Criticality Assessment of Lifeline Infrastructure for Enhancing Disaster Response

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Abstract: In normal and hazardous situations, critical infrastructure systems such as roads, bridges, electricity, gas, and waste treatment facilities play a very crucial role in sustaining communities and industries. It is thus very important to examine the functional and structural stability of these supporting infrastructure systems. An assessment analyzing the criticality of infrastructure systems should be performed before impact of facing extreme events, such as hurricanes, floods, and earthquakes. The criticality assessment involves using a decision support system that incorporates vulnerability and severity assessments to provide emergency agencies and experts, relevant information that will facilitate an enhanced disaster mitigation response. This paper introduces the criticality assessment based on the interrelationships between the critical infrastructure systems, associated industries, and communities. The social, economic, and technical data of the 2008 Midwest floods were collected through interviews, site investigations, and survey questionnaires as a part of this research. Methodology includes the zone of influence of critical infrastructure, activity analysis, social and economic contribution, and priority analysis between the activities and infrastructure systems. Finally, the relative criticality levels of infrastructure systems were derived. **DOI: 10.1061/(ASCE)NH.1527-6996.0000084.**

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Role of Critical Infrastructure

Failures of critical infrastructure are closely related to the conditions of critical infrastructure. The majority of infrastructure throughout the United States has been weakened because of age and deteriorated conditions, making them vulnerable to natural disasters. The 2009 ASCE Report Card for infrastructure gives an average grade of D to U.S. infrastructure, signifying a need for urgent rehabilitation (ASCE 2009).

Flood protection systems such as levee, canal systems, etc., were constructed to safeguard the city of New Orleans against floods. However, these systems were poorly maintained and did not withstand the impact of the Hurricane Katrina, resulting in widespread damage to the city of New Orleans. Failure of multiple infrastructure systems escalated the impact of Hurricane Katrina in the city of New Orleans (Leavitt and Kiefer 2006; Boin and McConell 2007). Disasters and aging interdependent infrastructure will lead only to increase in disaster impact (Leavitt and Kiefer 2006; Choate and Walter 1981).

Natural disasters affect critical infrastructure systems, which, in turn, affect the services and activities of industries and communities as well as response during the disaster occurrence. For example, during the Haiti earthquake, the fatalities and loss of property were significantly increased because the affected areas in Haiti had little or weak infrastructure. The damaged infrastructure impeded the relief effort of emergency-related agencies by delaying their reaching the affected areas in Haiti (Brattberg and Sundelius 2011). If they had identified and fortified the critical infrastructure (i.e., communication networks and main routes), which were vulnerable to earthquakes, ahead of time, damage and impacts due to the earthquake could have been significantly mitigated. Moreover, experts feel that restoring livelihoods of victims and creating and restoring jobs after natural disasters is a high priority and it helps communities and industries to quickly recover and function after disasters (World Bank 2010).

Thus, when natural disasters occur, critical infrastructure such as roads and bridges play a very important role in disaster response as they support activities for bringing life back to business as usual or normality as quickly as possible.

This paper illustrates a methodology to assess the level of criticality of infrastructure systems associated with communities and industries. For this research, criticality has been defined as dependency of a community or an industry on critical infrastructure systems in terms of their daily routine activities. Additionally, these activities may be supported by more than one infrastructure systems. In this research, infrastructure systems are identified as road and bridge systems, electricity systems, water systems, waste water systems, etc., that are required for sustenance of activities of communities and industries.

Therefore, if we know which infrastructure systems are more or less important for communities and industries, critical and vulnerable infrastructure can be protected and reinforced well ahead of time; this can be achieved by providing relevant information, such as the priority of improving resistance of the infrastructure and the priority of rehabilitation of damaged infrastructure. This would enable us to reduce the impact of natural disasters on industries and communities by protecting their activities and services.

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Literature Review and Previous Work

It is important to assess the level of criticality of the infrastructure to know which infrastructure systems should be protected and fortified against disasters. The role of critical infrastructure and varied viewpoints of the criticality analysis were identified through literature review with respect to social, economic, and technical factors. Previous researchers have used not only monetary factors but also social and technical factors, such as workforce losses, loss of customers, interdependency between industries, and infrastructure. They also highlighted the importance of considering social and technical factors in addition to the economic impact, such as the monetary value of the loss, to analyze the diverse impacts of any catastrophe.

Previous research has illustrated the relationship of the physical impacts of natural disasters and the social and economic factors on communities identifying the social and economic characteristics of communities (Lindell and Prater 2003; Cutter et al. 2003). Chang (2003), Cho et al. (2001), and Rose et al. (2007) have looked at impact on regional economics due to disruption of infrastructure systems after disasters. They estimated the largest of economic losses due to failure of a critical infrastructure. Rose et al. (2007) studied the effect of electricity outage in the context of a total blackout of electricity in Los Angeles, California, in 1994. Additionally, natural disasters influence the business and activities of industries and communities by damaging critical infrastructure, causing economic as well as social impact (Zhang et al. 2009).

Analyzing the technical aspect of disaster impacts on infrastructure is a basis for understanding the social and economic impacts (Chang et al. 2007). For example, Chang et al. (2002) applied a simulation approach to modeling disaster impacts on the urban economy. This was based on the linkage between physical infrastructure systems and industries for the recovery stage. They suggested an economic-loss methodology for water lifeline systems interrupted by an earthquake; this methodology integrated engineering-damage models and an economic-loss model. In addition, Chang (2003) pointed out the significant fact that the loss of critical infrastructure, such as electric power, water, transportation, and other lifeline infrastructure systems, can have far-reaching impacts on the economy.

In addition, Rinaldi et al. (2001) emphasized more the role of infrastructure observing interdependencies among infrastructure systems and their importance and influence over the functioning of industries. They provided a conceptual framework that shows a broad range of interrelated factors and system conditions based on six dimensions of infrastructure characteristics:

- State of operations;
- Types of interdependencies;
- Environment;
- Coupling and response behavior; and
- Type of failure.

