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Collaborative scenario modeling in emergency management through cross-impact[☆,☆☆]

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ABSTRACT

In this paper we analyze how to apply cross-impact modeling for developing collaborative scenarios in Emergency Preparedness. Scenarios can enhance the understanding of emergency teams about the factors which are involved in the definition of an emergency plan and how different actors participate in it. The version of Cross-Impact Analysis described aims at contributing to this goal through allowing the collaborative development of scenarios out of large event sets. This ultimately reduces the complexity for estimating a working model. In order to illustrate this research effort hypothetical results of a dirty bomb attack scenario exercise are presented, along with the final estimates of relationships based on four rounds of individual estimates followed by discussion of differences in the perceived relationships, in order to achieve a "consensus" model. The purpose of this exercise is to demonstrate the ability of a group to create a working model of the scenario that may be used to examine the consequences of various assumptions about preparedness, plans, and the actions taken during the crisis situation. The method may be used as either a planning tool and/or a training tool. We discuss the process for collecting inputs from a collaborative group and how to improve the consistency of the group inputs in a Delphi-like feedback process. Suggestions for improving details of the wording of items in order to minimize misunderstandings and miscommunication are included, along with suggestions for future extensions to this research.

1. Introduction

Scenario methods are aimed at developing alternative visions of the future in group decision-making contexts. These scenarios, as well as providing input for decision-making, can be used as a way of generating ideas and arguments about alternatives and courses of action in groups. The use of scenarios is especially relevant in complex situations such as emergencies in which it is difficult to create explicit relationships among events. A scenario in the form of a dynamic interacting model of a set of events allows one to vary the outcomes by controlling the likelihood of the occurrence or non-occurrence of individual events which are based upon preparedness decisions and actions prior to and during the response to the situation being modeled. In these complex contexts, the total number of combinations of possible future events can be very high and pragmatically infinite. This is why decision-makers need tools for the synthesis of these trends and events into a manageable number of alternatives making available the information required. Scenario methods provide this functionality to decision makers.

Since its inception, several authors from different domains of knowledge have contributed with different approaches to scenario-generation techniques. As pointed out by Harold Linstone (personal communication), reliance on

☆ "For, in reality, the knowledge of an effect is nothing else than the acquisition of the more perfect knowledge of its cause." — Spinoza.
☆☆ *On the Improvement of Understanding*, by Benedict de Spinoza, [1883], translated by R.H.M. Elwes; http://ebooks.adelaide.edu.au/s/spinoza/benedict/understanding/index.html.

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complex mathematical risk models, i.e., the technical perspective, has led to disastrous consequences. For example, most of the 2007–2008 financial models omitted a major variable, liquidity. When trading in the mortgage-backed securities stopped, the system froze, suddenly becoming illiquid, and the crash resulted. Another model weakness was the non-inclusion of the many interactive connections between low-risk institutions, resulting in overall excessive systemic risk, a phenomenon already experienced by the electric power industry, most recently in 2003 [1]. 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. Linstone [2] states that 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 users in becoming familiar with a wide variety of shocks and unanticipated situations*, *be they hostile or not*, *thereby becoming superior crisis managers when confronted with a novel emergency*."

Bañuls and Turoff [3] introduced the CIA-ISM approach in order to generate and analyze scenarios using cross-impact analysis. This approach aims at allowing researchers and practitioners to obtain a set of plausible snapshots of the future as well as to analyze interaction between critical events in the time horizon specified. The CIA-ISM approach can have several applications in emergency planning and preparedness, given that it (1) can be applied to any emergency, (2) is oriented to supporting the planning rather than the response process, and (3) is oriented to analyzing social factors rather than technical estimates. In addition, these scenario generation models can be integrated with other predictive models designed to estimate the evolution of a particular disaster (such as the indirect effects of a fire or an earthquake), providing a broader view of events which could occur in emergency situations [4,5].

In this paper we aim at expanding the CIA-ISM approach for supporting collaborative scenario generation. Group scenario generation could be a high-cost and time-consuming process, specifically when it is dealing with large and complex decision problems. Besides the large set of events that is involved in realistic scenario generation, it requires interaction with key actors in emergencies in order to develop strategic visions and anticipatory intelligence. This fact implies the design of a group interactive process in order to support the quality of the scenario output in terms of [6]: plausibility in the arguments, internal consistency, description of causal processes, and usefulness in making decisions. This collaborative feature of scenario generation is an added value regarding traditional planning techniques. The use of scenarios in this sense aims at helping emergency preparedness teams to analyze the key events that are involved in an emergency as well as their potential outcomes.

In order to illustrate the CIA-ISM application for supporting group-scenario generation, hypothetical results of a dirty bomb attack scenario exercise are presented, generated by the three authors through four rounds or phases of estimations. We are examining the impact of very specific event conditions affected by preparation and training. We discuss the process whereby we estimated the factors and went through a series of feedback processes to finally reach a consistent group judgment about the factors used as input to the model. We explicitly wanted to choose a "low probability, severe consequences" type of event, for which most emergency planning operations have no existing plans, because they think "it won't happen here." The "dirty bomb" is one of a number of possible radiation events that could cause catastrophes in large urban areas. Others include accidental meltdown of a nuclear power plant (e.g., Chernobyl, Fukushima), a terrorist attack on a nuclear power facility, or a military missile, or bomb attack. A recent report [7] points out that the U.S., for instance: "has not developed the capability to inform and direct emergency personnel and the public in real time during an unfolding severe event," such as a radiological emergency. This type of catastrophe is one for which previous experiences are limited; what is needed is inputs from a variety of different types of experts on both the technical and the social events that might occur after such an initial incident, that could lead to very different outcomes in terms of casualties and other types of losses.

The purpose of this exercise is to demonstrate the ability of a group to create a working model of the scenario that may be used to examine the consequences of various assumptions about preparedness, plans, and the actions taken before/during emergencies. Specifically our goals are (1) to sensitize responders and decision makers to the details that would mean the difference between a successful and an unsuccessful response to the type of threat being modeled; (2) to provide a model that that allows one to test different conditions and decisions in terms of their consequences for outcomes, including resource allocations and investments made before the event and different decisions or actions taken during the event; and (3) to develop a working example to encourage others to develop their own models for the risks they are most concerned about. We focus on illustrating the CIA-ISM mechanisms for group-scenario generation and analysis. The basics of the CIA-ISM methodology can be found in [3–5]. The Bañuls and Turoff paper [3] also discussed in detail the use of Delphi and/or Workshop processes to collaboratively develop the event set before applying the cross-impact methodology to develop a dynamic model. Other collaborative scenario generation method issues such as event set generation and process communication support can be also found in the literature (see Collario [8] for generating the set of events and the Dynamic Delphi [9] for supporting the group communication process). In this sense CIA-ISM is highly compatible with other group-scenario techniques.

2. Methodological background

2.1. CIA-ISM fundamentals

Cross-Impact Analysis (CIA) is a methodology developed to help determine how relationships between events may impact resulting events and reduce uncertainty in the future. Due to this ability of CIA to analyze complex contexts with various interactions, CIA is one of the most commonly-used techniques for generating and analyzing scenarios, both historically [10] and currently [11,12,3]. The main goal of

CIA is to forecast events based on the principle that the occurrence of events is not independent. An individual or a group must come up with a set of interrelated events that might occur in the future. This requires users to be able to modify or iterate their estimates until they feel the conclusions inferred from their estimates are consistent with their views. Following Turoff [10], for this type of event there is usually no statistically significant history of occurrence, which would allow the inference of the probability of occurrence. So, the cross-impact problem is to infer causal relationships from some relationships among the different world views of participating experts (knowledgeable participants in the planning process). This is established by perturbing the participant's initial view with assumed certain knowledge as the outcome of individual events. This approach deals with subjective probabilities that translate into causal relationships, notated as C_{ij} and G_i, C_{ij} being the linear impact factor of event E_j upon E_i, and G_i being the linear impact factor of the events that are not specified in the event set upon the i-th event [10]. By taking each event in turn and asking the user to assume it definitely will or will not occur and having them estimate the probability of the other events, we are asking for estimates for *n* different event sets. These resulting event sets do not follow a Bayesian relationship. Instead we are assuming they follow the Fermi Dirac Distribution in Quantum Mechanics. This and the other assumptions [10] allow us to transform a non linear probability scale (0 to 1) to the linear C_{ij} scale factors (− to +infinity) for influence factors providing linear relationships among events.

According to the nature of the events we classify them into three categories [3]:

- Dynamic Events (DE_i): Dynamic events could or could not occur during a certain time period. Within such a time period, the factor measures we are estimating between E_i and E_j are considered valid.
- Initial Conditions (IC_i): Initial conditions are assumptions, a priori or source events that have already occurred before the beginning of the time-period or which have a probability of being true or false at the beginning of the time period. All such initial conditions are assumed to have .5 probabilities at the time a person makes their subjective estimations, that is the zero point of probabilities, described by the subjective term of "maybe" it will occur or not occur. Initial conditions are chosen to reflect the preparedness situation and represent potential major influences on the dynamic events. The probability being evaluated for an initial condition is the probability of an initial condition being true at the start of the time-period. The initial value choice of a .5 probability indicates no influence factors are active within the model until the experts change the probability to be higher or lower than this neutral value.
- Outcome Events (OE_i): These measure the results of the system that is being modeled at the end of the time-period. For example, if one is measuring a conflict situation between two entities then one can define a probability of success for one entity, which is one minus the probability of success of the opposite of an objective (or the failure of the objective). The probability of an outcome event is the probability of it being true at the end of the time-period and the initial value is estimated at .5 probability as well.

Given the linear influence factors we can show estimators the consistent relative relationships between any event and those that influence it by plotting these relationships on a linear scale. We can then use a different modeling method, Interpretive Structural Modeling (ISM), to analyze the complexity of the resulting weighted influence graph [13]. The following extension would allow individuals to receive a graphical visualization of their judgments and increase their ability to make improvements. The extension will also allow a group to receive a linear visualization of their collective results. In Fig. 1 the methodological merger between CIA and ISM is shown. In this approach, the structural matrix model is obtained from processing the C_{ij} and G_i factors of the transposed cross-impact matrix. That is, the output of the CIA is the input to the ISM.

