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Addressing Criticality Levels in Critical Infrastructure System

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***Abstract*—Modern society depends on the operations of critical infrastructure system (CIs), such as transportation, energy, telecommunications, and water. Characterized by direct and transitive interdependencies, these systems have become so interconnected that disruption of one may lead to disruptions in all. The levels in critical infrastructures must firstly be classified in order to make a systemic perspective for critical infrastructure system protection). This paper discusses critical infrastructure interdependencies by highlighting some examples of cascading failure phenomena from references and experts. By utilizing the Interpretive Structural Modeling (ISM) methodology, we analyze the interactions of eight critical infrastructures according to their mutual influences, thereby we identify those driving infrastructures, which can aggravate a few more infrastructure and those dependent infrastructures, which are most influenced by driving infrastructure. It can be also observed that there are some infrastructures, which have both high driving power and dependency, thus needing more attention. The approach taken in this research can form the basis for the analysis of the system of systems that represents the CIs.**

***Keywords*—critical infrastructure system(CIs); interdependency; interpretive structural modeling(ISM)**

I. Introduction

Critical infrastructure was defined as a network of independent, mostly privately-owned, man-made systems and processes that function collaboratively and synergistically to produce and distribute a continuous flow of essential goods and services, its incapacity or destruction would have a debilitating impact on our defense and economic security [1].The protection of critical infrastructures has become a primary concern of many nation states in recent years [2,3,4]. While most governments estimate which infrastructures are the most critical to our society, an early report published in the United States (President's Commission on Critical Infrastructure Protection 1997) identifies and defines eight infrastructures that support the "life support systems" of the country and are therefore regarded as critical [1]: these systems are Information and Communications, Electrical Power Systems, Gas and Oil, Banking and Finance, Transportation, Water Supply Systems, Emergency Services, and Government Services. Table I shows these eight critical infrastructures and their components.

These could be used as the starting point for making critical infrastructure protection decision. However, the issue of which infrastructures is the most critical to the survival of our economy is still not obvious [5]. Researchers have been initiated to investigate problems related to criticality. Chris W. Johnson [6] considered infrastructures as "primary" for which represent the most vulnerable elements in national infrastructure, and "secondary" for which are essential to quality of life and commercial success but present less obvious targets for terrorist actions. Rae Zimmerman [7] identified types of infrastructures involved or affected due to system failures, i.e. infrastructure frequently the cause of failure to other infrastructure, infrastructure frequently affected by other infrastructure failures. Eric A.M. Luiijf [8] analyzed critical dependencies of thirty-one critical products and services in eleven critical sectors in Netherlands. The relative importance of a critical product or service was determined based upon its importance for other critical products and services, and upon the potential damages in case of disruption. While these researches are not proper to analyze the critical infrastructure criticality level, they did not try modeling systems include "interdependency" either.

A systematic way of evaluating the prevalence of these interdependencies is needed [7]. The methodology of interpretive structural modeling (ISM) can act as a tool for imposing order and direction on the complexity of relationships among elements of a system [9,10]. In this research, ISM has been applied to develop a framework which shows the interrelationships of critical infrastructures and to classify the infrastructures criticality according to their driving power and dependence. In this paper we use the eight infrastructures to illustrate the methodology.

The article is structured as follows: in the next section, the concept of critical infrastructures interdependencies will be discussed. In section 3 ISM will be proposed for capturing the interdependencies between the various infrastructures and assessing "criticality" levels. In section 4, MICMAC analysis of developed ISM model is carried out, an analytical planning framework will be integrated for critical infrastructures. In the conclusion, possible model improvements and research directions are described as the basis for future studies.