They identified multiple dependencies and interdependencies existing between the infrastructure systems, and through these connections, they demonstrated how the impacts of the energy crisis in California affected interrelated infrastructure systems.

Dueñas-Osorio et al. (2007) have proposed a framework by which to assess the effect of seismic disruption on the performance level of interdependent networks; they used various parameters of including infrastructure and topology of the region.

In addition to these conceptual models for analyzing natural impacts, the FEMA has developed a GIS integrated disaster response tool to estimate social and economic losses on communities. *Hazards U.S. Multi-Hazards (HAZUS-MH)* is customized for estimating losses from earthquake, floods, and hurricanes. It provides information about physical damage to residential and commercial buildings, economic loss in terms of lost jobs, business interruptions, repair and reconstruction costs; it also provides information about social impacts, including estimates of shelter requirements, displaced households, and population exposed to disasters. Furthermore, the model provides information on the generation of debris and shelter requirements (Scawthorn et al. 2006).

Resilient infrastructure facilitates rapid response to recovery after any disaster. For example, damaged but still serviceable routes might become evacuation routes or might help in quick movement of logistical relief supplies. Furthermore, if infrastructure is quickly restored, it can help the depending communities and industries revive from the aftermath of the disaster. One of the limitations of HAZUS-MH is that it does not provide information on the interrelationship existing between infrastructure, communities, and industries, which would be helpful in preparing better mitigation strategies. Because of this limitation, experts may have difficulties finding the right methods at the right time to temporarily mitigate the impacts on industries and communities in the longer term (Hastak et al. 2009).

The interrelationship between the infrastructure and associated industries is a key component to understanding a disaster impact mechanism. Critical infrastructure systems are considered life support networks that are essential to sustain the normal activities of the industries and communities, such as production, delivery, and supply chain issues for industries, as well as commuting to work, school, church, healthcare, etc., for communities. These activities are affected when the related critical infrastructures are unable to provide the necessary service for the activities sustenance.

Oh (2008) adopted President's Commission on Critical Infrastructure Protection's (PCCIP's) eight critical infrastructure (President's Commission on Critical Infrastructure Protection 1997) and five additional infrastructures (Rinaldi et al. 2001) as 13 lifeline-critical infrastructures for supporting industries and communities. Additionally, Burrus et al. (2002) aggregated industries from the Standard Industrial Classification (SIC) Code using the *IMpact analysis for PLANning (IMPLAN)* model that were severely affected by hurricanes. Oh (2008) focused on defining the interrelationship of 13 identified critical infrastructures and 51 associated industries to analyze how the impacts of a natural disaster diffuse within an interrelationship existing between the infrastructure and supported industries and communities (Fig. 1). A disaster impact mechanism model was proposed to show the diffusion path of the impact of natural disasters through the primary and secondary impact stages (Oh and Hastak 2008; Oh 2008).

Research Approach and Data Collection

The basic cell model was used to analyze the impact of the 2008 Midwest floods. Part of the work conducted in this research was supported by the National Science Foundation (NSF) through a small grant for exploratory research (SGER): A Short-Term Site Investigation of 2008 Midwest Floods (Award no. 0848016). During the NSF SGER project, the research team focused on critical infrastructure and the impact of floods on associated industries and communities through damaged critical infrastructure.

It is important to collect relevant data from the affected areas without losing the characteristics of the data. The significant data are best collected soon after the occurrence of disasters (Oh and Hastak 2008). Data regarding the affected infrastructure can be interpreted as impacts on industries and communities in terms of technical, social, and economic aspects. Thus, early site investigation is important for gathering the ephemeral data that in the end would support the development of a more robust disaster impact analysis model.

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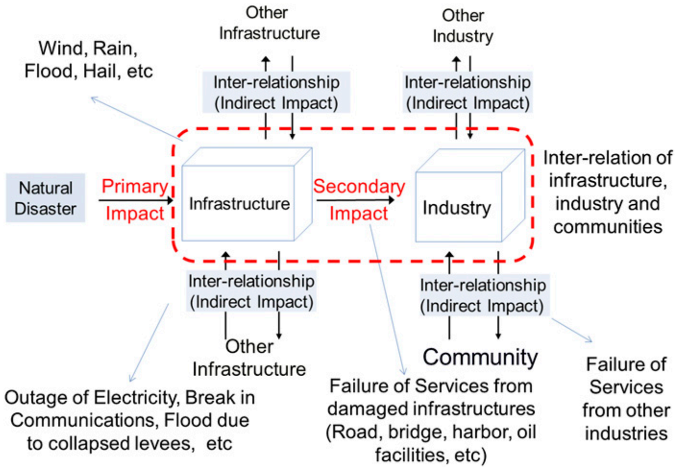

Fig. 1. Disaster impact mechanism: basic cell model (Oh 2008, with permission)

Three modes of data collection were used in this research: interviews, site investigations, and a questionnaire survey with respect to technical, social, and economic impacts. The nature of the data are focused on and include:

- Demographical information (e.g., population, gender, employment, income);
- Critical infrastructure (roads, bridges, office buildings, hospitals, manufacturing plants, wastewater treatment plants, etc.);
- Conditions (deteriorations, maintenance, etc), affected infrastructure (locations, reported damages, adjacent facilities, industrial activities or services that rely on the affected infrastructure, etc.);
- Level of damage of infrastructure, duration of service failure (e.g., hours, days, weeks, months, and years); and
- Description of details and main functions and services that are disrupted for specific industries in the affected area (distribution center, corporation office, manufacturing, retail center, warehouse, etc.)