These are the fundamentals of the CIA-ISM approach. Nevertheless, it is important to remark that the theory behind the CIA-ISM process requires additional reading [3–5]. In summary, an individual or a group constructing a model can take the final visualization of the impacts and recognize which events are the most critical and if there are any cyclic clusters of events that could be collapsed into a mini scenario to reduce the size of the event set into a more manageable model. The transformation from the cross impact model and the ISM model is a perturbation process where one takes the largest absolute value impacts between any two events and converts them to 1 and the rest 0 to form a standard binary network of 0 or 1 relationships. One examines the results and keeps adding more of the C_{ij} values converted to 1 to see how the graph gradually changes and to determine what might be a good point to use as a final conceptual model of the overall scenario.

2.2. Group estimation process

CIA-ISM requires two different collaborative activities if it is to be a useful part of the emergency preparedness process. The first is the creation of the event set in a process where the experts may propose events and then evaluate their significance for inclusion in building the model by a group. The second is the group process to make the estimates of the cross-impact relationships.

Event set creation is a straightforward process based on compiling a suggested list of events by members of the group and having the individuals judge their significance. This is a critical process in the sense that it requires a large problem solving capability of the group. It is important to get a rich and comprehensive set of possible events in order to have a good starting point in the model and thus one must include different views and perspectives on the problem by means of a heterogeneous expert panel. This heterogeneity is a risk and opportunity at the same time for the process. It is an opportunity in the sense that it could allow a rich debate about the key issues to be addressed in the scenario. But it is a potential risk because the different backgrounds of the team could be a communication barrier. Thus, at this stage the CIA-ISM could be combined with other methodologies aimed at enhancing group collaboration such as Focus Group, Delphi Technique, Brainstorming, or Role Playing, among other qualitative methodologies. For this exercise, event set creation occurred in a two day workshop at which the authors were joined by an

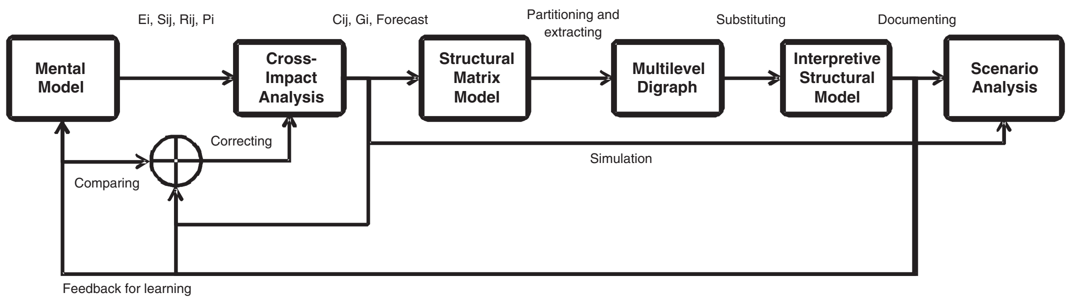


Fig. 1. CIA-ISM process [3].

emergency medicine doctor who worked for the emergency management agency in one of the largest Spanish cities.

The second stage – inputs elicitation – is a highly time consuming process that provides causal relationship estimates for the cross-impact process, and is the focus of this paper. It is our view that a system has to be designed and implemented that has the following properties [3]:

1. Each expert in the group can designate the subset of events he or she feels confident about for making estimates of the cross-impact probability factors.
2. There should on the average be at least three estimators for every cross-impact cell that is non-zero. These should end up to be consensus estimation at least with respect to the direction of impact of one event upon another (whether it makes the other event more probable than .5 or less probable). The .5 probability implies there is no influence relationship between the two events.
3. If there is any disagreement about the direction of impact between two events, this must be communicated to the current estimators in a manner in which they can discuss the disagreement, preferably in an anonymous or pen name mode on an online discussion system. If disagreement remains one should try to raise the estimators to at least 5 for that particular cell so one can determine if there is a true minority subgroup (2 out of 5).
4. If agreement is not reached on the direction of impact, one needs to bring in additional estimators capable of judging that particular interaction and/or a wider discussion is introduced to involve more of the participants.
5. Once there is agreement on direction of the relationship between any two events, one should also check that the estimated probability values for a single interaction are all in one of the following alternative ranges for probability: .6 or greater (likely), .4 or less (unlikely), or between .4 and .6 (uncertain). One might want to allow a discussion in some cases when there is not this level of agreement.
6. One should use Dalkey's formula (expression 1) derived Bayesian relationship to calculate a better group probability for a specific interaction as opposed to using simple averaging of the estimates [14]. This formula says that if all individuals agree on a non .5 probability being in one direction (i.e. more or less than .5), then the results will be stronger in that direction than the average of the estimates. In some cases, it might be useful to perform the analysis using both the average values and separately the Bayesian estimates. The latter will produce a model with stronger properties of influence when there is a strong consensus in the direction of the estimates for each cell.

$$P(J/R) = \frac{\prod_{i=1}^{n} Ri}{\prod_{i=1}^{n} Ri + \prod_{i=1}^{n} (1-Ri)} \tag{1}$$

where:

J	Represents an event
R	Are the estimations
N	Represents the number of estimations.

7. Once there is a complete set of estimates ISM should be applied in order to represent graphically the group vision of the scenario. This can bring about a significant reduction in the complexity of understanding the group view and could help the participants to revise again if their estimates for the direction of the group vision are not in agreement.
8. Once a model has been established for the group it is possible to vary the initial probabilities of individual events and see the degree of influence that this has on the occurrence of the other events by means of computer interaction. There are also internal measures that quantifiably express to what degree a given event is controlled externally to the set. This indicates either that it is truly external or that events might be missing that should have been included. One can also quickly list which events have the most influence on which other events.
9. For any event in the set one can list the other events influencing the particular event, ordered from most important to least important events influencing the event one is interested in, from the most positive influence to the most negative influence. These linear lists make the resulting model highly transparent to the producers and users of the model.

3. Illustrative application

In this section an illustrative application of the CIA-ISM for supporting collaborative scenario generation is described. We selected a potential terrorist attack with a dirty bomb, looking for complexity and variety of the set of events. This is a dynamic scenario exercise in which an initial scenario is presented describing a possible situation, and then various assumptions are specified as being relatively true or false at the start of the time interval over which the model is executed. This triggers the inference of the impact of these assumptions on the relationships in the model to determine which situations and actions are likely to occur during the time interval for which the model is valid and the resulting impact on various outcome events/variables at the end of the time interval.

The initial event set of the scenario was based on interviews with practitioners and was presented at several group meetings and conferences [15] with the aim of improving the definitive event set. The cross-impact estimations are based upon the judgments and estimates of the authors in creating the interacting elements and judging the relative impact they have upon one another to influence the probability of a degree of truth about assumptions, actions, events, and/or outcomes. The three contributors went through four rounds of estimations where they could see the disagreements on things like the direction of impact between two events and discuss which direction would be correct.

3.1. Assumptions of the model

A dirty bomb in a packing crate for a large restaurant refrigerator is delivered to the kitchen of a restaurant located on the top floor of a major shopping center in a popular downtown urban shopping area during the late morning hours. The kitchen manager is told that the installer will come in a few hours to unpack and install it. A short time after moving it into the kitchen there is a major explosion followed shortly by a smaller secondary one, and a fire. The bomb contains 1200 Ci of Cesium 137 in the form of CSC powder, giving about 350 rad per hour at 1 m. This is about half the amount contained in an industrial irradiator for agricultural seeds. The bomb blows a hole in the ceiling and an external wall allowing the escape of the radioactive powder into both the shopping mall and through the roof of the mall into the open air. There is considerable broken glass in the shopping area of the mall and numerous injuries in the immediate area as well as some deaths. Given a 3 to 5 mile variable wind in the surrounding courtyards and city streets, the area of major contamination possible is about 16 square blocks. The best estimates are there are about 30,000 to 40,000 people in this area both inside and outside the buildings as well as local traffic and transportation. No one is aware at the time of the explosion that this was a terrorist bomb containing a radioactive contaminant. Shopping center security sends a report to the fire department, the medical emergency service, and police that there has been an explosion in the kitchen of a restaurant and that it is assumed to be a natural gas explosion. This results in fire and medical responders to what is being treated as a gas explosion. The police come to aid in controlling traffic, curious crowds converging towards the area, and the evacuation of the shopping center.

To build a model of this situation we have the following types of events or potential assumptions: statements of initial conditions that have a degree of truth at the start of the time period over which the model is executed, cross impact dynamic events which can occur or not occur during the time period for the specified model, and potential outcome events or measures of outcomes at the end of the model's time period. The model is designed to determine the resulting occurrences, happenings, and consequences over a 24 h period from the explosion.

3.2. Events

The model presented here does reduce a somewhat larger set of potential events to 22 events, 4 of which are further identified to be Initial Condition Events, 14 as Dynamic Events, and 4 as Outcome Events. The problem of collaboratively treating the estimation of a larger set will be taken up after a brief description of the elements.

3.2.1. Initial conditions

Initial conditions are assumptions, a priori or source events that have already occurred (or not) before the beginning of the time-period (the onset of the hypothetical emergency). So they have a probability of being true or false. For this example, four were identified:

- IC1 Decontamination Preparedness: There are enough trained people, hand held detectors, and portable decontamination units to equip responder units and to decontaminate at least 1000 people per hour.
- IC2 Bomb Assessment: The equipment brought to any bomb explosion site by the police includes a radiation detector as a standard requirement.
- IC3 Bomb recognition: Firemen are trained to recognize indictors of a bomb-generated explosion.
- IC4 Public Trust: The public trusts the decisions of the local leadership and will follow their requests for public behavior in emergencies.

3.2.2. Dynamic events

The dynamic events are the core of the modeling process and their initial values are chosen to reflect current wisdom about their likelihood. They are also chosen to provide a balanced model where possible negative influences as well as positive influence events are somewhat equally represented. For obtaining estimates for each dynamic event within the model they are assumed to have an initial probability of .5. In this case the experts estimate possible interactions of the events with one another during the 24 h after the explosion:

- DE1 Bomb recognition: A fireman with training recognizes bomb fragments within the first hour after the explosion.
- DE2 Medical Recognition: A medical responder has demanded a radiation detector within the first hour after the explosion.
- DE3 Threat recognition: There is recognition of a radiation threat in the first four hours of the event.
- DE4 Military Control: The military under national government command takes charge of the situation within the first 12 h.
- DE5 Center cleared: The shopping center is cleared of all non-injured individuals within the first hour.
- DE6 Official Recognition: The leadership of the city and province declare a province-wide emergency by the fourth hour after the explosion to all other local and national government bodies.
- DE7 Containment Action: A containment effort for everyone in the possible contamination area is undertaken by the third hour by police and other emergency personnel.

