

Developing Fuzzy Cognitive Mapping Techniques for Consequence Analysis of Second and Third Order Effects

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Abstract: The Defense Threat Reduction Agency (DTRA) is the Department of Defense's (DOD) official Combat Support Agency for countering weapons of mass destruction (WMD). DTRA focuses on WMD and mitigating the consequences of a chemical, biological, radiological, nuclear and high yield explosive threat (CBRNE). The initial direct effects of a CBRNE incident are well defined and documented; however, the second and third order effects are complex and not thoroughly understood or documented. Consequence analysis is the practice of analyzing the effects of major events such as a CBRNE event and can assist in predicting the second and third order effects. Currently there is no method to predict or analyze the second and third order effects of CBRNE events. This research focused on identifying the entities associated with a CBRNE event initially. The use of experts and surveys developed an exhaustive list of entities and associated relationships. The follow-on research focused on the type and strength of the entity relationships. Next, Fuzzy Cognitive Mapping (FCM) techniques identify and evaluate the complex relationships of the second and third order effects. Using a mind mapping computer program, FCM techniques produced second and third order effect relationships. The final product provided a solid first attempt at analyzing a CBRNE event and the associated second and third order effects. Subsequent research will require greater effort to employ system dynamics techniques to enhance the product and develop a more thorough model.

Keywords: Consequence Analysis, Consequence Management, System Design, Forecasting, Simulation, Fuzzy Cognitive Mapping, CBRNE, DTRA

1. Introduction

The Defense Threat Reduction Agency (DTRA) is the U.S. Department of Defense's (DOD) official Combat Support Agency for countering weapons of mass destruction (WMD). DTRA focuses on weapons of mass destruction and mitigating the chances and consequences of a chemical, biological, radiological, nuclear and high yield explosive threat (CBRNE). Consequence Management (CM) is the current practice of looking at the relationships involved in CBRNE events. Consequence Analysis (CA) is the practice of predicting and analyzing the higher order complex effects of CBRNE events (Joint Chiefs of Staff, 2006). Researchers understand the initial and immediate effects of a CBRNE incident, specifically a 10-kiloton nuclear blast. However, background research has identified a gap in understanding within CA. Very little research has holistically examined the second and third order effects of a CBRNE event, which subsequently causes limitations in the ability to conduct CM. This project utilizes a system dynamics modeling tool and fuzzy cognitive maps (FCMs), to create a baseline methodology for estimating the second and third order effects of a CBRNE event and identifying areas of CA that require further study.

Events involving WMD and CBRNE have immense potential for catastrophic destruction. In fact, President Obama has called nuclear proliferation and nuclear terrorism "a threat that rises above all others in urgency." (Graham, 2010). Therefore, the US has a stake in the global capacity to conduct CA and CM for CBRNE events. However, the subsequent research identifies a gap in proper CA which has the secondary order affect of poor CM manifested in inadequate responses to CBRNE events.

CA aims to quantify the negative impacts of a hazardous event due to anticipated eventualities and predicts, analyzes, and helps model the higher order effects on a nation in a CBRNE event (Arunraj, 2009). Studies such as the one conducted by Arunraj and Maiti in "A Methodology for Overall Consequence Modeling in Chemical Industry" identify a

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successful process for CA by conducting accident scenario analysis, identifying and classifying losses, and finally estimating losses (Arunraj, 2009). When the literature considers second and third order effects, it does not examine the holistic outcomes or the entity interaction with one another. For example, in “The Day After: Action Following a Nuclear Blast in a US City”, (Carter et al, 2007) began to assess several second order effects, such as of individual fear of radiation and fear of additional strikes impeding a federal response. However, there is little attempt to pair the above effects or to include the multitude of other factors that would shape the post CBRNE event landscape. In Dodgen et al’s article “Social, Psychological, and Behavioral Responses to a Nuclear Detonation in a US City: Implications for Health Care Planning and Delivery,” the authors recognize that while the research provides a thorough look at psychological consequences, an approach that integrates a broader survey of variables and effects is needed to conduct CA (Dodgen, 2011). Ultimately, while some research exists conducting CA for individual higher order effects of a CBRNE event, there is a gap in analyzing the holistic and cumulative effect of said consequences.