Framework of Decision Support System for Disaster Mitigation

Plans and mitigation strategies for reducing the impacts are important at a wide range of levels in terms of communities, industries, local and federal governments, etc. Thus, various entities, such as city managers, emergency management agencies, industrial experts, and community leaders, should be able to generate plans and mitigation strategies according to their purposes after data collection is complete. The information they need will be similar and can be derived on the basis of the analyses of the collected data. For example, the purpose of disaster preparedness for a city manager and emergency managers in industries would be to identify vulnerable critical infrastructure from their viewpoints. To complete this, a prime question that a city government or associated parties may raise before preparing plans and strategies would be how much (or how relevant) information is available about the city in terms of the infrastructure and the impacts of natural disasters. The information for developing disaster mitigation strategies and plans can be the following:

- Identification of critical infrastructure for industries and communities in terms of the technical, social, and economic aspects (criticality);
- Identification of vulnerable infrastructure or vulnerable parts and sections of the critical infrastructure (vulnerability);

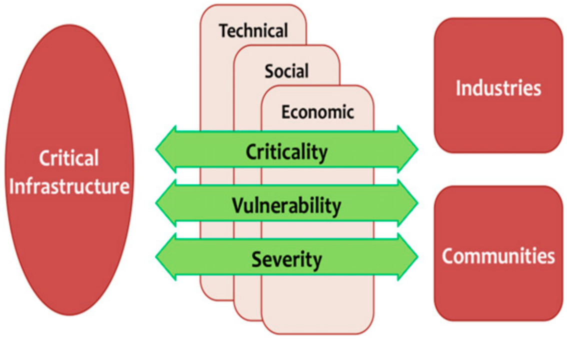

Fig. 2. Metrics of interrelationships

- Establishment of priority to retrofit vulnerable infrastructure;
- Impacts on industries and communities if vulnerable infrastructure fail during a disaster (severity or level of impact); and
- Mitigation plans to protect industries and communities.

Part of the research that was conducted was used to develop a disaster impact mitigation support system (DIMSuS) that would help city managers, emergency planners, and community and industry people to prepare better mitigation strategies (Oh 2010). The framework consists of three metrics, i.e., criticality, vulnerability, and severity.

Criticality refers to how much a company is critically interrelated with (or depends on) critical infrastructure. Vulnerability addresses the threats or real hazards to industries or communities in disaster situations and can vary according to the condition of the infrastructure. Severity refers to the extent of damage or impact when a disaster occurs in communities or near industries (Oh et al. 2009; Hastak et al. 2009). Thus, criticality, vulnerability, and severity are the key metrics to understanding how critical infrastructure, industries, and communities are interrelated in terms of the impacts of natural disasters and how the impact may be measured (Fig. 2).

Definition and Measurement Factors of Criticality

Together with vulnerability and severity, criticality is one of the most important aspects of disaster response and disaster risk reduction with vulnerability and severity (Hastak et al. 2009).

Criticality is the dependency of a community or an industry on critical infrastructure in terms of their daily routine activities and aims to measure the relationship between critical infrastructure, industries, and communities, based on the activity analysis.

Importance of Activities for Impact Measurement

Activities in this research are identified as social and economic actions/tasks that communities and industries perform daily. Each activity offers social and economic contributions for communities and industries and the activities are being supported by associated infrastructure. For example, production, as an activity associated with an industry, might be supported simultaneously by water utility, electricity, and gas utility. Thus, there exists a relationship between the activities and the infrastructure. This relationship implies a level of dependency of one or more activities on associated infrastructure and the level of dependency is called the level of criticality in this research.

Some industries and communities may be more dependent upon certain infrastructure than others to sustain their activities (e.g., for a manufacturing company, electricity may be the most significant infrastructure in operating their manufacturing lines, in communicating, and in maintaining their associated work activities). Additionally, electricity may be supporting other activities of a company such as storage, cooling, etc. In this sense, the multiplicity of a particular infrastructure uses is identified as an important factor in assessing the level of criticality.

Each infrastructure component offers assistance for sustaining an activity of community and industry, which is called the level of assistance in this research (Deshmukh et al. 2011). Each activity may have infrastructure alternatives. For example, there could be a certain number of combinations (or routes) of roads and bridges for supporting specific activities, such as shipping and commuting. The alternatives for shipping may have many combinations of roads and bridges. The assistance level of each alternative, however, may not be the same, as it is determined by the condition and the serviceability level of the infrastructure. Serviceability levels of infrastructure systems are defined as an ability of an infrastructure to support an activity or activities of the community or industry (Deshmukh et al. 2011). It is assumed that the as-is condition of an infrastructure component in a predisaster situation is equated to 100% serviceability of that infrastructure.

Criteria for Assessing Level of Criticality

The level of criticality is assessed using two criteria:

1. The number of activities depending on an infrastructure component for its sustenance and
2. The assistance level of an infrastructure component provided to support an activity.

In this paper, an infrastructure alternative indicates both a single infrastructure component and a combination of more than one infrastructure component to support a certain activity.

Process of Criticality Assessment

Using these two criteria, the criticality assessment consists of a four-step process:

1. Activity analysis (identification and prioritization of activities);
2. Zone of influence (identification of critical infrastructure that supports the activities);
3. Identification of alternatives for each activity and assistance level of each alternative; and
4. Calculation of the relative level of criticality (Fig. 3).

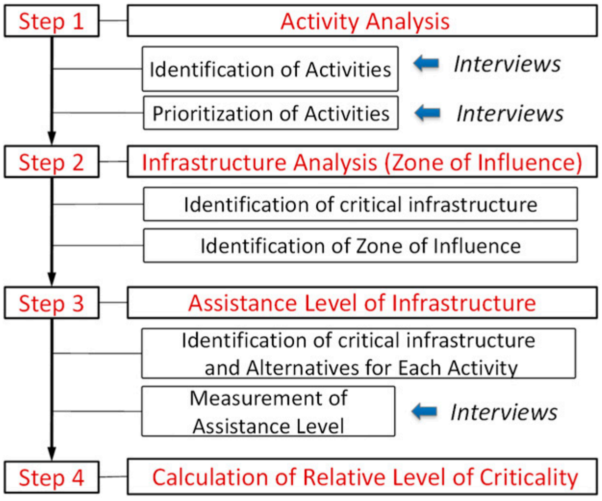

Fig. 3. Four-step process of measurement of the level of criticality

Step 1: Activity Analysis

Activities are important for industries to grow their economy and for communities to not only be economically stable, but to be socially well equipped. The major social and economic contribution activities of communities and industries are identified through interviews and survey and are prioritized using analytic hierarchy process (AHP).