- DE8 Leadership Disagreement: The city leadership does *not* agree to notify the public immediately upon determining there is a radiation contamination problem.
- DE9 Press Leak: The public is first notified of the radiation problem by a radio/TV reporter who is leaked the information by some unknown person.
- DE10 Makeshift decontamination: Makeshift/make-do decontamination centers are set up and made operational beginning in the fifth hour and stretching over the next twelve hours.
- DE11 Public Panic: There is a rush to leave the city by any means possible as public panic sets in.
- DE12 Non-Responders: A significant number of trained people refuse to carry out the decontamination procedures because there is no protective clothing and accessories for them to wear and use.
- DE13 Internal Contamination: Emergency medical treatment facilities are set up by the military for holding people with internal contamination for treatment.
- DE14 Public refusal: Many people refuse to wait in lines for contamination checks and leave the holding area without permission.

3.2.3. Outcome events

We have specified two typical negative outcomes followed by two positive ones. These reflect both the effectiveness vs. efficiency paradox and the difference between long and short term considerations as well as some of the consequences of the initial conditions and the dynamic event interactions during the initial 24 h of the emergency. These are also assumed to have an initial probability of .5 for the solicitation of the estimates to create the model:

- OE1 City Isolation: The total city area is quarantined from the rest of the world until contamination detection is conducted for all citizens and physical areas.
- OE2 Income Loss: The sum of the costs of this event and the income loss to the city is very large in terms of the Gross National Product contribution of that city to the national income for one year.
- OE3 Short term Success: About 80% of those estimated as contaminated are detected and decontaminated in the first 24 h.
- OE4 Public Trust: The public trust in local leaders after the emergency is high, so the public is cooperative and trusting in the advice and directions of the city leadership in the post-crisis stage.

3.3. Cross-impact estimations

The individuals involved in the estimation process (the three authors of this paper) expressed the relationships in the interaction among these three types of variables in the model in order for it to become a working dynamic model. In soliciting judgments about the interaction among these three types of components (i.e. initial conditions, dynamic events, and outcome events) we assumed an initial probability of .5 for either the occurrence of an event, the degree of truth about an initial assumption, or the truth about an outcome measure. A probability of .5 is the zero point for probability where no information is available to make any meaningful judgment. This represents about 219 consistent estimates that must be made by the group (Fig. 2).

This information was solicited from individuals. Each estimator supplied either a probability estimate change of the event E_i from .5, given that it is known that the event E_j was supposed to not occur. Each choice for each interaction had one of these alternatives:

1. A probability higher than the initial .5 if the event has a negative influence.
2. A probability less than the initial .5 if the event has a positive influence.
3. A judgment that there is no interaction; probability stays at .5.

By using the process described above in the section entitled "Group Estimation Process," we obtain the estimations. The interaction was supported by a four round process (Fig. 3).

In the first round we obtained the initial estimations. Then a first structural model was provided to the estimators in order to look for consistency in the individual judgments. Based on these results experts are able to compare the structural model results with their mental model and, in case they are not consistent, to correct their initial estimations. The main goal of this feedback process is avoiding any conceptual inconsistency on the individual level, which is likely to occur when hundreds of separate estimations are being made. Once the estimators were confident with their initial estimations their estimations were aggregated using expression 1. Then an initial analysis (both graphical and analytical) of the group response was provided to the estimators. In this round they were able to change their initial estimation in the direction of the group response. Finally, the estimators were asked to solve their conflicts, defined as a disagreement in the sense of the direction of the impact between two events. This process stopped when 0 conflicts were reached, or when the estimators "agreed to disagree" (Table 1). A "No Judgment" or a lack of interaction by a participant on a given interaction cell was not considered a disagreement when another person made an entry of a change of probability. The only cells in disagreement (a direction conflict) were those that had at least one estimate greater than .5 and at least one lower than .5 probability. After discussion someone might make a revised estimate.

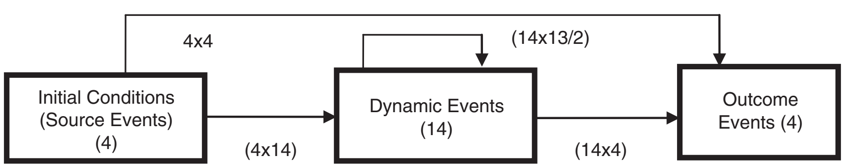


Fig. 2. Influence diagram with number of events and number of estimates needed (legs).

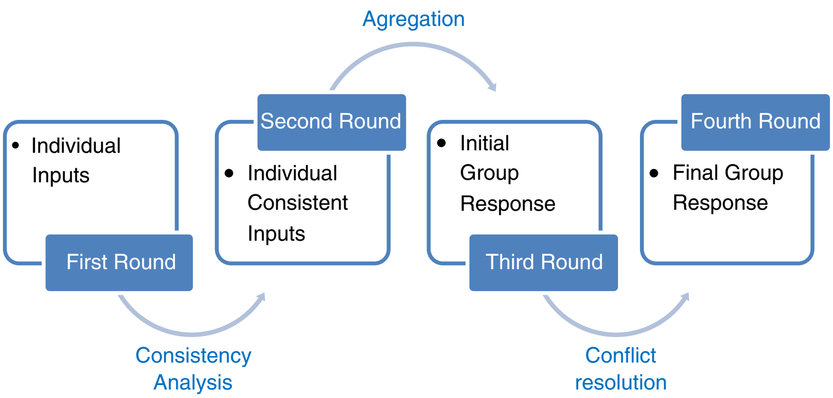


Fig. 3. Rounds in the group estimation process.

3.4. Cross-impact analysis

Table 1 shows how this process increased the intensity of the impacts (increasing sum of the absolute C_{ij} and G_i values as well as absolute C_{ij} mean) and the consensus among the estimators (decreasing the number of conflicts and the sum of the standard deviation of the individual C_{ij} estimations).

Due the nature of Dalkey's formula, an increase of the mean of the estimations means that estimators reached a consensus about the sense of the estimations (positive or negative) so it means an increase of the consensus. As long as the influences of the internal events are significantly smaller than the internal events this implies we have a good model where most of the impacts are represented by the internal event set in the minds of the participants.

Once we obtain the subjective probabilities, we are able to build the cross-impact matrix for the group estimation (Table 2). The rows (i) and the columns (j) of the matrix are the events, the cells are the influence factors C_{ij}, the diagonal being the overall probabilities (OPV). As we mentioned in Section 2.1, C_{ij} represents the impact of the j-th event on the i-th event. Positive C_{ij} means it enhances the occurrence of the event and negative detracts from the occurrence; note that in this context, the words “positive” and “negative” denote the mathematical direction of the impact (+ or −) and not its social desirability. The G vector represents the influence of external events on each i-th event. The logical interpretation of G factor is the total influence on the i-th event of those events we did not specify explicitly in the model. It is formally the constant of integration for forming the equation of the i-th event. The final result for the fourth round $83.29/(316.95+83.29)=.21$ shows that 21% of the impacts were in the events we did not include and 79% were due to the events we did include.

In order to get a numerical estimate of the total variability in the matrix of influence factors we examine the following linear sums of the cross-impact factors C_{ij} from the original C_{ij} matrix

$$|\text{Internal Event Influences}| = \sum \left|C_{ij}\right| = 316.94 \quad (2)$$

$$|\text{Initial Conditions Influences}| = \sum |C_{il}| = 94.81 \quad (3)$$

$$|\text{Dynamic Events Influences}| = \sum \left|C_{ij}\right| - \sum |C_{il}| = 222.13 \quad (4)$$

$$|\text{External (unspecified) Event Influences}| = \sum |G_i| = 83.29 \quad (5)$$

$$|\text{Total Impacts}| = \sum \left|C_{ij}\right| + \sum |G_i| = 400.23. \quad (6)$$

This allows us to calculate the relative fractions or percentages of the impacts due to each type of event.

$$|\text{Initial Conditions Impact}|/|\text{Total Impacts}| = 0.2368 = 23.68\% \quad (7)$$

$$|\text{Dynamic Events Impacts}|/|\text{Total Impacts}| = 0.555 = 55.50\% \quad (8)$$

$$|\text{External events Impacts}|/|\text{Total Impacts}| = 0.2082 = 20.82\%. \quad (9)$$

Therefore, 20.82% of the influences are due to the events we did not specify (External Events Impacts or G). The dynamic events make up 55.50% of the influences. We see that the initial conditions account for 23.68% of the influence. Essentially 79% of the impacts in the model are explained by the events made explicit in the model.

Table 1
Evolution of the group estimation process.

	Number of conflicts	Internal event influences $\Sigma\|C_{ij}\|$	External event influences $\Sigma\|G_i\|$	Internal event mean $\|C_{ij}\|$	Internal event dispersion $\Sigma(\sigma\|C_{ij}\|)$
First round	56	281.34	67.23	1.04	37.80
Second round	32	275.52	69.98	1.09	33.81
Third round	39	280.39	73.38	1.14	35.87
Fourth round	0	316.95	83.29	1.23	29.91

Table 2
Cross-impact matrix.