This gap in understanding has real world applications to nuclear events in history. For example, On March 28, 1979 there was a partial core meltdown at the nuclear power plant at Three Mile Island in Pennsylvania. Local and regional governments had not devoted adequate resources to planning and preparation for a meltdown because the perceived chance of a meltdown was low and the government believed that the integrity and design of the plant would minimize damage and radiation leakage (Collins, 1980). In addition, on 26 April 1986, the number four reactor at the Chernobyl nuclear complex located near Pripyat, Ukraine suffered a catastrophic series of events that led to an explosion in the reactor, a rupture of containment, and the spreading of radioactive material to more than 100,000 people (Lewis, 1986). Tremendous problems occurred during the CM of the Chernobyl disaster. Many technical failures by the USSR have been identified, such as a failure to treat all areas affected, insufficient planning to account for local conditions, insufficient removal of top soil, and an inability to identify where radiation was most likely to gather in quantifiable mass (Smith, 2014). Another example would be the Great East Japan Earthquake that caused excessive amounts of radioactive material to discharge from the Fukushima Daiichi plant on March 11, 2011. There were significant CM problems, to include the inability to control the spread of radiation and poor communication by Japanese officials resulting in widespread confusion and inadequate evacuations (Tucker, 2011), (Fitzgerald, 2012).

The research regarding CA shows that there is a lack of understanding concerning the holistic and cumulative second order effects of CBRNE events. Essentially, while some research identifies the effects of CBRNE events on a singular variable, little integration is done to reflect the overall state after a CBRNE event. The limited understanding of CA is reflected in historically inadequate CM. Examinations of Three Mile Island, Chernobyl, and Fukushima disasters illustrate this finding. Clearly, the disconnect in CA must be analyzed and researched in order to allow the US and partner nations (PN) to predict the effects of CBRNE event and to excel in CM.

2. Methodology

2.1 The Systems Decision Process

The Systems Decision Process (SDP) is a four-phased problem solving process that takes a holistic, iterative approach to finding a solution for the decision maker or stakeholder. The stakeholder is at the center of the SDP that places constant emphasis on value focused thinking and making decisions that add utility to the system (Figure 1). This provides the most comprehensive approach to solving this complex problem and satisfying stakeholder needs (Parnell et al, 2010).

2.1.1 Problem Definition

The first phase of the SDP, problem definition, is the critical foundation for the project. Problem definition seeks to ensure comprehensive and accurate understanding of the problem and the problem’s requirements so as to ensure maximum value for the stakeholders. Problem definition is composed of key tasks including, “...research and stakeholder analysis, functional and requirement analysis, and value modeling.”(Parnell et al, 2010) Problem definition concludes with identification of the redefined problem statement that guides the project through completion.

The initial problem as described was: “There is a gap in understanding second and third order effects during and after CBRNE events. Therefore, there is a need to research and model entity relationships of the effects of a CBRNE event in order to provide DTRA a mechanism that will guide resource allocation toward future areas of study in CA. This will be accomplished by blending methods and tools such as Fuzzy Logic/Cognitive Mapping and Consequence Analysis/Management.” This initial problem statement required greater refinement and understanding of the actual problem. The first part of that refinement included a thorough understanding of the stakeholder requirements.

Stakeholder and requirement analysis was conducted using two formal interviews with stakeholders and several informal updates and validations throughout the problem definition phase. The initial end state was consolidation into a findings, conclusions, and recommendations matrix which is used to develop a greater understanding of the major challenges facing the stakeholders. The stakeholder interviews provided invaluable insight to the challenges of CM and CA. In conjunction with the background research the final recommendations were consolidated:

1. FCMs can/will be used to map the influence relationships among entities, to include but not limited to, infrastructure, medical services, economy, international/domestic opinion, culture, social networks, power networks, etc. in order to find the more important relationships.
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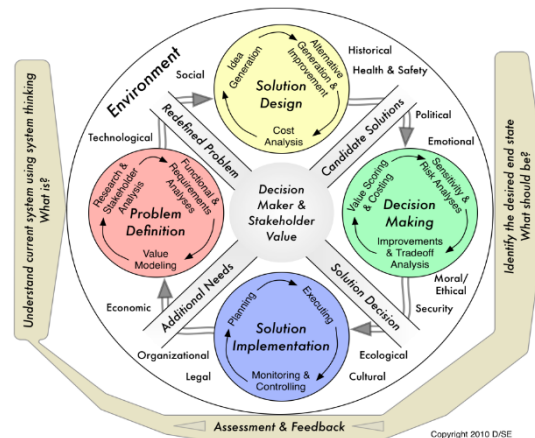


Figure 1. The Systems Decision Process (Parnell, 2010)

From these recommendations a fundamental objective was established. For this research, the fundamental objective is the most basic high level objective the stakeholders are trying to achieve (Parnell, 2010). Fundamental Objective: “Determine and validate the entity relationships resulting from a CBRNE event and development of a method for identifying the second and third order effects using Fuzzy Cognitive Mapping.

