas supply unusable	0,5000	0,5000	0,6533	0,5000	0,2118
Dynamic	5	Sewage untreated	0,5000	0,5000	0,4462	0,5000	0,3316
Dynamic	6	No Gasoline	0,5000	0,5000	0,6452	0,5000	0,3476
Dynamic	7	No Airports	0,5000	0,5000	0,5197	0,5000	0,2435
Dynamic	8	Emergency Responders lacking	0,5000	0,5000	0,7968	0,5000	0,4281
Dynamic	9	Problem/Hazardous Materials	0,5000	0,5000	0,7026	0,5000	0,2614
Dynamic	10	No Medical Service	0,5000	0,5000	0,6621	0,5000	0,2758
Dynamic	11	No Information and Command System (ICS)	0,5000	0,5000	0,5530	0,5000	0,1757
Dynamic	12	Community Response Lacking	0,5000	0,5000	0,7192	0,5000	0,5064
Dynamic	13	Road Network clogged	0,5000	1,0000	1,0000	1,0000	1,0000
Dynamic	14	Public Communications in difficulty	0,5000	0,5000	0,5289	0,5000	0,1579
Dynamic	15	Local Government not functioning	0,5000	0,5000	0,6831	0,5000	0,5206
Dynamic	16	Private sources not supportive	0,5000	0,5000	0,8141	0,5000	0,3746

Figure 6: CIASS – www.ciass.org

CONCLUSIONS

Since its inception, several authors from different domains of knowledge have contributed with different approaches to scenario-generation techniques. Reliance on complex mathematical risk models using solely technical variables has led to disastrous consequences such as the 2007- 2008 collapse of financial markets.

Thus, in building scenarios to help in planning for potential disasters, one must take into account a wide range of social factors and events, as well as technical ones, and obtain inputs from experts with differing training and experience and perspectives, to try to maximize the probability that all important factors and relationships among those factors will be considered. The history of calamities such as the financial meltdown, Bhopal, and the Chernobyl nuclear accident point to the potential value of using multiple scenarios, not to select the most likely one, but to train crisis managers in becoming familiar with a wide variety of shocks and unanticipated situations, be they hostile or not.

The results of our effort have provided some significant insights into the interactions among Critical Infrastructures. We have shown that this collaborative modeling methodology is able to allow a group of professionals in Emergency Management to develop a single model exhibiting their collective viewpoints on interactions of Critical Infrastructure conditions in a timely manner. From a methodological perspective this paper is a step further in our research about collaborative scenario modeling (blinded 2) because of the involvement of a large group of experts dealing with a very complex problem. We demonstrate how to deal with conflicting views when we have people with different backgrounds and geographic origins. Moreover, the results of this paper are a contribution itself. There is a lack of unified research on interdependencies between critical infrastructures and behavioral aspects of EM. In this paper, we present a full working model of interactions among critical infrastructures that might be used as reference in different contexts and by different groups for supporting emergency plans and risk analysis. This is especially necessary in this field because in critical infrastructures management, planning is required to include communications with other facilities that could be affected. Additionally the results of the modeling process could be used for training.

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