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TABLE I. EIGHT CRITICAL INFRASTRUCTURES

No.	Critical infrastructure	Components
1	Emergency services	medical, police, fire and rescue systems
2	Transportation	air, rail, highways and waterways systems and delivery services
3	Information and communications	computing and telecommunications equipment, software, processes and people
4	Electric power	generation stations, transmission, and distribution networks
5	Banking and finance	banks, nonbank financial services companies, payments systems, investment and mutual fund companies, securities and commodities exchanges
6	Gas and oil	Gas and oil production, storage, and transportation facilities
7	Water supply systems	sources of water, reservoirs and holding facilities
8	Government services	levels of Federal, state, and local governments which provide essential services to the public

II. CRITICAL INFRASTRUCTURE INTERDEPENDENCY

Numerous recent policy documents recognize the importance of interdependencies, and discussed the reliance or dependence of the critical systems [see 2,3,4].The spirit of studying interdependencies is mainly based on the early work done by Rinaldi [11,12]. In their work, *dependency* is defined as a linkage or connection between two infrastructures, through which the state of one infrastructure influences or is correlated to the state of the other, *interdependency* is defined as a bidirectional relationship between two infrastructures. There are four general categories of dependencies: physical, cyber, geographic, and logical. Zimmerman [7] believes that two ways that different infrastructure sectors can be connected or interdependent are spatially or functionally .Spatial interdependency refers to the proximity of one infrastructure to another as the major relationship between the two systems. Functional interdependency refers to a situation where one type of infrastructure is necessary for the operation of another.

Spatial interdependency is too detail and obscure to discriminate from districts, while function interdependency is a general way. We use functional interdependencies in the context of infrastructure systems which refer to two or more systems relying upon each another, a disturbance in one system can cause disruption of other systems, e.g. the national electric power grid and natural gas network are functionally interdependent – natural gas fuels many electrical generators, and elements of the natural gas infrastructure (e.g., gas conditioning plants, compressors, and computerized controls) require electricity to operate. A disturbance in the electrical system can cascade into the natural gas system, and loss of natural gas pressure can curtail the generation of electricity.

III. ISM METHODOLOGY AND MODEL DEVELOPMENT

Interpretive structural modeling (ISM), proposed by Warfield [13,14] is a computer-assisted methodology to construct and understand the fundamental of the relationships of the elements in complex systems or situations. Based on the relationships, an overall structure can be acquired and well depicts the relationships graphically. Adapted from Singh's [15] general ISM methodology, the various steps used in this paper are as follows:

Step 1: A contextual relationship is established among the eight infrastructures with respect to which pairs of infrastructures would be examined.

Step 2: A Structural Self-Interaction Matrix (SSIM) is developed, which indicates dependencies or interdependencies among critical infrastructures under consideration.

Step 3: Reachability matrix is developed from the SSIM and the matrix is checked for transitivity. The transitivity of the contextual relation is a basic assumption made in ISM. It states that if an infrastructure A is related to B and B is related to C, then A is necessarily related to C.

Step 4: The reachability matrix obtained in Step 3 is partitioned into different levels.

Step 5: Based on the relationships given above in the reachability matrix, a directed graph is drawn and the transitive links are removed.

Step 6: The resultant digraph is converted into an ISM, by replacing infrastructures with statements.

Step 7: The ISM model developed in Step 6 is reviewed to check for conceptual inconsistency and necessary modifications are made.

A. *Structural self-interaction matrix(SSIM)*

ISM methodology suggests the use of the expert opinions based on various management techniques such as brain storming, nominal technique, etc., in developing the contextual relationship of "leads to" type among the variables. We firstly list a variety of functional interdependencies examples among the eight infrastructures. Additionally, experts of our research team were consulted to identify the existence of a relation between any two infrastructures (i and j) and the associated direction of the relation. Based on this, final functional interdependency among the eight infrastructures is developed (see Table Ⅱ).

Four symbols are used for the type of the relation that exists between the two infrastructures under consideration:

- V—infrastructure j depends on infrastructure i;
- A—infrastructure i depends on infrastructure j;
- X—infrastructures i and j are interdependent; and
- O—infrastructures i and j are unrelated.

Based on the rules, the SSIM is developed for the 8 critical infrastructures (see TableⅢ).