The fundamental objective is used to derive a hierarchy of functions, objectives, and values that illustrate the full extent of the problem and explains how the value is derived for the stakeholder (Figure 2). The fundamental objective establishes two functions: Establish Entities and Establish Entity Relationships. Under Function 1.0, “Establish Entities”, Objective 1.1 is to “conduct research”. From this objective, the value measures of “Maximize Sources,” “Maximize Stakeholder Input,” and “Maximize Number of Entities” are established. The solution to this problem will require an extensive amount of research which maximizes sources and stakeholder input as well as maximizing the number of entities identified. The research component of the project was extensive and provided a tremendous amount of data. The stakeholder input included experts in the field who had worked in this field for years and knew the entity relationships well. The results of this process provided an extensive list of entities.

Within the “Establish Entity Relationships” function there are three objectives with corresponding value measures. Objective 2.1, “Research Entity Relationships” has the value measure “Maximize Sources.” Objective 2.2, “Establish Entity Relationship Value” has the value measure “Maximize Entity Relationships.” Objective 2.3, “Validate Entity Relationships” has the value measure “Maximize Model Accuracy.” Once the entities were identified it was necessary to engage experts in the field to establish and validate the entity relationships.

From this value hierarchy, a redefined problem statement was developed to guide the rest of the research. “Currently there are no established second and third order entity effects for CBRNE events. As such, there is a need to research and model entity relationships and effects from a CBRNE event in order to provide DTRA a mechanism that will guide resource allocation toward future areas of study in CA. This will include blending methods and tools such as Fuzzy Logic/Cognitive Mapping and Consequence Analysis/Management.”

2.1.2 Solution Design

The second phase of the SDP, solution design, begins the process of generating a solution for the problem defined in phase 1. The progression of this project was guided by the principles of solution design, such as idea generation and alternative generation. This helped develop the solution.

In order to create a FCM for a CBRNE event, a list of entities and the relationship between each entity must be determined. The first fundamental objective in the value hierarchy was to generate entities. The entities for the FCM were created with a constraint of a 10 kiloton nuclear blast being the catalyzing event. Entities from previous work done by project members were examined and included as a foundation for entity generation (Sanchez, 2014). Additional entities generated came from stakeholder input and subject matter expert interviews. Brainstorming and research into Army operational environment considerations also helped in forming entities of a CBRNE environment (US Army, 2009). Seventy entities were established, defined and substantiated through these methods.