AHP is a process of multicriteria decision making that is useful for measuring intangible factors (Saaty 1982). AHP requires a scale of numbers that indicates how many times one element is more important or dominant over another element. A pairwise comparison is made between activities and they are rated using a predetermined scale ranging from 1 to 9, where 1 represents equal importance between elements, 2, 4, 6, and 8 have intermediate importance, 3 has weak importance of one activity over the other, 5 represents strong importance of one activity over the other, 7 represents very strong importance of one activity over the other, and 9 represents absolute importance of one element over another (Saaty 1982).

Step 2: Infrastructure Analysis (Zone of Influence)

Infrastructure systems are interdependent and set of infrastructures form a multi-infrastructure network with nesting communities and industries. Each infrastructure has a zone of influence (ZOI).

ZOI has been defined as an imaginary area surrounding an infrastructure that is capable of influencing social/economic activities of communities and economic functions of industries.

Zones of influence of each infrastructure component will be identified on the basis of the interrelationships of the identified activities of industries and communities actually supported by the critical infrastructure, for example, the highway support for shipping materials and products and transporting people. Similarly, all infrastructure systems are interrelated with the activities of associated industries and communities. The zone of influence is established to identify all interrelationships and to assess the level of criticality for the interrelationships as shown in Fig. 4.

The zones of influence of three infrastructure systems, i.e., water (wells), power plant, and highway, are capable of supporting the activities and functions of community and industry (Fig. 4). Based on the zone of influence, the three infrastructure systems appear very critical to sustaining the community and industry located within the area mentioned previously.

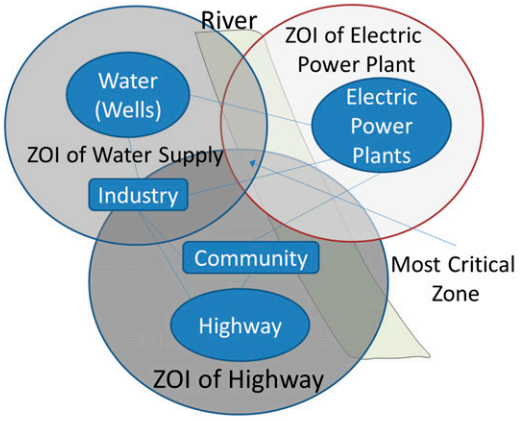

Fig. 4. Example of interrelationships between critical infrastructure systems and associated industries and communities and its zone of influence

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Step 3: Assistance Level of Infrastructure

However, we need to understand how the communities and industries depend on the critical infrastructure using either a quantitative or qualitative method. Each activity makes either a social or an economic contribution to an industry or a community. The activities of the communities and industries can provide a metric to measure the level of criticality as previously discussed. Thus, in the third step, the priority of the activities and the level of assistance of the infrastructure will be identified.

Step 4: Calculation of Relative Level of Criticality

The social and economic contribution has been combined because all activities of communities and industries are related to social and economic purposes, such as visiting friends, commuting to schools and health care centers, and attending theaters, for the social purpose, and production, shipping, commuting to work places, etc., for the economic purpose. These social and economic contributions can be assessed by using the AHP, which facilitates users' assessment of the relative importance of the activities and infrastructure component. In addition, the AHP method will help identify the level of assistance of each infrastructure component (or each combination of infrastructure component) that supports the activities.

The level of criticality can be obtained by using the following equation:

$$\text{Relative level of criticality of infrastructure}_{j,(j=1\text{ to }m)} = \text{PSC} \times \sum_{i=1}^{n}\left(\text{NwSc}_i \times \text{AL}_{ij}\right) + \text{PEC}* \sum_{i=1}^{n}\left(\text{NwEc}_i \times \text{AL}_{ij}\right)$$

where PSC = portion of social contribution, PEC = portion of economic contribution, NwSc_i = normalized weight of social contribution of each activity i, NwEc_i = normalized weight of economic contribution of each activity i, and AL_{ij} = assistance level of each infrastructure j for each activity i.

Application of Criticality Assessment Model to 2008 Midwest Floods, United States

Introduction

Relevant data that were affected by the Midwest Floods in June 2008 were collected from Cedar Rapids, Iowa. Past historic flood heights were 6.096 m (20 ft) in 1929 (maximum) and 5.88 m (19.3 ft) in 1993; however, a new crest of 9.485 m (31.12 ft) was recorded for the 2008 Midwest floods. There were no fatalities; however, the estimated property and damage loss was as much as $5 billion, including residential, commercial, and industrial. All bridges and routes near the Cedar River, except I-380, were totally closed, and around 5,000 houses (900 in the downtown area) and 14% of the city area (or 1,300 city blocks) were inundated.

An aftermath of the 2008 Midwest floods was that the flood area was expanded beyond the designated 500-year flood plain. The southwest area of the city was included in the new floodplain, including nearly all of the Czech Village area. The east area including Oakhill Jackson Village was also severely affected.

Critical infrastructure systems that sustain the functions and activities of industries and communities in the affected areas, such as Diamond V, Quaker Oats, Penford, Time Check Village, Czech Village, and Oakhill Jackson, are transportation (i.e., I-380, FH151, F Ave., 1st Ave., A Ave. bridge, etc.), two power plants (6th St. Power Plant and Prairie Power Plant), and wastewater treatment plant, wells, etc., as shown in Fig. 5.

The critical infrastructure systems are interconnected and concentrated around the industrial and residential areas and downtown to support their functions and activities. Among these industrial and residential areas, two focal areas were selected around which to structure the system of the proposed model in this paper. The two are Oakhill Jackson, a community for establishing the model, and Diamond V, an industry, in the area of Time Check Village for evaluating the model.

Application of Criticality Assessment: Oakhill Jackson Village

Oakhill Jackson Village was considered for the case study because the assessment of criticality had been applied as discussed in the four-step process explained earlier.

