FRAMEWORK FOR IDENTIFYING OPTIMAL RISK REDUCTION STRATEGIES TO MINIMIZE THE ECONOMIC IMPACTS OF SEVERE WEATHER INDUCED POWER OUTAGES

by

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“Where the mind is without fear
and the head is held high,
where knowledge is free.
Where the world has not been broken up into fragments by
narrow domestic walls.
Where words come out from the depth of truth,
where tireless striving stretches its arms toward perfection.
Where the clear stream of reason has not lost its way
into the dreary desert sand of dead habit.
Where the mind is led forward by thee
into ever widening thought and action.
Into that heaven of freedom, my father,
Let my country awake!”

- Rabindranath Tagore

Dedicated to the unprivileged children around the world who dream of the life I am living in.

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ABSTRACT

Every year power outages cost billions of dollars and affect millions of people. Historical data shows that between 2000 and 2016, 75 percentage of the outages (in terms of durations) were caused due to severe weather events. Due to the climate changes, these severe weather events are becoming more frequent. The National Association of Regulatory Commissioners have recently emphasized the importance of building electricity sector's resilience thus ensuring long term reliability and economic benefits for the stakeholders. These severe weather events are often considered to be High Impact Low Frequency or HILF events, which means that these events may not occur every year but when they happen the impact is likely to be severe. Therefore, it is imperative that the risk of power outages due to severe weather events and their economic impacts is persistent. To mitigate this risk, utilities need to invest heavily for building resilience so that the impact due to these HILF events can be minimized. Under this situation, the utilities face three key questions (1) where to invest (2) how much to invest and (3) how to justify the investment. However, before investments can be planned for building resilience in the electricity sector, it is equally important to understand the cascading impacts of the sustained power outages during natural disaster events.

The existing frameworks to assess the benefits and costs of the severe weather induced power outages grossly undermines the overall economic impacts. Therefore, there is a need to have a framework for the risk-based decision making, which can holistically gauge the economic impacts of severe weather induced power outages and provide the optimal strategies for minimizing the economic impact under different budget conditions. This research has established (1) a methodology to assess the economic loss due to severe weather induced power outages in terms of the nation's Gross Domestic Product (GDP) and (2) a framework for risk-based decision making for identifying optimal risk reduction strategies for minimizing the economic impact. The framework proposed in the research has the flexibility to accommodate the risk appetite of the decision maker. The framework can be used by the investor owned utilities for rate approvals from the state utility regulatory commissions by justifying the importance of their resilience building projects to the state's economy.

1. INTRODUCTION

Disasters due to natural hazards can cause severe damage to infrastructures, which in turn can significantly affect the society, economy and environment. In the United States, the Presidential Policy Directive (PPD -21) has identified 16 critical infrastructures, whose disruption can cause significant threat to the national security. One of those 16 critical infrastructures is Energy. The energy sector is vulnerable to natural and man-made disasters. Every year power outages cause billions of dollars of economic losses and devastate millions of people (Campbell 2012, Executive Office of The President 2013, Mukherjee, Nateghi, and Hastak 2018a). In the U.S. the Department of Energy (DoE) collects the historical data of major power outages. DoE requires utilities to report any sustained service interruption event through form OE – 417. The historical data (Mukherjee, Nateghi, and Hastak 2018b) from 2000 and 2016 shows that 75 percent of the power outages (in terms of durations) were caused due to severe weather events. Historically, severe weather induced power outages have had widespread impact. In 2005, during Hurricane Katrina some 2.6 million customers in Louisiana, Mississippi, Florida, Alabama and Georgia reported power outages on August 30, 2005 (Hurricane Katrina Situation Report #11 https://www.oe.netl.doe.gov/docs/katrina/katrina_083005_1600.pdf accessed on May 3 2020). Again in 2012 super storm Sandy left over 8.5 million people without power across seven states (Kenward and Raja 2014; Mukherjee, Nateghi, and Hastak 2018a). Due to climate change these natural disasters are getting more frequent (Kenward and Raja 2014).