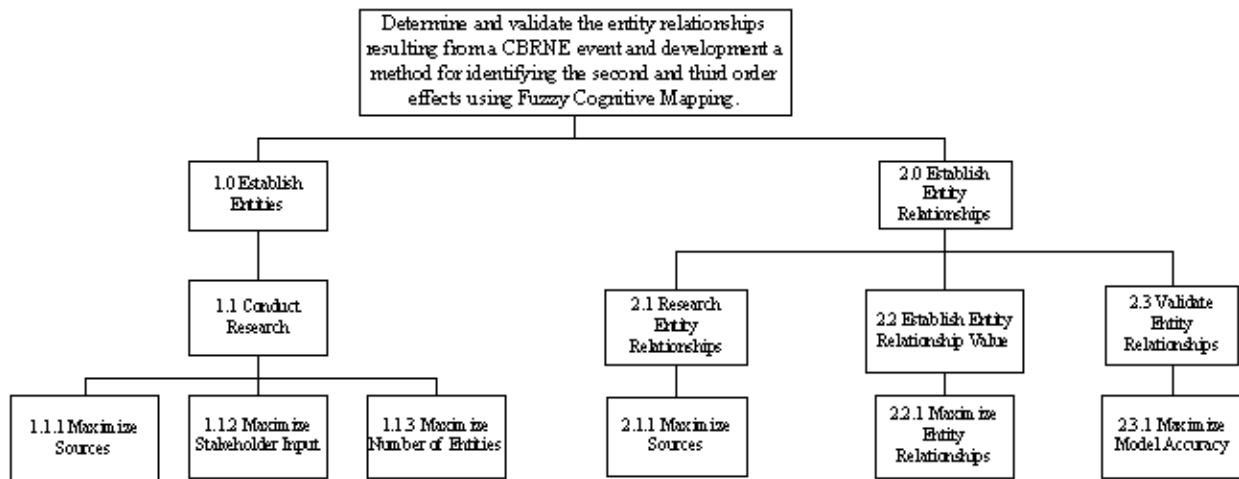


Figure 2. Value Hierarchy

2.1.2.1 Grouping Entities

While seventy entities provide a lot of nuance to the simulation, the number of entities creates a problem. Seventy entities with a possible relationship to every other entity requires 4,830 relationships, which is significantly more relationships than this project would be able to meaningfully investigate and substantiate. Consequently, entities were grouped to create “entity domains” that would allow for nuance internal to the domain but would greatly reduce the number of relationships. For instance, 15 entity domains would require only 225 relationships. The entity grouping relationships were established and placed into a systemigram (Figure 2).

Table 1. Entity Groupings

Entity Domain	Entities
Armed Forces	Army, Navy, Air Force, Marines, Homeland Security Capabilities
Public Opinion	International Opinion, Domestic Opinion, Foreign Outreach
Government	Governance, Political Power Network
Will to Fight	Peacekeeping, Deterrent, Vulnerability, Counter Proliferation, Non-Proliferation
Security	Threats, Stability Operations, Domestic Terrorism, Intelligence
Public Safety	Police, Firefighter, Search and Rescue, Emergency Operations, Civil Humanitarian Relief, Jails and Prisons, Oil and Hazardous Material Response
Government Income	Income, Taxes, Tariff, Foreign Exports
Production	Labor Force, Raw Material, Industrial Capacity
National Wealth	Gross Domestic Product, Stock exchange, Economic Consequences
Medical	Medical, Psychological Consequences, Health Service Support, Public Health, Medical First Responders
Resiliency	Resiliency, Uncertain Environments
Food and Water	Food Security, Agricultural Production, Water Accessibility
Culture	Culture, Religion, Education
Weather	Weather
Industrial	Sewage, Electric Power Grid, Transportation System, Public Work and Engineering, Disaster Housing
Communications	One-Way Tele-communication, Two-Way Telecommunications, Social Media, Internet Services

The average values of the sample data were used in the FCM, but it was still necessary to analyze the raw data beyond just looking at the average values. The statistical analysis method “bootstrapping” was used as a statistical tool that simulates the sample data over 10,000 times and with the sample values used for weighted distribution of those samples. A mean was taken of each sample and the sample means were ordered, by magnitude, from 1 to 10,000. The 251st and 9,750th values were then extracted as the 95% confidence interval values for the true mean of each relationship.

3. Model

3.1 Fuzzy Cognitive Mapping

Modeling CBRNE effects are difficult. There are many factors involved, some of which are not completely tangible or may be vague ideas. Accurately modeling a system this complex using only concrete numbers and facts is impossible. The real world often operates in a system of insubstantial structures. There are no completely right or wrong answers, the truth is usually somewhere in between. FCMs are mapping tools that deal with this complexity. FCM is a parameterized form of concept mapping where one can develop qualitative static models that are transformed into semi-quantitative dynamic models (Gray, 2015).

Historically, FCMs have been used to model social and economic scenarios. FCMs have been successful in modeling a number of unique things to include the impact of social factors on homelessness as well as relationships between social and ecological factors to determine illegal hunting in Serengeti National Park, Tanzania (Mago, et al, 2013 and Nyaki, 2013). FCMs demonstrate their usefulness in bringing many abstract ideas together to model real world scenarios. The power of this tool is only limited by the considerations of those who apply it. If done properly with the correct research, FCMs can successfully model CBRNE effects. The flexibility of Fuzzy Cognitive Mapping means it can be used as a functional tool, even when modeling international interactions and strategic decision making due to CBRNE effects. FCM is not an all or nothing decision making tools, rather, it provide scope and a range of possibilities to guide decision makers.

FCMs are based upon the theory of fuzzy logic. FCMs are “signed digraphs” that give and accept feedback (Khan, 2004). FCMs are visually represented in tools by nodes (or entities) with arcs and edges (relationships) linking them. The purposes of these tools are to model scenarios “described in terms of significant events (or concepts) and their cause and

effect relationships” in a clear and concise manner (Khan, 2004). The nodes, representing concepts, are interrelated through the arcs and edges defined in the model. The links between nodes represent causal links which in turn affect the outcome of the nodes. Once a node is affected, it goes on to affect other nodes and may also eventually change the initial catalyzing node. The system then changes all over again (Gerla, 2001). FCMs are useful tools for predicting the aforementioned future events. FCMs serve as a tool to guide decision makers to their objectives.