Step 1: Activity Analysis

As explained earlier, activities are social, economic tasks or actions that industries and communities perform can be identified by the people involved, such as employers and employees in a company and residents in a community. Interviews were used to identify the main activities contributing socially and economically to Oakhill Jackson Village in Cedar Rapids, Iowa. These activities are commuting to work, access to shopping and local businesses, access to medical services, and livelihood.

To assess the social and economic contributions made by the identified activities of Oakhill Jackson, two methods may be used:

1. Direct input from users: Direct input is useful when the users can provide the portion of social and economic contributions for their activities. For example, it is very easy for residents to determine that commuting to work is equally important for social and economic purposes.
2. Indirect input using AHP through interviews: In instances, where the users are unable to provide a direct portion of contribution, AHP may be useful to perform a pairwise comparison among activities for obtaining the social and economic contribution of activities. Also, selecting the best infrastructure alternatives for sustaining activities, for example, routes for the residents to reach a hospital, may prove difficult if the route alternatives provide similar serviceability to sustain activities. The AHP method would then be a useful aid in decision making.

The weightings of each activity for social and economic contributions were obtained through interview and are shown in Table 1. Each activity offers a 100% contribution to both social and economic contribution. For example, the social and economic contributions of the activity named Commuting are 50% each, while activity Shopping has 80% and 20% split for social and economic, respectively.

Moreover, the maximum cumulative total contribution of all the identified five activities is 500% (i.e., $5 \times 100\% = 500\%$) either socially or economically. However, the cumulative subtotals for the identified activities for the social and economic contributions are 320% and 160%, respectively.

The portions of social and economic contributions were obtained by normalizing the subtotal contributions by the maximum contribution possible. Thus, the portion of economic contribution (PEC) was obtained as follows: 0.64 ((320%)/(500%) = 0.64) and the portion of social contribution (PSC) was obtained as follows: 0.36 [(180%)/(500%) = 0.36]. It was observed that the activities in this community provided more social contribution than economic contribution.

In addition, the individual social and economic contribution of each activity was normalized using the respective proportion of

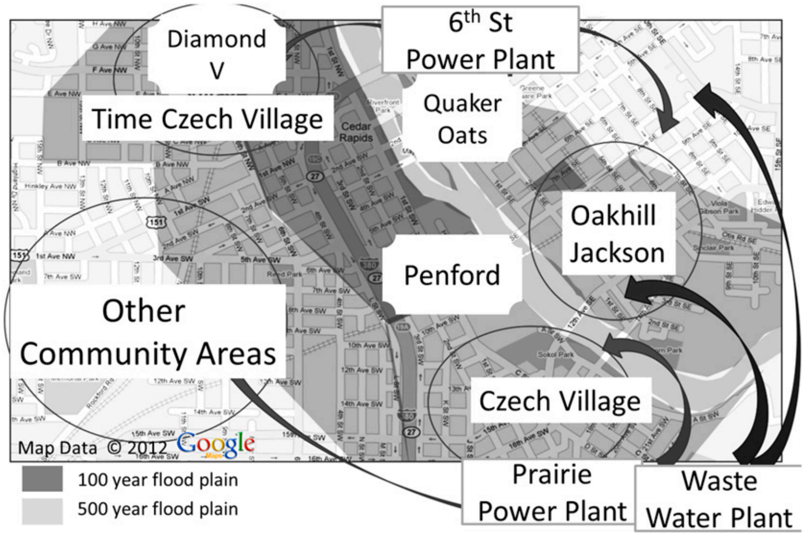


Fig. 5. Interrelationships of critical infrastructure systems and associated industries and communities in Cedar Rapids, Iowa (background image, Google Maps)

Table 1. Main Activities of Oakhill Jackson Village (Cedar Rapids) and Their Contributions

	Social contribution		Economic contribution	
Activities	Weight (%)	Priority (NwSc: normalized weight of social contribution)	Weight (%)	Priority (NwEc: normalized weight of economic contribution)
Commuting	50	0.16 (50/320%)	50	0.28 (50/180%)
Local business	50	0.16 (50/320%)	50	0.28 (50/180%)
Shopping	80	0.25 (80/320%)	20	0.11 (20/180%)
Medical service	50	0.16 (50/320%)	50	0.28 (50/180%)
Livelihood	90	0.28 (90/320%)	10	0.06 (10/180%)
Total	320	1.0 (320/320%)	180	1.0 (180/180%)
Portion of social and economic contributions (PSC and PEC)	0.64 (320/500%)	—	0.36 (180/500%)	—

social or economic contribution made by all the activities. For example, the normalized social contribution (NwSc_i) of activity Livelihood was found to be 0.28 (90%/320% = 0.28) (Table 1).

Step 2: Infrastructure Analysis (Zone of Influence)

The required public infrastructure for the community that Cedar Rapids provides include electricity, water supply, wastewater treatment, gas, transportation (i.e., local and interstate routes), and levee sections.

Commuting requires transportation infrastructure, including local roads, such as 1st Ave. E, 3rd Ave. SE, 8th Ave. NE, 12th Ave. NE, etc., and bridges to cross the river. Other public infrastructure systems are categorized in two groups, utility and transportation, and their importance levels are weighted. The relationships between infrastructure and the activities were identified from the interview information and are indicated in Table 2. However, only local roads are required to access shopping centers and medical services located in the nearby area.

The public utilities, such as electricity, water, sewer, and gas are also very crucial to sustaining local businesses and livelihood in the community.

Step 3: Assistance Level of Infrastructure

From the matrix of activities and critical infrastructure systems (Table 2), we could identify the interrelationships of the activities and associated infrastructure. Some activities need many infrastructure systems at the same time, while others require systems or parts of an infrastructure or combinations of infrastructure systems as alternatives. For example, activity Local Business require electricity, gas, water, sewer, and the levee simultaneously, while Commuting and Shopping activities make use of many alternatives (i.e., 1st Ave. E, 8th Ave. SE, 12th Ave. SE, 8th Ave. Bridge, and 12th Ave. Bridge). When alternatives are available, it would be better if one or few of them are selected if they have more benefits, such as a shorter route length or wider road with more lanes. Thus, these characteristics that support alternatives should be considered for the criticality assessment.