Infrastructures are connected between themselves. Their connections form a complex network. The interdependencies between different infrastructures make them more vulnerable (Oh, Deshmukh, and Hastak 2010). The interrelationship between infrastructures in a post disaster situation can be explained by a basic cell model (Hastak et al. 2009; Oh, Deshmukh, and Hastak 2013), which essentially says that any affected infrastructure will affect other infrastructures due to interdependencies. The same logic can be applied for utilities. When there is a wide-spread power outage, the impact of that outage is not limited to utility industry only. It also affects other industries which are dependent upon it. This resulting ripple effect is circulated throughout the economy.

Due to the increasing frequency of natural disasters and increasing complexity of infrastructure interdependencies, utilities are facing a huge challenge to provide undisrupted service to the customers (Mukherjee, Nateghi, and Hastak 2018a). To overcome the aforementioned challenges, utilities need to invest in building resilience. The utility sector is highly regulated in the U.S. (Regulatory Assistance Project 2011). So, the investments need to be justified to the State Utility Regulatory Commissions for rate approval.

1.1 Background and Need

Severe weather induced power outages have caused devastating loss during the last two decades. As highlighted above, during the Hurricane Katrina, some 2.6 million people reported power outage. Because, the infrastructures are heavily dependent on electricity, any service interruption causes cascading impact on the infrastructures which are dependent upon electricity. Therefore, the impact of severe weather induced power outages are not limited to utility sector. The impact of sustained power outages is widely spread over the economic system. A report published by the Executive Office of The President (2013) estimated that between 2003 and 2012 weather related outage events have costed U.S. an inflated annual average of $18 billion to $33 billion. The annual cost fluctuated over the years and are maximum when any major hurricanes took place. In 2008 Hurricane Ike happened. The outages cost in 2008 was approximately $40 billion to $75 billion. In 2012 when super storm Sandy devastated the east coast, the said cost was approximately between $27 billion to $52 billion. Another Congressional Research (Campbell 2012) estimated the annual cost of power outages to be between $20 billion to $55 billion.

Due to climate changes, these incidents are becoming more frequent and that trend is likely to continue. Therefore, the utilities need to be prepared for these extreme situations. For that they need to invest to make the grid robust, reliable and resilient to the perturbation. The current practice to assess the benefit and cost of the investments to make the grid resilient grossly undermines the widespread economic impacts of the prolonged outages. In fact, the approval by the State Utility Regulatory Commissions for investments to improve the grid resilience can be biased (Keogh, Cody 2013). Under this situation, the utilities are challenged with three key questions (1) where they should invest (2) how much they should invest and (3) how they justify the investment. This research is intended to answer these three questions.

1.2 Research Statement

This research is conducted to help the utilities and the utility regulatory commissions for investment related decision-making problems. The risk due to the severe weather induced power outages are persistent, which is the reason the utilities need to invest in building resilience and the Utility Regulatory Commissions need to understand the importance of resilience building projects for the State's economy.

Hence, there is a need to develop a framework that can prudently identify the optimal risk reduction strategies under different budget situations so that the economic loss due to severe weather induced power outages can be minimized.

This research has (1) assessed the impact of weather-related power outages in terms of Gross Domestic Product at both state and national level (2) developed a benefit-cost analysis-based framework to help the utilities for identifying optimal strategies to mitigate the risk of severe weather events. The risk-based framework which has been proposed in the research would have the flexibility to accommodate the risk appetite of the decision maker.

1.3 Research Objectives

The ultimate objective of the research is to develop a risk-based framework which can be utilized by the utilities and the state utility regulatory commissions to make key investment decisions related to grid resilience. To achieve this ultimate goal, there are multiple objectives that need to be fulfilled which are listed below:

- Objective 1 – Develop inter-industry relationships of the U.S. economic system.
- Objective 2 – Derive an equation that can estimate the loss in GDP due to severe weather induced power outages at the national level.
- Objective 3 – Develop state level multipliers which can be used to estimate the impact of severe weather induced power outages at the state level.
- Objective 4 – Identify vulnerabilities in the electricity grid and identify risk factors which are causing sustained power outages.
- Objective 5 – Find the strategies that can mitigate the risk due to weather-related power outages.