Often the objective of using an FCM is to reach a desired end state with the defined nodes. FCMs allow users to alter initial states in order to reach that goal. This process develops the causal relationships between nodes and how these relationships can be altered to more effectively reach ones goal. The process of finding the correct initial state in order to reach a desired end state may be optimized through either the use of back solving from the desired end state or several iterations of trial and error (Khan, 2004). Generic algorithms are used to back solve from a desired end state to an initial state. Given an initial state, an FCM can simulate “evolution over time to predict its future behavior” which is the purpose and usefulness of FCMs. This evolutionary prediction is where FCMs can prove useful in CA.

3.2 CBRNE FCM

The software “Mental Modeler” was used to create and run the FCM because of its ease of use and the lack of other options (Gray, 2015). Mental Modeler used the relationships and entity domains derived to create the FCM which is visually depicted in Figure 4.

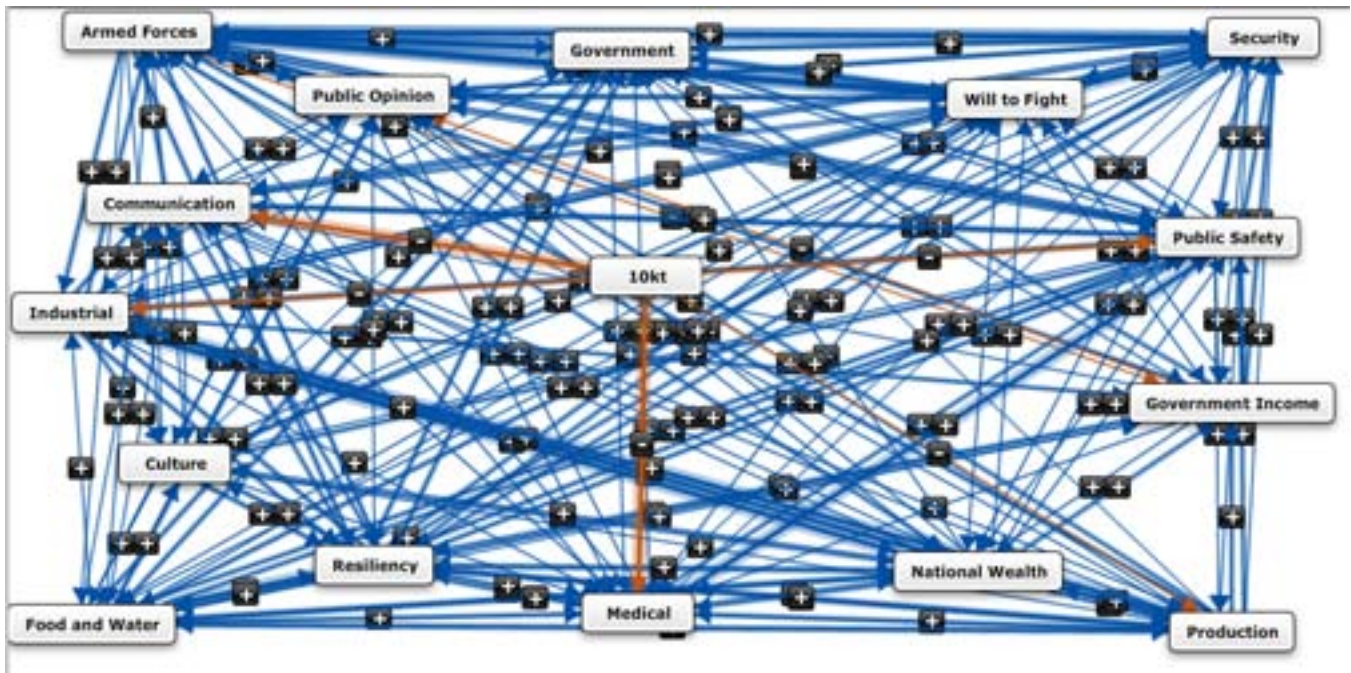


Figure 4. CBRNE Fuzzy Cognitive Map

Blue lines represent a positive relationship, while the orange lines represent a negative relationship. Additionally, thicker lines depict numerically stronger relationships. For example, the relationship between a 10 kiloton blast and communication is strongly negative, as depicted by the thick orange line between the two entities (Figure 4). Communication has a relationship with all other entity domains, all of which are impacted to varying degrees by the effects a 10 kiloton blast. There are a number of relationships that depict a very complex system when holistically displayed. The power of this research and using this tool is that the initial relationships produce results that would normally not be apparent. These hidden effects are what can allow organizations to prepare for an area that traditionally would not be the primary focus.