B. *Initial and final reachability matrix*

The SSIM is transformed into a binary matrix, called the initial reachability matrix by substituting V,A, X, O by 1 and 0 as per the case. The rules for the substitution of 1's and 0's are the following:

TABLE II. FUNCTIONAL INTERDEPENDENCIES AMONG CRITICAL INFRASTRUCTURES

Infrastructures independency examples	**8Government services**	**7Water supply systems**	**6Gas and oil**	**5Banking and finance**	**4 Electric power**	**3Information and communications**	**2Transportation**
1Emergency services	emergency service is mainly organized by local and federal government	water supply system is required by emergent rescue (e.g. fire fighting)	gas and oil is required to run emergency machines		a portable power generator may be used in emergency services	Information and communications are required for emergency emergency control and coordination center(s), for answering where, what, and when to initiate response.	Emergent large-scale evacuation needs transportation
2Transportation			Gas and oil are required to fuel transport equipments.(e.g. aircraft)		electric power is required to run the signals, switches, and control centers of the transportation infrastructure(e.g. railroad.) / The transportation such as railroad provides coal for fuel and delivers large repair and replacement parts to the electrical generator.	transportation networks often use sophisticated computerized control and information technologies for exact operation	
3Information and communications	telecommunications for e-government services	a supervisory control and data acquisition (SCADA) system is required in moniting and controling elements of water supply system	a supervisory control and data acquisition (SCADA) system is required in monitoring and controling elements of the gas and oil system	telecommunications for e-commerce	a supervisory control and data acquisition (SCADA) system is required in monitoring and controling elements of the electrical power grid./ telecommunication networks require electricity		
4Electric power		Large amount of water is necessary for power plant cooling and emissions reduction./ Power is required by pumps and lift stations, and control systems is necessary in water supply system	Electric power infrastructure requires natural gas and petroleum fuels for its generators, lubricants / Energy pumping stations, compressors, storage,and control systems require electric power	Electrical power is necessary in the functioning of banking systems and ATM machines			
5Banking and finance							
6Gas and oil		Water for Production, Cooling, Emissions Reduction in gas and oil system					
7Water supply systems							

TABLE III. STRUCTURAL SELF-INTERACTION MATRIX (SSIM)

elements	8	7	6	5	4	3	2
1	O	A	A	O	A	A	A
2	O	O	A	O	X	A	
3	V	V	V	V	X		
4	V	X	X	V			
5	O	O	O				
6	O	A					
7	O						

- If the (i, j) entry in the SSIM is V, then the (i, j) entry in the reachability matrix becomes 1 and the (j, i) entry becomes 0.
- If the (i, j) entry in the SSIM is A, then the (i, j) entry in the reachability matrix becomes 0 and the (j, i) entry becomes 1.
- If the (i, j) entry in the SSIM is X, then the (i, j) entry in the reachability matrix becomes 1 and the (j, i) entry also becomes 1.
- If the (i, j) entry in the SSIM is O, then the (i, j) entry in the reachability matrix becomes 0 and the (j, i) entry also becomes 0.

Following these rules, initial reachability matrix for the eight infrastructures is shown in Table Ⅳ.

The final reachability matrix is obtained by incorporating the transitivities as enumerated in Step 4 of the ISM methodology. This is shown in Table Ⅴ. In this table, the driving power and dependence of each barrier are also shown. The driving power of a particular barrier is the total number of infrastructures (including itself) which it may help achieve. The dependence is the total number of infrastructures which may help achieving it. These driving power and dependencies will be used in the MICMAC analysis, where the eight critical infrastructures will be classified into four groups of autonomous, dependent, linkage, and independent (driver) barriers.

TABLE IV. INITIAL REACHABILITY MATRIX

elements	1	2	3	4	5	6	7	8
1	1	0	0	0	0	0	0	0
2	1	1	0	1	0	0	0	0
3	1	1	1	1	1	1	1	1
4	1	1	1	1	1	1	1	0
5	0	0	0	0	1	0	0	0
6	1	1	0	1	0	1	0	0
7	1	0	0	1	0	1	1	0
8	1	0	0	0	0	0	0	1

TABLE V. FINAL REACHABILITY MATRIX

elements	1	2	3	4	5	6	7	8	driving power
1	1	0	0	0	0	0	0	0	1
2	1	1	1	1	1	1	1	1	8
3	1	1	1	1	1	1	1	1	8
4	1	1	1	1	1	1	1	1	8
5	0	0	0	0	1	0	0	0	1
6	1	1	1	1	1	1	1	1	8
7	1	1	1	1	1	1	1	1	8
8	1	0	0	0	0	0	0	1	2
dependences	7	5	5	5	6	5	5	6	