Events	IC1	IC2	IC3	IC4	DE1	DE2	DE3	DE4	DE5	DE6	DE7	DE8	DE9	DE10	DE11	DE12	DE13	DE14	OE1	OE2	OE3	OE4
IC1	OVP	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
IC2	0.00	OVP	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
IC3	0.00	0.00	OVP	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
IC4	0.00	0.00	0.00	OVP	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
DE1	0.27	2.65	3.31	0.00	OVP	0.00	3.06	0.00	0.92	0.00	0.00	−0.56	0.00	0.00	−0.56	−0.27	0.92	0.00	0.00	0.00	0.00	0.00
DE2	1.19	1.19	1.40	0.00	0.54	OVP	3.06	0.00	0.92	0.00	0.00	−0.56	0.00	0.00	−0.56	−0.27	0.92	0.00	0.00	0.00	0.00	0.00
DE3	0.54	2.05	2.05	0.00	0.84	1.76	OVP	0.00	0.92	0.00	0.92	−0.56	0.00	0.00	−0.56	−0.27	0.92	0.00	0.00	0.00	0.00	0.00
DE4	0.00	0.98	1.34	1.69	1.25	1.13	2.22	OVP	−0.27	1.49	−0.54	−1.86	−0.56	0.54	−1.19	−1.19	0.54	−0.54	0.00	0.00	0.00	0.00
DE5	0.92	0.54	1.19	0.00	0.84	1.93	1.85	0.00	OVP	0.00	1.46	−0.56	0.00	1.19	0.00	0.00	0.56	0.00	0.00	0.00	0.00	0.00
DE6	0.84	1.19	1.13	1.46	1.76	1.76	5.09	1.46	0.00	OVP	0.27	−1.43	−1.46	0.56	−2.39	−1.19	0.00	−1.11	0.00	0.00	0.00	0.00
DE7	3.55	1.49	1.85	0.00	0.92	1.49	4.07	1.85	3.06	3.90	OVP	−0.81	−0.92	0.92	−1.74	−1.66	1.34	−0.27	0.00	0.00	0.00	0.00
DE8	−1.19	−0.56	−0.92	−1.74	0.00	0.00	−1.96	−1.85	0.00	−1.74	−0.27	OVP	1.74	−0.27	1.46	0.92	−0.27	0.54	0.00	0.00	0.00	0.00
DE9	−0.56	0.00	−0.56	−1.60	−0.27	0.00	−1.96	−1.85	−0.27	−1.69	−0.54	1.76	OVP	−0.27	1.46	0.92	−0.27	0.27	0.00	0.00	0.00	0.00
DE10	1.76	0.84	0.00	0.00	0.27	0.54	2.22	1.85	0.00	0.41	1.49	−0.81	0.00	OVP	0.00	−0.73	1.34	0.27	0.00	0.00	0.00	0.00
DE11	−0.84	−0.56	−0.27	−2.66	0.00	−1.85	−2.53	−1.49	−1.25	0.27	−0.81	0.97	0.84	0.27	OVP	1.69	−0.27	1.19	0.00	0.00	0.00	0.00
DE12	−2.58	0.00	−0.27	−1.74	0.00	0.00	−1.96	−2.77	−0.27	−0.27	−0.81	0.27	1.46	−0.54	1.46	OVP	−0.56	0.84	0.00	0.00	0.00	0.00
DE13	1.76	1.13	1.13	2.77	0.00	0.00	1.49	2.20	0.00	1.13	0.56	−0.56	0.00	0.84	−0.54	0.54	OVP	0.00	0.00	0.00	0.00	0.00
DE14	−1.76	−0.92	−0.92	−2.80	0.00	0.00	−1.46	−1.13	−0.40	−1.13	−0.54	0.70	0.54	−0.27	2.44	1.76	−0.97	OVP	0.00	0.00	0.00	0.00
OE1	−2.66	−1.19	−0.84	−1.60	−0.40	−0.67	−2.15	0.54	−0.54	0.54	−1.69	1.40	0.27	−0.67	1.76	0.54	−0.81	0.54	OVP	0.00	0.00	0.00
OE2	−1.76	−0.70	−0.54	−1.74	−0.54	−0.54	−1.88	0.27	−0.68	−0.40	−1.69	1.76	0.27	−1.76	1.61	0.84	−0.81	0.54	0.00	OVP	0.00	0.00
OE3	2.80	1.90	1.90	2.30	0.56	0.84	3.45	0.54	0.84	0.84	1.90	−1.40	−0.27	1.61	−1.19	−1.76	1.27	−1.11	0.00	0.00	OVP	0.00
OE4	1.85	1.19	1.19	5.95	0.56	0.56	2.50	0.67	0.81	1.54	1.26	−1.76	−1.11	1.11	−1.76	−1.90	1.70	−1.70	0.00	0.00	0.00	OVP
G	0.00	0.00	0.00	0.00	−4.87	−3.92	−4.31	−2.51	−4.96	−3.98	−9.52	3.06	2.72	−4.72	3.65	3.87	−6.22	3.44	3.82	3.88	−7.51	−6.35

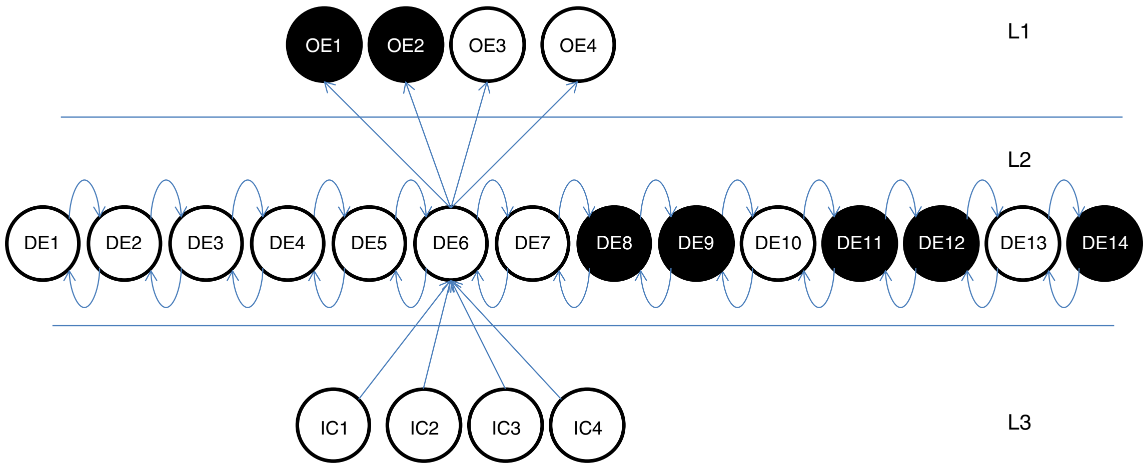


Fig. 4. Digraph for the limit $|C_{ij}|>0.56$ — percentile 30.

3.5. Scenario analysis

By applying the CIA-ISM approach, we can represent the forecasted scenario by means of a digraph (Fig. 4). This process is based on the incorporation of more of the larger C_{ij} factors and reviewing the resulting model for all C_{ij}'s greater than (or equal) to an absolute value. We may continue this process until we find a $|C_{ij}|$ value for which an E_i event has at the same time, as antecessor or successor, the occurrence and non-occurrence of an event E_j. We call to this $|C_{ij}|$ value the limit of the forecasted scenario [3]. In this example the limit is $|C_{ij}|=0.56$. By adding all the $|C_{ij}|$ values between the limit and the maximum value of the $|C_{ij}|$ frequency distribution, we obtain the forecasted scenario expressed in Fig. 4, which includes 89.10% of the linear sums of $|C_{ij}|$. This value is an indicator of the boundary of the estimation. This is the largest perturbation that can be made to the model and the most compacted hierarchical model that can be formulated. As we shall see the most informative version of the model for decision understanding is Fig. 8 which shows three very prominent mini scenarios for understanding the influences in this hypothetical crisis.

Following the CIA-ISM notation [3], the color of the events (black and white) represents the different senses of the impacts. Relationships between two events of the same color represent positive impact, while relationships between two events with different colors are negative impacts. For instance, this digraph shows that having an adequate number of resources (IC2) and training skills (IC3) together with adequate resources for responding to the emergency (IC1) and the existence of public trust in local leadership (IC4) would trigger the occurrence of a set of dynamic events (DE1, DE2, DE3, DE4, DE5, DE6, DE7, DE10, DE13) that will decrease the probability of city isolation (OE1) and large income loss (OE2) and increase short term success (OE3) and the subsequent public trust (OE4). L*x* expresses the level of the digraph. We obtain the same result by means of the perturbation simulation method [10] when we use the probability of the initial conditions IC1 = IC2 = IC3 = IC4 = 0.99. Following this simulation methodology, we take each initial condition and set each one in turn to a value of .99. The rest of the events keep their initial .5 value. In the perturbation model approach this causes that event to either occur or not occur first in the sequence, causing the other events affected to change their values, and then one takes the value closest to 0 or 1 to next be determined to not occur or occur. The process continues until all the outcomes are determined. In this case, the simulation requires 19 steps (S_k) for obtaining a complete forecast (expression 10).

$$\text{Occuring Events Summary: IC1, IC2, IC3, IC4} \rightarrow \text{DE1, DE2, DE3, DE4, DE5, DE6, DE7, DE10, DE13} \rightarrow \text{OE3, OE4.} \tag{10}$$

Table 3 is useful for understanding the graphical results and also for the group of estimators to understand better the implications and consistency of their estimates. In this case, it makes it quite clear what the group thought.

Using this simulation tool, other options might be explored by the group. In Table 4, all the different unique combinations of initial conditions (IC1-IC4 columns in bold) are displayed in the resulting sixteen (24) scenarios (rows) providing the resulting occurrence or non occurrence of all the other events. In this table a cell with a value “1” represents that an event (column) occurs in a scenario (row); and a value “0” indicates that an event (column) does not occur in a scenario (row). Please note that the results of Table 3 are shown in the first row of Table 4 (Scenario 1). The other fifteen scenarios have been obtained using the same procedure (perturbation model approach) that is explained above in the text. This simulation capability can also be used for outcome event analysis.

Table 5 shows for each event whether the occurrence or non occurrence of that event impacts on the good outcome or the bad outcome, where OE1 city isolation and OE2 income loss are bad, and O3 short term success and O4 public trust are good. Table 5 is a summary of a large number of different runs of the model and it includes both the direct and indirect impact (cascading effect) of each event on the outcome events. These results are consistent with the graphical analysis shown in Fig. 4. For example, Table 5 shows that the model predicts that the occurrence of event DE1 (Bomb Recognition) might have a positive impact on the good outcome as well as a negative impact on the bad outcome. This

Table 3
Forecasted scenario — simulation for IC1 = IC2 = IC3 = IC4 = 0.99.