The relationships between a 10 kiloton blast and the other entity domains are the independent variables the user adjusts in order to manipulate the scenario. The input of an initial catalyst (i.e. a nuclear blast) initiates the FCM and creates the output of the relative changes to the systems as first order effects. The 10 kiloton relationships used in this project were derived from analysis by Buddemeier and Dillon (2009) for the Department of Homeland Security. This project’s initial

nuclear blast scenario created a relatively strong negative change in the communication entity and a relatively low negative change in the medical and industrial entities (Figure 4).

The second order effects can be found by iterating the first order effects through the FCM. The output of iterating the first order effects is included in Figure 5.

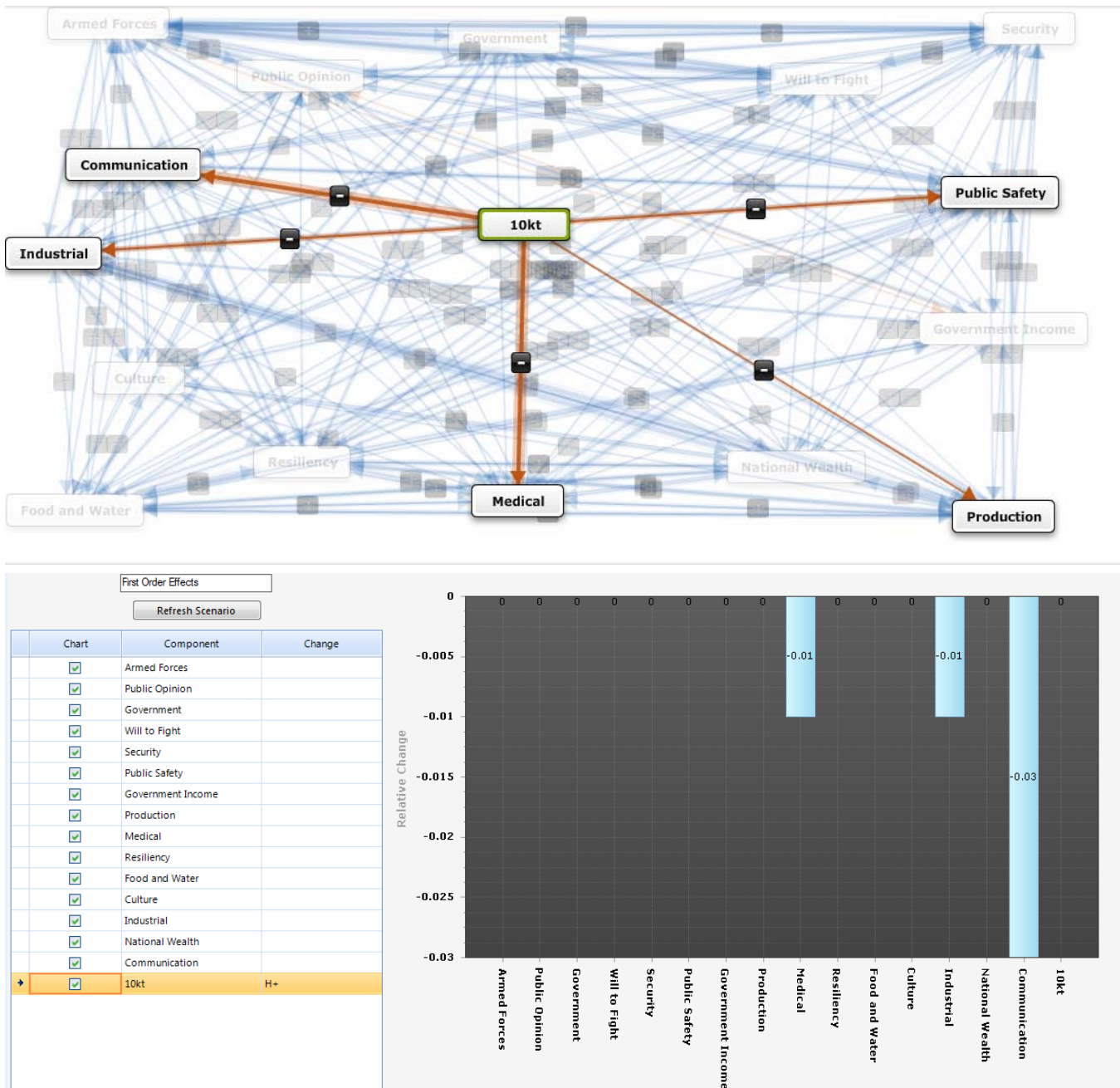


Figure 5. First Order Effects Relative Change Diagram

The relative change data allows approximations of the second and third order effects of a nuclear blast from an inputted scenario. For example, the second order effect (Figure 6) predicts a 7% drop in the national wealth domain, such as gross domestic product or employment. This drop is defined as a decrease in capability, activity, production, and/or