C. *Partitioning the reachability matrix*

The matrix is partitioned, by assessing the reachability and antecedent sets for each variable. The reachability set consists of the element itself and other elements, which it may help to achieve, whereas the antecedent set consists of the element itself and other elements, which may help achieving it. Then the intersection of these sets is derived for all the elements. The elements for which the reachability and intersection sets are same are the top-level elements in the ISM hierarchy. The top-level elements of the hierarchy would not help to achieve any other element above their own level in the hierarchy. Once top-level elements are identified, it is separated out from the rest of the elements. Then, the same process is repeated to find the next level of elements. The process is completed in three iterations (Tables Ⅵ,Ⅶ,Ⅷ) as follows:

In Table Ⅵ, the element 1 (Emergency services) and element 5 (Banking and finance) are found at level I. Thus, they will be positioned at the top of hierarchy of the ISM model. After removing elements 1 and 5 from Table Ⅵ, we get second and third column of Table Ⅶ. In Table Ⅶ, the element 8 (government services) are all put at level II. This iteration is continued till the levels of each critical infrastructure are found out. The elements, along with their reachability set, antecedent set, intersection set and the levels, are shown in Tables Ⅵ–Ⅷ.

TABLE VI. ITERATION 1

Elements (P_i)	Reachability set:R (P_i)	Antecedent set:A (P_i)	Intersection $R(P_i) \cap A(P_i)$	Level
1	1	1,2,3,4,6,7,8	1	Ⅰ
2	1,2,3,4,5,6,7,8	2,3,4,6,7	2,3,4,6,7	
3	1,2,3,4,5,6,7,8	2,3,4,6,7	2,3,4,6,7	
4	1,2,3,4,5,6,7,8	2,3,4,6,7	2,3,4,6,7	
5	5	2,3,4,5,6,7	5	Ⅰ
6	1,2,3,4,5,6,7,8	2,3,4,6,7	2,3,4,6,7	
7	1,2,3,4,5,6,7,8	2,3,4,6,7	2,3,4,6,7	
8	1,8	2,3,4,6,7,8	8	

TABLE VII. ITERATION 2

Elements (P_i)	Reachability set:R (P_i)	Antecedent set:A (P_i)	Intersection R(P_i)∩A (P_i)	Level
2	2,3,4,6,7,8	2,3,4,6,7	2,3,4,6,7	
3	2,3,4,6,7,8	2,3,4,6,7	2,3,4,6,7	
4	2,3,4,6,7,8	2,3,4,6,7	2,3,4,6,7	
6	2,3,4,6,7,8	2,3,4,6,7	2,3,4,6,7	
7	2,3,4,6,7,8	2,3,4,6,7	2,3,4,6,7	
8	8	2,3,4,6,7,8	8	II

TABLE VIII. ITERATION 3

Elements (P_i)	Reachability set:R (P_i)	Antecedent set:A (P_i)	Intersection R(P_i)∩A (P_i)	Level
2	2,3,4,6,7	2,3,4,6,7	2,3,4,6,7	III
3	2,3,4,6,7	2,3,4,6,7	2,3,4,6,7	III
4	2,3,4,6,7	2,3,4,6,7	2,3,4,6,7	III
6	2,3,4,6,7	2,3,4,6,7	2,3,4,6,7	III
7	2,3,4,6,7	2,3,4,6,7	2,3,4,6,7	III

D. Formation of ISM-based model

From the final reachability matrix, the structural model is generated. If the relationship exists between Elements j and i, an arrow pointing from i to j shows this. This resulting graph is called a digraph. Removing the transitivities as described in the ISM methodology, the digraph is finally converted into an ISM model as shown in Fig. 1.

From the ISM model (Fig. 1), it is observed that Transportation (2), Information and communications (3), Electric power (4), Gas and oil (6), and Water supply systems (7) play significant driving role in critical infrastructure system and they come at the base of ISM hierarchy. Emergency services (1) and Banking and finance (5) depend on the operation of other critical infrastructures and they appear at the top of the hierarchy. Government services (8) provides an environment which helps in effective Emergency services (1), but it also depends on the operation of Information and communications (3), so it is in the middle of the hierarchy. It is indicated that while planning for critical infrastructure system considering interdependencies, a higher priority should be placed on the infrastructure, which has a high driving power and thus possessing more capability to influence other infrastructure, which are shown at the root level of the ISM.