Events	Pi	S1	S2	S2	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15	S16	S17	S18	S19
IC1	0.990	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
IC2	0.990	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
IC3	0.990	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
IC4	0.990	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
DE1	0.500	0.957	0.996	0.998	0.998	0.998	0.998	0.998	0.998	0.998	0.998	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
DE2	0.500	0.869	0.988	0.994	0.995	0.995	0.995	0.995	0.995	0.995	0.995	0.995	0.995	0.995	0.995	1.000	1.000	1.000	1.000	1.000
DE3	0.500	0.911	0.992	0.996	0.996	0.996	0.996	0.996	0.996	0.996	0.996	0.996	0.996	1.000	1.000	1.000	1.000	1.000	1.000	1.000
DE4	0.500	0.706	0.991	0.996	0.996	0.996	0.996	0.996	0.996	0.996	0.996	0.996	0.996	0.996	1.000	1.000	1.000	1.000	1.000	1.000
DE5	0.500	0.791	0.974	0.984	0.985	0.985	0.985	0.985	0.985	0.985	0.985	0.985	0.985	0.985	0.985	0.985	0.985	0.985	1.000	1.000
DE6	0.500	0.910	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
DE7	0.500	0.969	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
DE8	0.500	0.099	0.003	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
DE9	0.500	0.181	0.005	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
DE10	0.500	0.809	0.982	0.990	0.991	0.991	0.991	0.991	0.991	0.991	0.991	0.991	0.991	0.991	0.991	0.991	0.991	1.000	1.000	1.000
DE11	0.500	0.103	0.010	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.000	0.000	0.000	0.000
DE12	0.500	0.060	0.003	0.001	0.001	0.001	0.001	0.001	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
DE13	0.500	0.707	0.894	0.952	0.952	0.953	0.953	0.953	0.953	0.953	0.953	0.953	0.953	0.953	0.953	0.953	0.953	0.953	0.953	1.000
DE14	0.500	0.039	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
OE1	0.500	0.041	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
OE2	0.500	0.086	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
OE3	0.500	0.988	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
OE4	0.500	0.994	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000

Table 4
Scenario analysis.

	IC1	IC2	IC3	IC4	DE1	DE2	DE3	DE4	DE5	DE6	DE7	DE8	DE9	DE10	DE11	DE12	DE13	DE14	OE1	OE2	OE3	OE4
Scenario 1	**1**	**1**	**1**	**1**	1	1	1	1	1	1	1	0	0	1	0	0	1	0	0	0	1	1
Scenario 2	**0**	**1**	**1**	**1**	1	1	1	1	1	1	1	0	0	1	0	0	1	0	0	0	1	1
Scenario 3	**0**	**0**	**1**	**1**	1	1	1	1	1	1	1	0	0	1	0	0	1	0	0	0	1	1
Scenario 4	**0**	**0**	**0**	**1**	0	0	0	0	0	0	0	1	1	0	1	1	0	1	1	1	0	0
Scenario 5	**0**	**0**	**0**	**0**	0	0	0	0	0	0	0	1	1	0	1	1	0	1	1	1	0	0
Scenario 6	**1**	**0**	**0**	**0**	0	0	0	0	0	0	0	1	1	0	1	1	0	1	1	1	0	0
Scenario 7	**0**	**1**	**0**	**0**	0	0	0	0	0	0	0	1	1	0	1	1	0	1	1	1	0	0
Scenario 8	**0**	**0**	**1**	**0**	0	0	0	0	0	0	0	1	1	0	1	1	0	1	1	1	0	0
Scenario 9	**1**	**0**	**0**	**1**	0	0	0	0	0	0	0	1	1	0	1	1	0	1	1	1	0	1
Scenario 10	**0**	**1**	**1**	**0**	1	1	1	1	1	1	1	0	0	1	0	0	1	0	0	0	1	0
Scenario 11	**1**	**0**	**1**	**0**	1	1	1	1	1	1	1	0	0	1	0	0	1	0	0	0	1	0
Scenario 12	**0**	**1**	**0**	**1**	0	0	0	0	0	0	0	1	1	0	1	1	0	1	1	1	0	1
Scenario 13	**1**	**1**	**0**	**0**	0	0	0	0	0	0	0	1	1	0	1	1	0	1	1	1	0	0
Scenario 14	**1**	**0**	**1**	**1**	1	1	1	1	1	1	1	0	0	1	0	0	1	0	0	0	1	1
Scenario 15	**1**	**1**	**0**	**1**	1	1	1	1	1	1	1	0	0	1	0	0	1	0	0	0	1	1
Scenario 16	**1**	**1**	**1**	**0**	1	1	1	1	1	1	1	0	0	1	0	0	1	0	0	0	1	1

outcome events analysis could be complemented with the direct impact of initial conditions and dynamic events on such specific outcome events (Tables 6 to 9).

For example, Table 6 indicates that the model predicts public panic and leadership disagreement as the strongest precursors of possible imposed isolation of the city, whereas the existence of public trust, early containment action, early threat recognition, and decontamination preparedness strongly decrease the likelihood of this outcome.

These same predictors are the strongest influence on substantial income loss, except that the establishment of makeshift decontamination procedures soon after the event also as seen as making income loss substantially less likely (Table 7).

Table 5
Outcome Events Analysis.

Event	Good outcome +OE3 and +OE4 −OE1 and −OE2	Bad outcome +OE1 and +OE2 −OE3 and −OE4
Initial conditions		
IC1 decontamination preparedness	+	−
IC2 bomb assessment	+	−
IC3 bomb recognition	+	−
IC4 public trust	+	−
Dynamic events		
DE1 bomb recognition	+	−
DE2 medical recognition	+	−
DE3 threat recognition	+	−
DE4 military control	+	−
DE5 center cleared	+	−
DE6 official recognition	+	−
DE7 containment action	+	−
DE8 leadership disagreement	−	+
DE9 press leak	−	+
DE10 makeshift decontamination	+	−
DE11 public panic	−	+
DE12 non-responders	−	+
DE13 internal contamination	+	−
DE14 public refusal	−	+

On the other hand, the strongest influences on both short term success and public trust are early threat recognition, decontamination preparedness, and initial public trust (Tables 8 and 9), whereas the factors that make these desirable outcomes least likely are refusal by responders to participate in decontamination, public panic and leadership disagreement.

The four Tables 6 to 9 show the most important events for causing each of the four outcomes to occur or to not occur. Since events OE1 and OE2 are bad outcome events and OE3 and OE4 are good outcome events (Table 5) we can determine which events have a direct impact on any given outcome. If we take each of these four outcomes and list the events that encourage the occurrence of the outcome, we can list the events that are common to a good event outcome (Table 10). The score numbers of Table 10 are obtained by adding the absolute values of the C_{ij} influencing the good outcomes.

For the production of bad event outcomes, the most important seven events are shown in Table 11. The rank-ordered weights shown represent the total bad impact and are calculated as the sum of the absolute values of the C_{ij} influencing the bad outcomes.

Table 6
OE1 — city isolation (ordered influences table).

J Event ID	Short title E_j	C_{ij}
DE11	Public panic	1.76
DE8	Leadership disagreement	1.40
DE4	Military control	0.54
DE6	Official recognition	0.54
DE12	Non-responders	0.54
DE14	Public refusal	0.54
DE9	Press leak	0.27
DE1	Bomb recognition	−0.40
DE5	Center cleared	−0.54
DE2	Medical recognition	−0.67
DE10	Makeshift decontamination	−0.67
DE13	Internal contamination	−0.81
IC3	Bomb recognition	−0.84
IC2	Bomb assessment	−1.19
IC4	Public trust	−1.60
DE7	Containment action	−1.69
DE3	Threat recognition	−2.15
IC1	Decontamination preparedness	−2.66

Table 7
OE2 — income loss (ordered influences table).

J Event ID	Short title E_j	C_{ij}
DE8	Leadership disagreement	1.76
DE11	Public panic	1.61
DE12	Non-responders	0.84
DE14	Public refusal	0.54
DE4	Military control	0.27
DE9	Press leak	0.27
DE6	Official recognition	−0.40
IC3	Bomb recognition	−0.54
DE1	Bomb recognition	−0.54
DE2	Medical recognition	−0.54
DE5	Center cleared	−0.68
IC2	Bomb assessment	−0.70
DE13	Internal contamination	−0.81
DE7	Containment action	−1.69
IC4	Public trust	−1.74
IC1	Decontamination preparedness	−1.76
DE10	Makeshift decontamination	−1.76
DE3	Threat recognition	−1.88

Table 9
OE4 — public trust (ordered influences table).

J Event ID	Short title E_j	C_{ij}
IC4	Public trust	5.95
DE3	Threat recognition	2.50
IC1	Decontamination preparedness	1.85
DE13	Internal contamination	1.70
DE6	Official recognition	1.54
DE7	Containment action	1.26
IC2	Bomb assessment	1.19
IC3	Bomb recognition	1.19
DE10	Makeshift decontamination	1.11
DE5	Center cleared	0.81
DE4	Military control	0.67
DE1	Bomb recognition	0.56
DE2	Medical recognition	0.56
DE9	Press leak	−1.11
DE14	Public refusal	−1.70
DE8	Leadership disagreement	−1.76
DE11	Public panic	−1.76
DE12	Non-responders	−1.90

The numbers in Tables 10 and 11 act as a scoring factor for the events in the outcome lists. The scores provide the relative importance of the event in that role. Please note that this result is consistent and complementary to the outcome event analysis (Table 5) and the graphical representations of the scenario (Figs. 4, 6–8). This scoring method adds measures of the relative strength of influence on a linear scale, providing a powerful tool for examining relative scoring in a more enlightening approach to traditional ISM scoring [16].

3.6. Sensitivity analysis

Fig. 4 represents the limit for the scenario. Nevertheless, it could be more interesting to analyze a previous state of the system in order to try to understand the links among the different events. We will show this by means an incremental analysis of the forecasted scenario. Our starting point is the $|C_{ij}|$ distribution analysis. If we take the non-zero $|C_{ij}|$ values and plot the number of them as a histogram from zero to the largest absolute value, we have the $|C_{ij}|$ distribution. At this stage, we need to look for $|C_{ij}|$ values that represent the highest k% of the values of the distribution (Fig. 5). Note that we are going to take these values as cutting points of the digraphs. So for instance, if we take percentile 90 as the cutting point the digraph includes 10% of the highest impacts.