Interviews were used to prioritize and determine the assistance level of related critical infrastructure systems. For example, as shown in Table 3, infrastructure systems sustaining commuting activity were compared pairwise and scores were provided using the AHP scale. Once the normalized scores were obtained for each infrastructure component, they were renormalized using the best score.

Table 2. Matrix of Activities of Oakhill Jackson Village and Related Critical Infrastructure Systems

	Critical infrastructure systems											
	Utility group				Frontline group	Transportation group						
Activities	Electricity	Gas	Water	Sewer	Levee	1st Ave. E	3rd Ave. SE	8th Ave. SE.	12th Ave. SE	8th Ave. Bridge	12th Ave. Bridge	I-380 E19A
Commuting					√	√	√	√	√	√	√	√
Local business	√	√	√	√	√							
Shopping					√	√		√				
Medical service					√			√	√			
Livelihood	√	√	√	√	√							

Note: The symbol √ implies relationships between infrastructure systems and activities. For example, Levee is related to all activities in the community, while 3rd Ave. SE is related to Commuting only.

Table 3. Prioritization of Alternative Using aHP for the Activity of Commuting

	AHP scores					
Infrastructure name	3rd Ave. SE	8th Ave. SE	12th Ave. SE	8th Ave. Bridge	12th Ave. Bridge	I-380 exit 19A
3rd Ave. SE	1	1	5	7	7	9
8th Ave. SE	1	1	6	7	7	9
12th Ave. SE	1/5	1/6	1	3	3	6
8th Ave. Bridge	1/7	1/7	1/3	1	1	4
12th Ave. Bridge	1/7	1/7	1/3	1	1	4
I-380 exit 19A	1/9	1/9	1/6	1/4	1/4	1

Table 4. Result of aHP Prioritization of Alternatives for Each Activity

Activities	Alternatives of infrastructure	Score of AHP	Normalized score
Commuting	3rd Ave. SE	0.37	1.00
	8th Ave. SE	0.37	1.00
	12th Ave. SE	0.12	0.32
	8th Ave. Bridge	0.06	0.16
	12th Ave. Bridge	0.06	0.16
	I-380 exit 19A	0.03	0.07
Shopping	8th Ave. SE	0.67	1.00
	1st Ave. E	0.33	0.50
Medical services	8th Ave. SE	0.67	1.00
	12th Ave. SE	0.33	0.50

As shown in Table 4, route 8th Ave. provides the maximum assistance level to sustain the shopping activity when compared with 1st Ave. Thus, 8th Ave. acts as a benchmark for comparing the assistance level of infrastructure alternatives. Levee is the most important infrastructure that protects the community area and the nearby infrastructure, thereby playing a very important role in protecting against flood events. Thus, the assistance level of the levees is considered to be 1.0 as shown in Fig. 6.

Step 4: Calculation of Relative Level of Criticality

Finally, the criticality assessment for Oakhill Jackson Village was computed as shown in Fig. 6. As previously discussed, the portions of social and economic contributions govern the level of criticality. The weights of the social and economic contributions (PSC and PEC) are multiplied by the normalized assistance level of each infrastructure component, using the equation to calculate the relative level of criticality as discussed earlier.

The assistance level (AL) of each infrastructure component was multiplied by the normalized weight of social and economic contributions according to each activity to calculate the level of criticality from each activity. And the summation of the level of criticality of each activity will be the relative level of criticality of each infrastructure. Using the equation discussed earlier to calculate the relative level of criticality, i.e.,

$$\text{Relative level of criticality of infrastructure}_j = \text{PSC} \times \sum_{i=1}^{n}\left(\text{NwSc}_i \times \text{AL}_{ij}\right) + \text{PEC} \times \sum_{i=1}^{n}\left(\text{NwEc}_i \times \text{AL}_{ij}\right)$$

The relative levels of criticality for Levee Section A and 8th Ave. SE were 1.0 and 0.5, respectively, as calculated below:

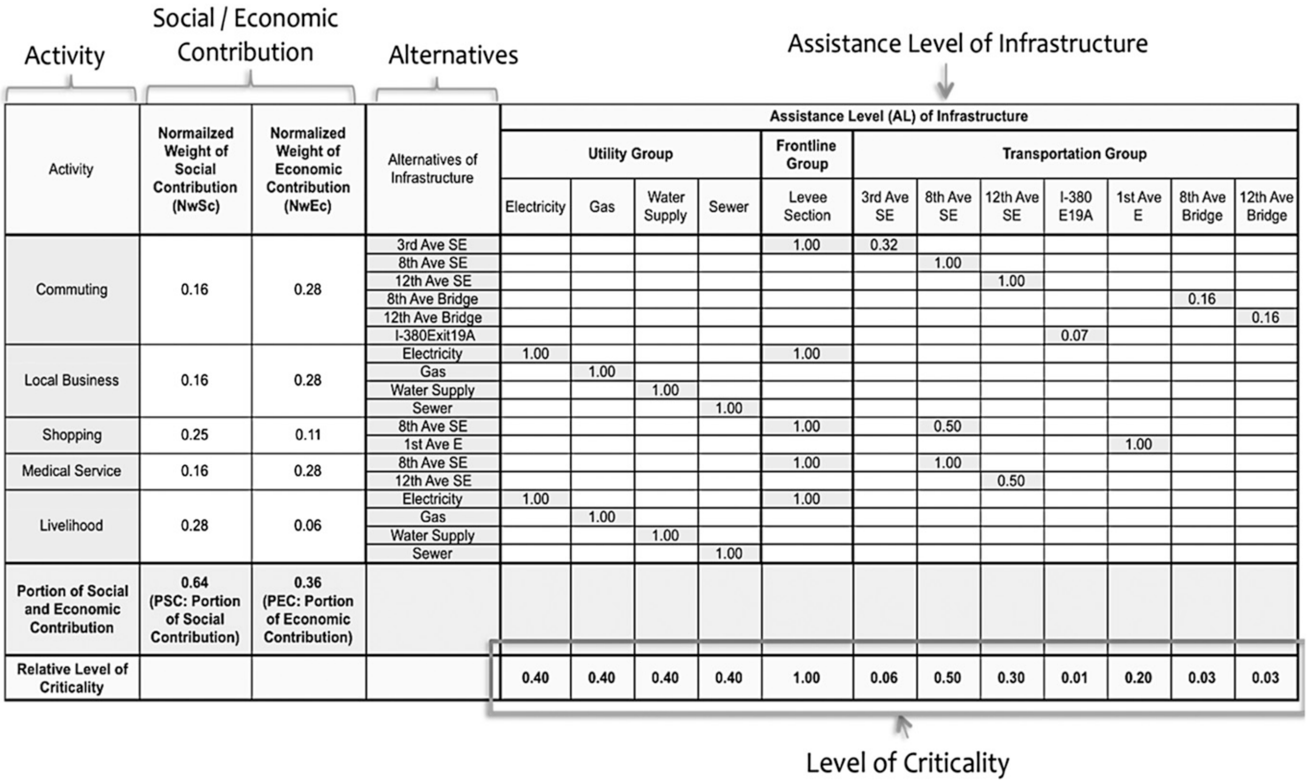
$$\begin{aligned}\text{Relative level of criticality for levee section A} &= 0.64 \times (0.16 \times 1.0 + 0.16 \times 1.0 + 0.25 \times 1.0 + 0.16 \\ &\quad \times 1.0 + 0.28 \times 1.0) + 0.36 \times (0.28 \times 1.0 + 0.28 \\ &\quad \times 1.0 + 0.11 \times 1.0 + 0.28 \times 1.0 + 0.06 \times 1.0) \\ &= 1.0\end{aligned}$$