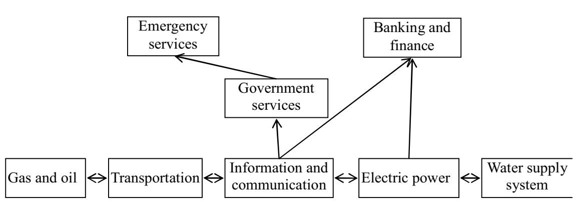

Figure 1. ISM-based model for the critical infrastructures

IV. MICMAC ANALYSIS

The objective of the MICMAC analysis is to analyze the variables according to their driving power and dependence towards system of systems [16]. The eight critical infrastructures are classified into four clusters (Fig. 2).

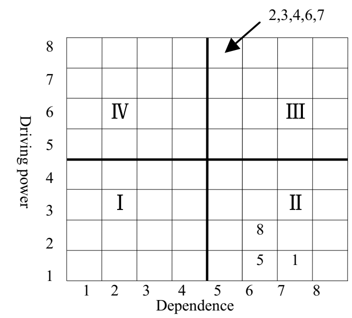

Figure 2. Driving power and dependence diagram

The first cluster consists of critical infrastructures that have weak driving power and weak dependence. These critical infrastructures are relatively disconnected from the system, with which they have only few links, which may be strong. These are autonomous critical infrastructures. Second cluster consists of critical infrastructures that have weak driving power but strong dependence. These are termed as dependent critical infrastructures. Critical infrastructures in third cluster have strong driving power and strong dependence. These critical infrastructures fall into the category of independent or linkage critical infrastructures. These critical infrastructures are unstable. Any action on these critical infrastructures will have an effect on others and also a feedback effect on themselves. Fourth cluster includes independent critical infrastructures having strong driving power but weak dependence.

From the diagram (Fig. 2) it is observed that there are no infrastructures in cluster Ⅰ or Ⅳ, which means no autonomous critical infrastructure and no strong driving power but weak dependence infrastructures occur. Emergency services (1) and Banking and finance (5) are kept under cluster Ⅱ, which means they are heavily dependent critical infrastructures. Also, it is observed that Government services (8). Transportation (2), Information and communications (3), Electric power (4), Gas and oil (6), and Water supply systems (7) having strong driving power and strong dependence are kept under the cluster Ⅲ, which means they are unstable. Any disruption on one of these critical infrastructures will have an effect on others and also a feedback effect on itself.

V. CONCLUSION

This research gives some valuable insights about the relative importance among national critical infrastructures. Some main infrastructures considered have been identified and the relationships among the infrastructure are analyzed by the ISM model. In addition, these infrastructures are categorized according to their driving power and dependence. An examination of direct and indirect relationships among the critical infrastructures can give a clearer picture of the situation than considering individual factors alone in isolation. Though

ISM is developed on the basis of perception of the experts, the results are quite generic and helpful for the top management to drive the efforts towards the roots of the problem. The research will be useful to practitioners who are interested in implementing policies, planning procedures, and decision support systems to move toward critical infrastructure protection. It will also benefit researchers who are interested in advancing analytical tools and policy instruments, as well as educators interested in expanding their existing curricular to address criticality in civil infrastructure systems.

However, it should be mentioned that technological, economic, and regulatory changes have being dramatically altered the relationships among infrastructures, a precise definition of what is and what is not part of a "critical infrastructure" and the criticality level of the CIs are still hard to obtain. Indeed, each time the government defines a list of critical infrastructures, the list grows longer and longer. For example, by 2002, this list had grown to 13 according to the report of the Department of Homeland Security [4] and included: Agriculture, Food, Water, Public health, Emergency services, Government, Defense industrial base, Information and telecommunications, Energy, Transportation (people and product), Banking and finance, Chemical industry, Postal and shipping.

Next generation infrastructures are increasing in size, scope and complexity. The overall system design must not only consider design of individual components but also the design of the interrelationships between the components. System architecture and design of next generation infrastructures require a holistic, enterprise wide perspective rather than the reductionist top-down approach of traditional engineering design. Identifying and understanding these interactions using a holistic and hierocracy/multi-layer perspective can lead to more efficient infrastructure systems [17].

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