The evolution of the scenario is shown from Figs. 6 to 8. The digraph in Fig. 6 includes only the pairs with high impacts between events ($|C_{ij}|>2.16$), including just 16 of the 22 events in the representation. That is, this digraph includes the highest values of the distribution but it doesn't bring a complete forecast of the situation.

Fig. 7 illustrates the digraph for the highest 20% of the values of the distribution. At this level of analysis, we have all the events but no clear path in the occurrence of the events. In order words, this digraph does not help us understand the logical sequence of the events. So we need to add more information to the working model.

We continue this process until obtaining the output of the CIA-ISM for the highest 40% of the values of the distribution (Fig. 8).

Reviewing Fig. 8 helps in understanding the specific influence paths and underlying logical clusters of scenarios leading to this result. Moreover, it helps in making sense of the sequence and potential implications of the occurrence of events. Basically the

Table 8
OE3 — short term success (ordered influences table).

J Event ID	Short title E_j	C_{ij}
DE3	Threat recognition	3.45
IC1	Decontamination preparedness	2.80
IC4	Public trust	2.30
IC2	Bomb assessment	1.90
IC3	Bomb recognition	1.90
DE7	Containment action	1.90
DE10	Makeshift decontamination	1.61
DE13	Internal contamination	1.27
DE2	Medical recognition	0.84
DE5	Center cleared	0.84
DE6	Official recognition	0.84
DE1	Bomb recognition	0.56
DE4	Military control	0.54
DE9	Press leak	−0.27
DE14	Public refusal	−1.11
DE11	Public panic	−1.19
DE8	Leadership disagreement	−1.40
DE12	Non-responders	−1.76

Table 10
Scoring factor for the events — total good direct impact.

Event	Short description	Total good impact
IC4	Public trust	11.59
DE3	Threat recognition	9.98
IC1	Decontamination preparedness	9.07
DE7	Containment action	6.54
DE10	Makeshift decontamination	5.15
IC2	Bomb assessment	4.98
DE13	Internal contamination	4.59
IC3	Bomb recognition	4.47
DE5	Center cleared	2.87
DE2	Medical recognition	2.61
DE6	Official recognition	2.78
DE1	Bomb recognition	2.06
DE4	Military control	1.21
Total above		67.9

Table 11
Scoring factor for the events — total bad direct impact.

Event	Short description	Total bad impact
DE8	Leadership disagreement	6.32
DE11	Public panic	6.32
DE12	Non-responders	5.04
DE14	Public refusal	3.89
DE9	Press leak	1.92
DE4	Military control	0.81
DE6	Official recognition	0.54
Total above		22.84

mental model of the group is that an adequate number of resources (IC2) and training skills (IC3) to recognize a bomb will imply the detection of the radiation (DE2, DE3) and the bomb recognition (DE1). This recognition together with adequate resources for responding to the emergency (IC1) and the existence of public trust in local leadership (IC4) will impact on a scenario in which there is military control of the situation (DE4) and the local government recognizes the threat (DE6) and there is an agreement on the notification (−DE8). This avoids situations of press leaks (−DE9), public panic (−DE11) and non-responders (−DE12). This situation allows for a scenario in which emergency medical treatment facilities are set up by the military for holding people with internal contamination for treatment (DE13) as well as controlling the situation (DE14). These facts also allow for an adequate contamination containment action by the non-military emergency personnel (DE7) and makeshift/make-do decontamination centers being set up and made operational (DE10) to get the center cleaned (DE5). All the previous sequence impacts on a short term success of the response (OE3) to avoid the city's isolation (OE1) and a large income loss (OE2,) thus enhancing the public trust in the local leadership.

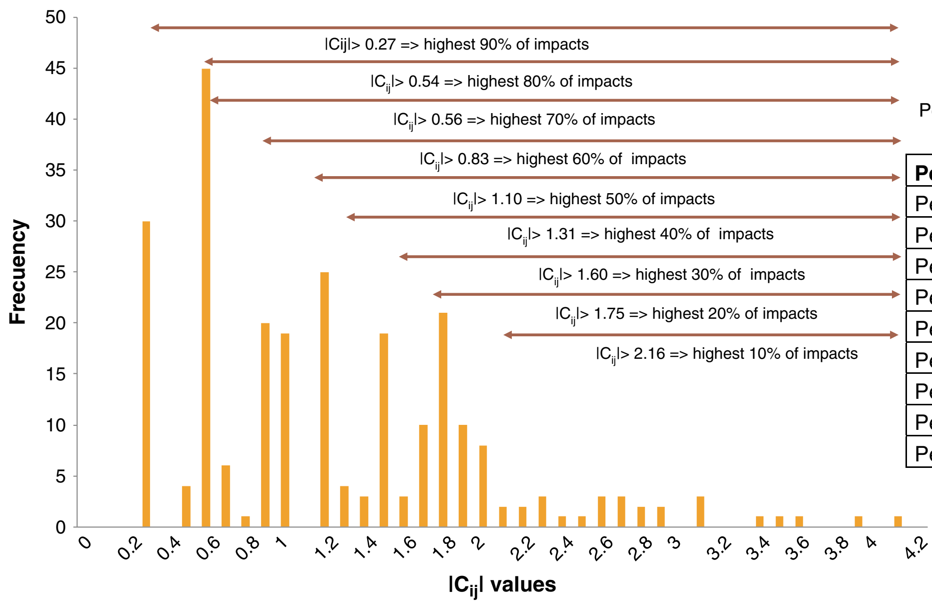
Reviewing Fig. 8 also helps in understanding the specific influence paths and underlying logical clusters scenarios leading to this result. Looking at Fig. 8, we have the following cluster possibilities:

$$((DE2, DE3), (DE5, DE7), (DE4, DE6, -DE8, -DE9, -DE11, -DE12)). \tag{11}$$

If one is trying to replace the original 14 dynamic events with a simpler model, then one can choose to cluster any of the two doublets and one 6 event inner model into 3 macro events and a remainder of 4 individual dynamic events. If a new reduced cross impact model is to be composed it will treat each chosen mini-scenario as a single event. This represents taking the 14 dynamic events and creating out of them 7 events that essentially represent the original model. It may also be that the user or users of this model decide they need to create some new events to describe potential increased control over the outcomes of the model. This would be normal in terms of any use of the model in a continuous planning process.

4. Discussion

The objective of the collaborative method we have described is to produce a dynamic scenario for a possible disaster that can be used in planning and training. To generate a scenario for planning and training uses, the values of some of the variables, including the input variables, would be changed for different exercises. Thus, each of several iterations could present a new and unique "practice event." On the one hand, these scenarios could be used to develop emergency plans. An Emergency Plan compiles both the prevention rules and the procedures to be applied in an emergency situation by detailing all potential incidences that might occur and influence its management. In order to design a good Emergency Plan, experts from different areas need to



Percentile	$\lvert C_{ij}\rvert$
Percentile 90	2.16
Percentile 80	1.75
Percentile 70	1.60
Percentile 60	1.31
Percentile 50	1.10
Percentile 40	0.83
Percentile 30	0.56
Percentile 20	0.54
Percentile 10	0.27

Fig. 5. Histogram of the $\lvert C_{ij}\rvert$ distribution.

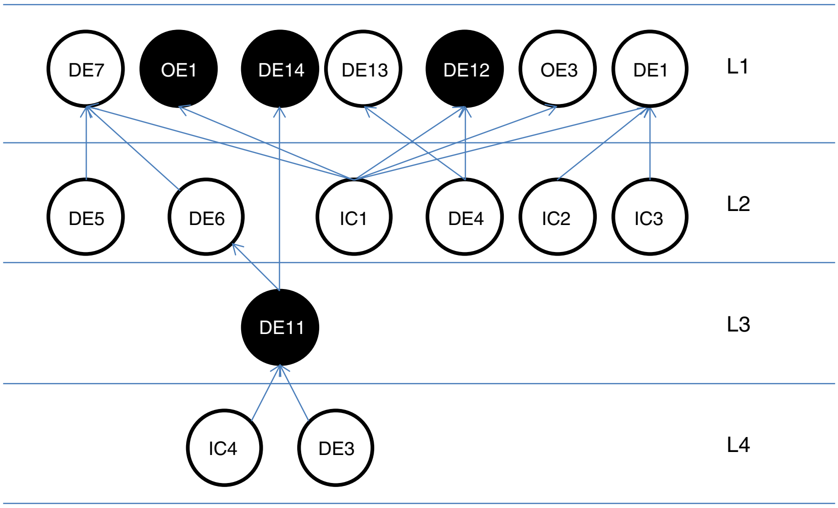


Fig. 6. Digraph for percentile $90|C_{ij}|>2.16$.

work collaboratively to identify all the events and the relationships among such events. This methodology is focused on supporting this process, allowing experts to work with a broad range of events. This innovative feature aims at creating new plans by helping to support foresight and understanding, and to structure complex emergency situations. On the other hand, the results of the training simulations could then be used to improve disaster response plans for a range of possible events, based on the problems encountered during the training. Comprehensive planning in response to any emergency situation and appropriate personnel training are both required to help in a crisis resolution and to reduce its impacts. The simulation feature of the proposed methodology could help emergency teams to analyze different potential situations that might occur during a crisis as well as simulating the effects of different possible actions that could be taken by the main actor in order to mitigate the potential negative consequences of a disaster.