$$\begin{aligned}\text{Relative level of criticality for 8th Ave. SE} &= 0.64 \times (0.16 \times 1.0 + 0.25 \times 0.50 + 0.16 \times 1.0) \\ &\quad + 0.36 \times (0.28 \times 1.0 + 0.11 \times 0.5 + 0.28 \times 1.0) \\ &= 0.50.\end{aligned}$$

Implication of Criticality Assessment for Oakhill Jackson Village

The decision support system in this paper measures the level of criticality (or the level of dependency) that exists between critical infrastructures and associated communities and industries. Thus, activities were used as measures to reflect their social and economic contributions. As a result of the criticality assessment, the levels of dependency that the Oakhill Jackson Village have on critical infrastructure systems were identified.

The portion of social and economic contributions of all activities in the community were also identified and normalized to have a combined social and economic value. For the Oakhill community, the total portions of social and economic contributions are 0.64 and 0.36, respectively. This indicates that activities in that community may have more social priority when compared with industrial activities, which have more economic contribution than social contribution.



Activity	Normailzed Weight of Social Contribution (NwSc)	Normalized Weight of Economic Contribution (NwEc)	Alternatives of Infrastructure	Assistance Level (AL) of Infrastructure											
				Utility Group				Frontline Group	Transportation Group						
				Electricity	Gas	Water Supply	Sewer	Levee Section	3rd Ave SE	8th Ave SE	12th Ave SE	I-380 E19A	1st Ave E	8th Ave Bridge	12th Ave Bridge
Commuting	0.16	0.28	3rd Ave SE					1.00	0.32						
			8th Ave SE							1.00					
			12th Ave SE								1.00				
			8th Ave Bridge											0.16	
			12th Ave Bridge												0.16
			I-380Exit19A									0.07			
Local Business	0.16	0.28	Electricity	1.00				1.00							
			Gas		1.00										
			Water Supply			1.00									
			Sewer				1.00								
Shopping	0.25	0.11	8th Ave SE					1.00		0.50					
			1st Ave E										1.00		
Medical Service	0.16	0.28	8th Ave SE					1.00		1.00					
			12th Ave SE								0.50				
Livelihood	0.28	0.06	Electricity	1.00				1.00							
			Gas		1.00										
			Water Supply			1.00									
			Sewer				1.00								
Portion of Social and Economic Contribution	**0.64 (PSC: Portion of Social Contribution)**	**0.36 (PEC: Portion of Economic Contribution)**													
Relative Level of Criticality				**0.40**	**0.40**	**0.40**	**0.40**	**1.00**	**0.06**	**0.50**	**0.30**	**0.01**	**0.20**	**0.03**	**0.03**

Fig. 6. Calculation of relative level of criticality of each infrastructure system for Oakhill Jackson Village

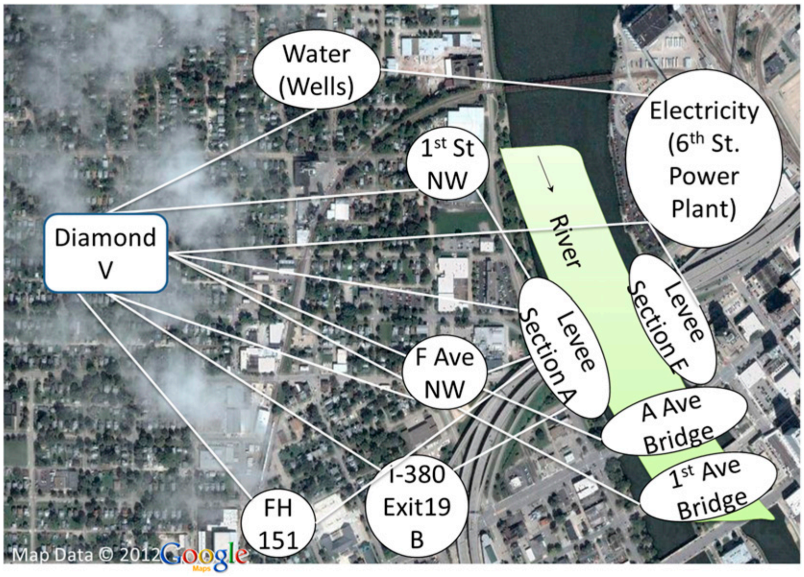


Fig. 7. Network system of critical infrastructure systems for Diamond V in Cedar Rapids, Iowa (background image, Google Maps)

The level of criticality of infrastructure important to Oakhill Jackson neighborhood was assessed and is shown in Fig. 6.