functionality of the entities within the entity domain as a result of the initial decrease in medical, industrial, and communication. Figure 4 reflects the scenario set by the project. Different base conditions would yield different results that allow DTRA and other users to have flexibility. The initial effects of a nuclear blast in the capital of a developed country would be immensely different from a nuclear blast in a smaller city of a developing nation because of the different dynamics of how the entities interact.

An important note is that limitations with the software do not allow previous changes to cause changes in the follow on iteration. For that reason, the cumulative effects should be seen as the summation of the effects in the second and third order relative change graphs. The relative changes graph for the third order effects is in Figure 7.

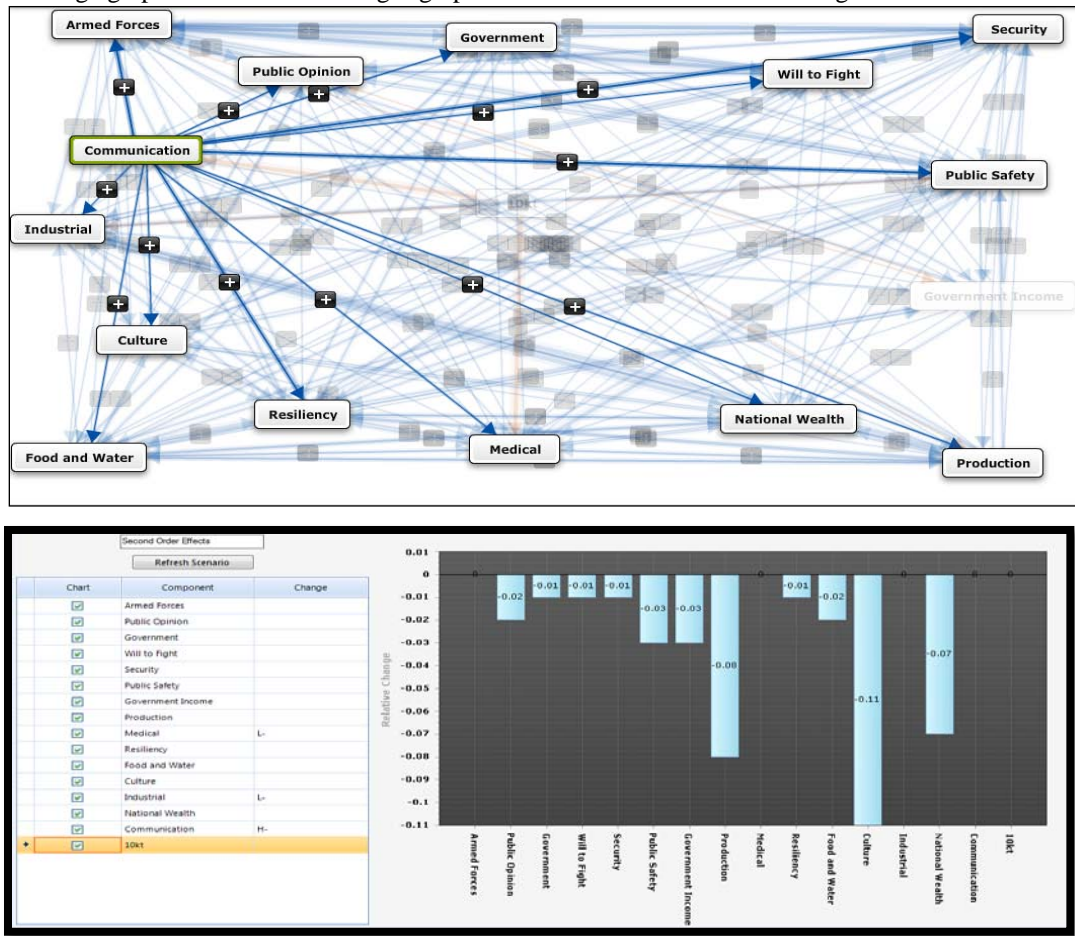


Figure 6. Second Order Effects Relative Change Diagram

The results of this FCM showed some surprising results. For example, the largest immediate effect of a 10 kiloton nuclear blast is on communication. The decrease in communication is then the driving factor for the second and third order changes, as shown in the above figures. This suggests that a decrease in the effects of communication (i.e. making communication more resilient to change) would lead to less of a negative impact on the rest of the entities over time. A real world example of this communication effect was seen in Hurricane Katrina. Although not a CBRNE event, the single most impact was on communication, which affected all the relief efforts.