4.1. Lessons learned about event wording and estimation

It is not the objective of a cross-impact exercise to obtain complete agreement among the experts involved. In fact, it is important to retain "real" disagreement and to take notice of the opinions of the "outliers" in the process, especially if they

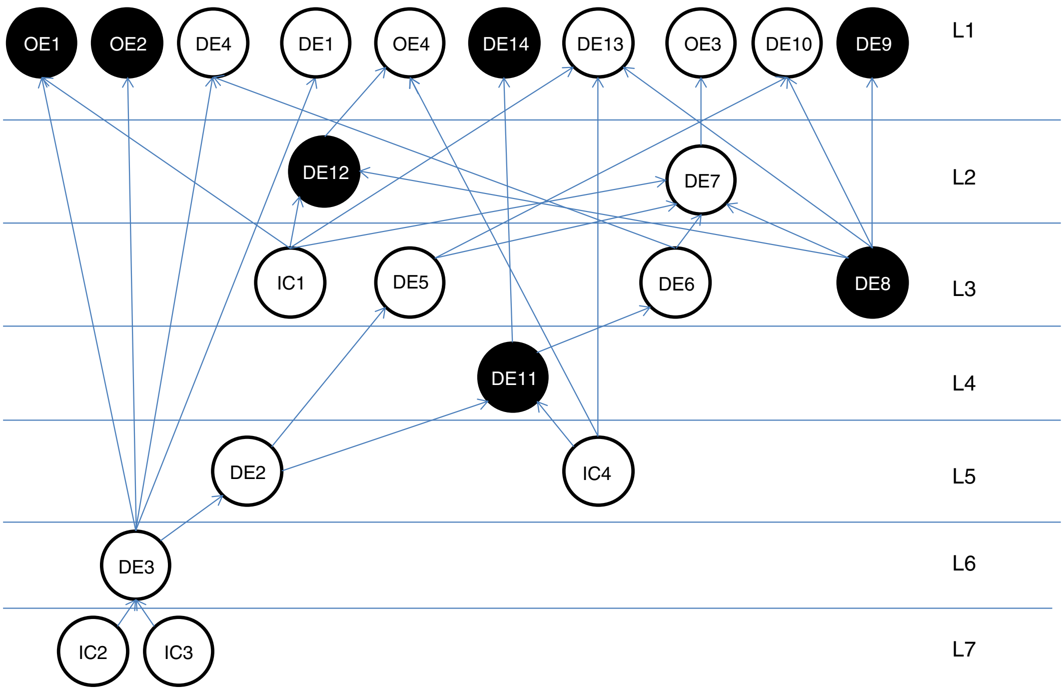


Fig. 7. Digraph for percentile $80|C_{ij}|>1.75$.

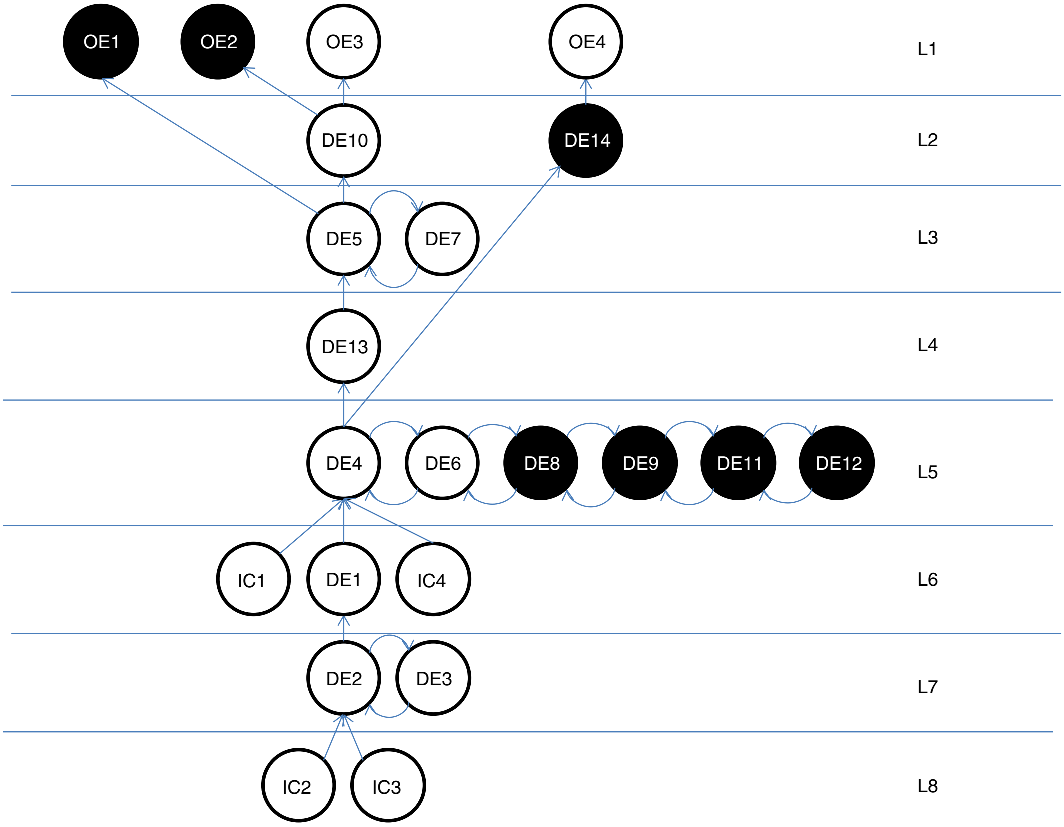


Fig. 8. Digraph for percentile 60$|C_{ij}|>1.31$.

relate to possible events that are low probability but potentially high impact. However, upon examining some of the disagreements that were evident in rounds 1 and 2, we realized that some of them were caused by poor choices made in the wording of events, which could confuse the participants. We summarize here the guidelines we suggest for future exercises of this type.

1. Mix positive and negative events, but give examples of the logic of determining the nature of the relationship.

It is important to have both "positive" and "negative" events/outcomes as possibilities in the scenario. However, this sometimes makes it difficult to follow the logic of the direction of a relationship (positive or negative), when one is estimating whether there is an impact of, for instance, a negative event on a later positive one. Respondents probably should be given an example of how to "sign" such perceived relationships. There is going to be a mix of events that can be considered good events or bad events if they occur and there are others that could be either good or either bad depending on what causes them to occur. One example is DE4, the military taking control and the impact on the set of events (Table 12) as well as the impact of the events on it (Table 13). This makes it an interesting event to examine and Tables 12 and 13 compare the two opposite roles for this event.

As might be expected, Table 12 indicates that the model predicts that if the military take control, it is much less likely that trained responders will refuse to take orders to participate in decontamination procedures. As an occurrence event, this influences both the good and bad outcome events. However, it is clear from Table 12 that military control has large negative impacts on critical events like public panic; that is, military control greatly decreases the probability of panic. This property and its influence in carrying out actions that local resources would have trouble with seem to be the critical factors in making military control a very important event. Therefore, a scoring process alone can sometimes hide critical aspects of this type of problem.

Table 12
DE4 — military control impact on the events (ordered influences table).

I Event ID	Short title E_i	C_{ij}
DE13	Internal contamination	2.20
DE7	Containment action	1.85
DE10	Makeshift decontamination	1.85
DE6	Official recognition	1.46
OE4	Public trust	0.67
OE1	City isolation	0.54
OE3	Short terms success	0.54
OE2	Income loss	0.27
DE14	Public refusal	−1.13
DE11	Public panic	−1.49
DE8	Leadership disagreement	−1.85
DE9	Press leak	−1.85
DE12	Non-responders	−2.77

Table 13
Impact of the events on DE 4 — military control (ordered influences table).

J Event ID	Short title E_j	C_{ij}
DE3	Threat recognition	2.22
IC4	Public trust	1.69
DE6	Official recognition	1.49
IC3	Bomb recognition	1.34
DE1	Bomb recognition	1.25
DE2	Medical recognition	1.13
IC2	Bomb assessment	0.98
DE10	Makeshift decontamination	0.54
DE13	Internal contamination	0.54
DE5	Center cleared	−0.27
DE7	Containment action	−0.54
DE14	Public refusal	−0.54
DE9	Press leak	−0.56
DE11	Public panic	−1.19
DE12	Non-responders	−1.19
DE8	Leadership disagreement	−1.86

Table 13 is the list of events that indicate their influence in making DE4 occur. What this list indicates is that early recognition of the problem and having initial public trust in the leadership may be a key in allowing the leadership to request the military early on when they realize they do not have the resources to completely handle the situation. It says in this planning model that the decision to call upon military support should be an important preparedness issue in designing a local plan for this type of situation. It also show the critically of a training program for police, fire and medical professionals that incorporates the ability and equipment for quick recognition of a nuclear contamination situation. If the military is called in later when the local plan has failed and panic has ensued a very bad outcome situation has already started to occur. This could be "good" if there are not sufficient adequate resources locally or "bad" if it occurred because of a lack of trust in the leadership and unprepared local response.

2. Do not word any items with a "negative" word, e.g., "not" in them; also be careful with the use of symbols.

We made the mistake of having one such item, "DE8 Leadership Disagreement: The city leadership does *not* agree to notify the public immediately upon determining there is a radiation contamination problem." We should have worded this as "agrees," since it is especially hard to follow the logic of this lack of an event (not occurring) on possible subsequent positive events. For example, it is probable that if the leadership cannot agree on the problem that this will raise the likelihood of longer term negative outcomes; e.g., "city isolation" or "income loss." This would mean that the nature of the impact would be "positive," a + sign, but the logic of the lack of something (a negative event) on a negative outcome, turning into a "+" sign for a positive relationship, may be confusing to participants. It has to be clear that good and bad measure a different concept than the occurrence of an event (+) and the non occurrence of an event (−) since an event occurrence can be either good or bad depending on the wording of the event.

3. Be consistent with temporal ordering (we were not).

Labeling an event with a certain time period might be profitable. Especially it might help planners to be consistent with the sequence of the dynamic events. But it is not necessary for all the events. For instance, dynamic events that represent risks, such as public panic, might occur anytime during the timeline of the emergency. In other events, such as economic costs or decontamination preparedness, the time label is not necessary or relevant for the working model, so it need not be included. Notwithstanding, if the time period dimension is included, there are some issues that should be considered.

The sequence of some "dynamic events during the (first) 18–24 hours" needs to be distinguished. First of all, we should have labeled these as being within the first 24 h, not the vaguer "18–24" hours. One probably does need to distinguish, e.g., very short term in the first 1–3 h; later events that day, within 24 h; events a few days later, and longer term events or outcomes. However, we did introduce too many different and imprecise time frames, some of which overlapped. We included things specified as being in the first hour; by the third hour; within the first four hours; between the fifth and the 17th hours; within 12 h; and during the initial 24 h; and many events had no specific time frame. This was too many different time frames and confused the estimation of whether one event impacts another event. For example, can something which is said to occur "within 12 hours" influence something that is said to occur "within the first four hours?" It is desirable to be very careful of events occurring in different time frames during the dynamic event time-period. It was clearly critical that certain things be recognized early on (e.g. in the first four hours) and these can still influence things that occur at any later period. However, for such an event, another event that is assumed to occur only after 4 h are over can have no affect on the other event, backward in time. For example, if calling in the military to take over was part of an expected option in the response plan, this could affect other events early on. If it was not part of the plan or expected then it would not influence events in an early period. A group doing this process the first time probably needs the facilitation of someone who understands these sorts of considerations when the events are formulated.