Criticality Assessment Validation

Criticality assessment methodology was validated by using it to assess 2008 Midwest flood impact on Diamond V. Diamond V is a feed ingredient supplier industry, which provides natural, yeast culture products, and high-selenium yeast to animal feed companies, dairy milk producers, beef cattle feedlots, and integrated swine and poultry operations around the world. The major facilities of Diamond V include dryers, tanks, electronics, laboratories, and buildings, etc., as well as critical infrastructure for sustaining operations, including storm sewer lines (storm storage pipes are connected to the city sewer line), and a levee section protects Diamond V's plant and its facilities from the river.

Fig. 7 illustrates the critical infrastructure systems that sustain the functions and activities of Diamond V, and those are Levee Section A, wells (water), electricity (6th St. Power Plant), roads (1st St. NW, F Ave. NW, and FH151), 1-380 Exit 19B, and bridges (A Ave. Bridge and 1st Ave. Bridge). The arcs between the critical infrastructure and Diamond V indicate the interrelationships and levels of dependency. This network of the critical infrastructure systems for Diamond V was used as the network system for testing the model.

The main activities of Diamond V and the critical infrastructure systems that support the activities were identified by conducting interviews of the industry officials (Table 5 and Table 6). The activities were ranked by their economic contributions only and the weights for the prioritization were obtained from the interview using the AHP method that was outlined in step 4 earlier.

The alternatives infrastructure component supporting each activity and their assistance levels were identified. For example, the transportation activities (procurement materials, shipping, and commuting) were considered to have the same assistance level by the president of Diamond V. Finally, the relative levels of criticality of all infrastructure to Diamond V were derived as shown in Table 7.

Interpretation of Results from Criticality Assessment

The results obtained from criticality assessment will help the city managers, community people, and the industry to strategically prepare mitigation strategies in pre- and post-disaster situations in the following ways:

- Identification of infrastructure systems that are critical in sustaining the social and economic activities of communities and industries and their fortification well ahead of any disaster situation;
- Prioritization and allocation of resources to fully utilize critical infrastructure systems in the preparedness stage as well as during a disaster, thereby significantly reducing the technical, social, and economic impact; and
- Restoration of their most important social and economic activities using the criticality assessment, helping the communities and industries to restore the livelihoods of victims but also to create and restore jobs after a disaster.

This community restoration process is dependent upon the critical infrastructure systems being rehabilitated and restored as soon as possible after disasters.

Table 5. Main Activities of Diamond V (Cedar Rapids) and Its Contribution

Activities	Priority (normalized economic contribution)
Administration	0.089
Procurement of materials	0.249
Manufacturing	0.366
Warehousing	0.023
Shipping products	0.183
Financing	0.056
Commuting	0.034
Total	1.0
Portion of economic contributions	1.0

Note: Social contribution was given as zero value because it was assumed that there is no value of social contribution for industries.

Conclusion

In terms of social and economic contribution, critical infrastructure systems play a very important role in sustaining associated industries and communities. This paper describes the establishment of a criticality assessment module that can be effectively used by emergency management agencies to develop mitigation strategies. The module establishes the level of criticality for critical infrastructure associated with industries and communities. In this research, activities were identified as important factors to assess the level of criticality. The level of criticality was assessed by using data relevant to activities and infrastructure in terms of technical, social, and economic aspects. The criticality assessment module was applied to the Oakhill Jackson Village community, Cedar Rapids, Iowa, to establish the level of the criticality for critical infrastructure. The assessment was performed by prioritizing critical infrastructure based on the number of activities it support and the assistance level of critical infrastructure.

This tool also helps in identification and prioritization of activities that when restored in a post-disaster situation will help in reducing social and economic impacts by quickly restoring the livelihoods. This module is a part of DIMSuS, which also includes two more assessment modules, i.e., vulnerability and severity. The results obtained from the criticality assessment were used for developing the vulnerability module to identify the vulnerability of critical infrastructure systems against the impacts of disasters (for more information, refer to Oh 2010).

Table 6. Matrix of Activities of Diamond V and Related Critical Infrastructure Systems

Activities	Electricity	Water	Sewer	Levee	1st St. NW	FH-151	3rd St. NW	6th St. NW	G Ave. NW	I Ave. NW	A Ave. Bridge	I-380 E19B	I-380 E20A
Administration	√	√	√	√									
Procurement material				√	√		√			√	√		
Manufacturing	√	√	√	√									
Warehousing	√			√									
Shipping products				√	√	√	√	√	√	√	√	√	√
Financing	√	√	√	√									
Commuting				√	√	√	√	√	√	√	√	√	√

Note: The symbol √ implies relationships between infrastructure systems and activities.

Table 7. Relative Level of Criticality of Each Infrastructure System for Diamond V

	Electricity	Water	Sewer	Levee	1st St. NW	FH-151	3rd St. NW	6th St. NW	G Ave. NW	I Ave. NW	A Ave. Bridge	I-380 E19B	I-380 E20A
Relative level of criticality	0.53	0.51	0.51	1.00	0.47	0.22	0.47	0.22	0.22	0.47	0.22	0.47	0.22

The vulnerability module was used in conjunction with the severity assessment proposed by Deshmukh (2010) for assessing social and economic impact on industries and communities, to demonstrate how these may be used as part of a disaster impact mitigation strategy. The severity assessment is based on impact analysis based on reduced level of serviceability for damaged infrastructure; it aims to provide relevant information for rehabilitation of the damaged infrastructure, as well as the recovery of the affected industries and communities.

With this research, community leaders, industry people, and city managers will be greatly helped in systematically making decisions and devising methods for minimizing flood impact based on the condition of related critical infrastructure.

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