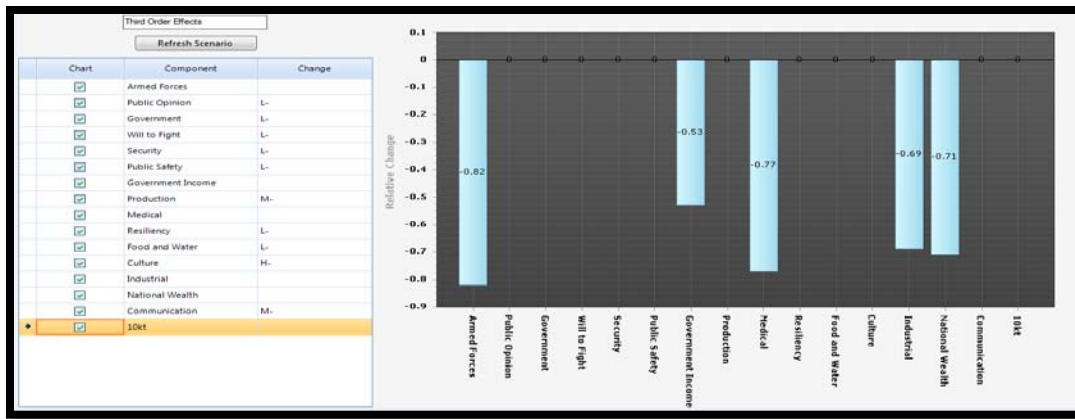


Figure 7. Third Order Effects Relative Change Diagram

4. Summary

4.1 Results

This research begins to fill the gap identified by DTRA. A user can input conditions for any CBRNE event into the model and a base estimate for the relative changes into multiple key entities will be generated. The results capture a holistic complexity as each entity domain responds to the changes in other entity domains. Therefore, a user making decisions about system level behaviors benefits in contrast to a model that examines, as an example, economic effects alone.

However, four key limitations of FCMs and the results are important to highlight. First, simplifying the FCM by creating entity domains allowed the problem to be manageable. This limitation reduces the intricacies of the initial 70 entities and adds greater uncertainty in the results. Second, the assumption that 10 kiloton nuclear blasts are representative of all CBRNE events. The results may be useful in planning for a potential biological or chemical event, but to claim that the outcome will be the same is an extrapolation of the project’s results. Third, rounding that occurred with the survey data due to the limitation of the software used increases the uncertainty in the results. Finally, results were derived from subject matter expert input. Our initial state change scenario was derived from a single publication written about a single city. There may be other limitations, but these four are the most impactful to the uncertainty of the entire outcome.

4.2 Conclusions

The prior research regarding CBRNE events indicates that there is a gap in the understanding of the cumulative effects of a CBRNE event. This research successfully begins to close the gap in CA by providing insight into relationships in a CBRNE environment. These relationships allow quantifiable predictive changes in the system that was not readily identifiable before. This project also provides a focused recommendation for guiding future research. The use of the constructed FCM serves as the initial process to estimate the relative changes to a set of entities, or systems, due to a 10 kiloton nuclear blast in varying scenarios. This research can lead to a predictive model that organizations can use as a decision tool and as a means of understanding a CBRNE environment. This will allow organizations who operate with limited funds to target the most impactful areas of CA and CM in order to research and to respond more efficiently and effectively, thus saving lives and money.

There is significant capability for follow on research. Application of the same methodology would allow the construction of FCM simulations of CBRNE events for other than nuclear events, increasing the accuracy of the user’s scenario. Additionally, each domain of entities is a complex and dynamic system in and of itself. Constructing an FCM for an entity domain may allow greater understanding of the overall system and enable more direct and efficient CM. Finally, this same methodology could be used for any catastrophic event: war, weather, volcanoes, etc. This can add to the CA/CM developments for greater use world-wide.

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