4. In addition, we should have supplied two different answer categories for when no substantive answer is entered:

No *judgment* (I am unclear about an interaction occurring or not occurring, or I lack the knowledge to make this judgment); and

No *influence* of this event on the other (I believe there is no influence of the event on the other event).

By allowing only one non-substantive response (in our case, an X in the cell), we confounded these two types of responses, which mathematically should be treated differently.

5. Allowing Initial Conditions (or Source Events) and/or Outcome Events to be physical variables.

Once a group of professionals has developed the initial model, this same group can decide to convert some or all of the source or outcome events to physical variables that could be easier to understand by those using the resulting model as a training or learning tool. For example, an event could be: "A rainfall will occur resulting in very heavy flooding of the area." The professionals can construct an X–Y conversion curve from the probability values of the nature shown in Table 14.

In terms of our example, the size of the contaminated region or the number of potentially contaminated persons could be expressed as examples of initial or outcome events.

Table 14
Example of conversion curve from probability values.

Probability	Rain fall in in./h
0	0
.5	Average for locality and time of year
1.0	Highest ever in known history

The actual users for training would not have to deal with probabilities or odds as input and output variables. They could very simply set various items to true or false and see the resulting outcomes.

6. Gathering estimates.

The original 1972 [10] formulation asked people to establish the expected prior probability of each event in the set. Whereas in this approach of building a general purpose model for testing different possibilities we choose to use .5 as the baseline for the model so we can more effectively use it as an evaluation tool for planning. However, we feel it would be desirable to ask any individual or group working on such a model to make estimates of these prior probabilities before the estimation process is undertaken. There are two reasons for this.

1. It would allow us to use a more desirable way of soliciting the cross impact question as used in the 1972 approach. We could decide to ask an individual to estimate the interaction that is most unlikely, given his current view. If a participant thinks an event has a probability greater than .5, we would ask him to assume it was not going to occur and solicit the impact this would have on the other events. If he assumes it was unlikely to occur (less than .5), we would tell him to assume it was going to occur. This forces the person to give us his greatest variations in judgment, thereby improving the scope of the resulting model.
2. The second motivation is that we can compare prior judgments with what the model predicts as outcomes and this can provide an incentive to try to determine if the model or what were his original views provides a better result for understanding the relative importance of the influence factors in what can be a very complex problem.

Our current work aims to reach a point where we can allow an individual online the ability to create their own personal model of any situation, or allow a group to collaborate on a model requiring a wider scope of experts. If we ask for initial values of the probabilities (referred to as "priors"), we can automate the preferred way of asking for influence impacts using the initial priors once a set of events is established.

4.2. Limitations

The working model presented in this paper was accomplished by the three authors doing all the estimates they could. This is a limitation in the sense that this model should be developed by a somewhat larger, more diverse group of experts or at least validated by a larger group. In addition, the process we have described needs to be tested in a real emergency planning/training process; we hope to have the opportunity to work with such a group.

Notwithstanding, this pilot application taught us some lessons about the process, especially the need for an interface for the estimate preparation that would provide support for the following steps:

1. The development of the events by the expert group doing the estimates which was also a process that we went through manually.
2. The need for an analysis of a single individual's estimates that will provide feedback on the consistency of the model that he or she developed.
3. After resolution of any individual inconsistencies and the generation of the next set of estimates, the participants should be shown where there is disagreement among the distribution of estimates in the single interaction cells.
4. There should be a discussion of these to insure that it is a true disagreement (high uncertainty) or a group inconsistency that cannot be resolved. Note that Dalkey's formula (expression 1) will be pushed back to a .5 value when there are disagreements about direction. When all estimates are in the same direction, it will provide a stronger estimate in that direction and not an average.
5. After the above, a final analysis produces a model such as shown in this paper as a result of the multiple estimators' actions.

With the above process automated, one would be able to have a large number of experts concentrate on a large problem and restrict their individual estimates to the combinations they are most familiar with. It would be desirable to have 5 estimators for each cell in that this is the group size necessary for a reliable disagreement since it is the first case where a true minority (three to two) is possible.

4.3. Future research

In our approach, experts supply the potentially important events/factors that have to do with human decisions and behavior. This approach should be combined with other modeling tools aimed at supporting technical estimations, and should not use first responders and emergency managers to make technical estimations. In fact, this is one of the strong points of CIA-ISM: combining technical estimations/outputs with social events based on subjective estimations, and subsequently analyzing their interrelationships and non specified relationships. This is an added value point regarding traditional emergency management approaches for supporting the preparedness stage. With this tool, emergency managers are able to map and analyze the social impact of an emergency beyond the causalities or the economic impact. To underline this capability we have included several events related to public trust and panic as well as political decisions. For example, in the field of radiological disasters there are several tools aimed at giving technical estimations for nuclear incidents, i.e.

ARGOS

http://en.wikipedia.org/wiki/ARGOS_DSS.

EMCAPS

http://www.hopkins-cepar.org/EMCAPS/EMCAPS.html
http://www.ncbi.nlm.nih.gov/pubmed/18986730.

Additionally there are other EM fields such as firefighting, earthquakes, tsunamis and floods with existing tools for making technical estimations. We could combine these estimations with source, dynamic and outcome events to build a complete socio-technical model. We hope to demonstrate this ability in future research.

5. Conclusions

In this paper, the CIA-ISM methodology is extended in order to support group collaboration. Using this methodology, we have developed a hypothetical emergency scenario in which the potential implications of different events on good or bad outcomes could be analyzed. By means of this exercise, we demonstrate how to create a consistent working model for complex emergency situations to support multi-risk analysis as well as to explore different courses of action. By means of this exercise, we also observed how the group estimation process enhances the consistency and coherency of the individual estimations. Moreover, the CIA-ISM process helps groups to deal with conflict resolution, obtain consensus and increase the quantity of information included in the model. This methodological tool could be used in the emergency preparedness stage in order to structure relevant knowledge and develop working models for building and sharing a collaborative vision between different groups.

Many attempts to model potential emergencies restrict themselves to the physical variables and attempt to make one dimensional assumptions about the behavior of the people involved. The approach we have evolved allows the incorporation of social behavior of any group pertinent to the disaster situation. While the concept of leadership trust used in this model is one example, there is a host of other considerations dealing with the reactive behavior decision makers, responders, and various types of participants that are often left out of plans. Many examples exist in major disasters where significant numbers of individuals in these categories never behaved as the plans assumed they would. For example, many bus drivers in Katrina never showed up because they were told they could not bring their families on the buses to evacuate New Orleans.

We also illustrate in this application how the views of different participants could be combined in an emergency scenario. This fact is especially relevant in emergency preparedness in which issues related to the performance and preparedness of emergency teams could impact the potential outcomes of an emergency situation. This fact implies tasks of coordination for actors with different and possibly conflicting goals over a long period of time. Not only the emergency teams are involved in emergency situations, but many different actors such as local or national government officials are also involved in emergencies. So, as well as taking into account several potential futures, the role of the stakeholders in the current and foresighted situation should be considered.

Additionally, it is important to remark that users do not limit themselves to what appear to be consistent cross-impact factors and probabilities. Low likelihood events need to be introduced and the lessons of analyzed disasters should not be ignored. In particular, the Exxon Valdez oil spill, the Bhopal chemical accident and the Chernobyl nuclear accident all demonstrated that the occurrence was a confluence of about a half dozen highly unlikely events. If any one event had not occurred, the emergency would not have taken place. To be useful as a training device the scenario cross-impact evaluation should therefore contain low likelihood/severe consequence events that are clearly counterintuitive. One assumption of High Reliability Theory about the occurrence of disasters is that a set of small problems can combine to allow a much larger disaster than one would expect by examining each possible small problem independently.

In a group process, outliers should be taken into full account, not merely agreed-upon probabilities, and estimates of consistency that are crucial. A cross-impact scorned by the team as highly unlikely should nevertheless be considered because its impact may prove overwhelming. In this sense, the strength of the proposed method is that as many low probability events can be included as is desired to create a detailed model as long as a sufficient group of estimators can be provided.

The method that we have described seems especially suited for "thinking the unthinkable"; that is, developing scenarios that can be used for planning for response to potentially catastrophic events that will need rapid and correct dissemination of information and directions to the populace. For example, recent press reports indicate that the Japanese government feared during the first chaotic days of the Fukushima accident that it would need to evacuate Tokyo. "*No one has ever evacuated tens of millions of people, and it probably cannot be done in the time frame that would be required. But that is exactly what we would have to do here in the U.S. in the event of a major accident at Indian Point* [in Buchanan, N.Y.]." [7].

In the first draft of this scenario and exercise, we identified a specific city and described the specific location of the bomb and of nearby high-density structures such as a soccer stadium with a game in progress. Those familiar with local attitudes strongly requested that we not identify the city, as it might end up in the local press that university professors were planning a dirty bomb attack on the city, or might give terrorists ideas. So now, it is "any big city." Many others objected to the "improbable" nature of the scenario and insisted that we should spend our time on something more "realistic." More recent press reports show that the "dirty bomb" scenario is a realistic threat. For example, On March 14, 2012, the New York Times included an article entitled "Hospitals with Radioactive Materials Expose Weakness in Antiterrorist Rules" [17]. The cesium kept in hospitals for medical treatments cannot be used to make a nuclear device, but it could be used to make a "dirty bomb" that could contaminate significant areas of a city with radiation, as in the scenario developed in this research. It has been over ten years since the U.S. started a post-911 effort to make such radioactive materials harder to steal, but "*Congressional auditors have found one hospital where cesium was kept in a padlocked room but the combination to the lock was written on the door frame and another where radioactive material was in a room with unsecured windows that looked out on a loading dock*." Perhaps even more disturbingly, the radiation safety officer at another hospital "*did not know how many people were allowed unescorted access to the radioactive sources, because the computer program that the hospital used could not count beyond 500*" (ibid, p. A 21).

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