- Objective 6 – Identify optimal risk reduction strategies that will minimize the economic impacts of weather-related outage events under different budget conditions.
- Objective 7 – Combine the framework with the risk appetite of the decision makers to enhance the flexibility of decision making.

Once, these objectives are fulfilled, the framework will be able to answer the three key questions about where to invest, how much to invest and how to justify the investment under different situations. The decision makers will have the flexibility to modify the framework to accommodate their risk appetite, budget constraints and different investment mechanisms.

1.4 Scope of the Research

As mentioned before, this research is intended to produce a risk-based framework to help the utilities and the state utility regulatory commissions to make investment decisions related to grid resilience under uncertain conditions. To realize the objective the research has been divided into two stages. The first stage of the research will assess the economic loss of severe weather induced power outage events at both state and national level. To achieve this, historical data between 1997 and 2016 were collected from the DoE's Bureau of Economic Analysis (BEA). The U.S. Input-Output accounts are a primary constituent of the U.S. economic system (Planting 2006). The Make Table and the Use Tables were collected from the BEA's input-output accounts. There are three types of Make and Use tables. The three types consider 15, 71 and 405 industries. In this research the tables containing 71 industries have been used. It should be noted that the 71 industries do not include electricity as a separate industry. It lists utility as an industry which consists of electric power generation, transmission and distribution industry, natural gas distribution industry and water, sewage and other industries. It is worth mentioning that Electricity is the single highest contributor of the three, contributing nearly 70% of the utility sectors production output. To overcome this barrier, *this research has assumed the inoperability in the utility sector to be approximately equal to the inoperability in the electricity sector*. This research has used BEA's historical data to develop the inter-industry relationships which exist in the U.S. economy. This research has used Bureau of Labor Statistics (BLS) employment data to develop state level multipliers.

The research further used the relationships to assess the cascading economic impact due to weather-related power outages. This research has developed a disaster impact assessment mechanism and an equation to calculate the economic loss in terms of loss of GDP at both national and state level. It should be mentioned that, the loss does not account for the physical damage to any facility, cost of restoration etc. It only measures the loss in production of different industries due to inoperability in the utility sector. Therefore, if someone is interested in understanding the cost of physical damage to the utilities, this research may not fulfill that requirement.

The second stage of the research has developed the risk-based decision-making framework which uses the economic loss data derived from stage one to realize the risk due to severe weather induced power outages which can affect the state's economy. First, the vulnerabilities in the electricity grid have been identified through existing literature and various technical reports. The next step was to identify the major causes of the failures, which is again done through extensive literature survey. It should be mentioned that the list of risk factors finalized in the research is not exhaustive. The decision makers can incorporate any other risk factors based on their judgement and historic evidences. A list of risk reduction strategies has also been proposed in the research. Again, the list of the risk reduction strategies is not exhaustive. Different utilities can adopt different strategies for mitigating the risk. Finally, the risk-based decision-making framework has been proposed.

Unlike the first stage, the second stage does not produce any concrete numeric results. It rather focuses on developing the framework which describes the detailed process of decision making that can be used by utilities and the state utility regulatory commissions. Thus, it has been made fairly flexible to adjust the requirements of the decision maker.

1.5 Research Methodology

The research has two stages. Stage I is focused on assessing the economic impact of severe weather induced power outages and Stage II is focused on developing a framework for risk-based decision making. The two stages have individual methodologies. However, the two stages are interconnected. Stage II uses the outcomes of Stage I as an input for the decision-making process. The combined methodology is shown in figure 1.1

In Stage I, historical input-output tables between 1997 and 2016 were collected. The data were used to perform Input-Output Analysis as proposed by Wassily Leontief (Leontief 1951, 1986). Input-Output Analysis is a type of economic analysis that maps the inter-relationships between different producing and consuming sectors of the economy (Planting 2006). It has been used for that purpose. The outcome of the Input-Output Analysis using Make and Use Tables is a matrix which is called the Technical Coefficient Matrix. This matrix captures how different industries are linked between each other. To understand the economic impact of the reduced production in the utility sector, the interdependence between different industries need to be mapped. This technical coefficient matrix has been derived for all the years between 1997 and 2016 using the Make and Use Tables.

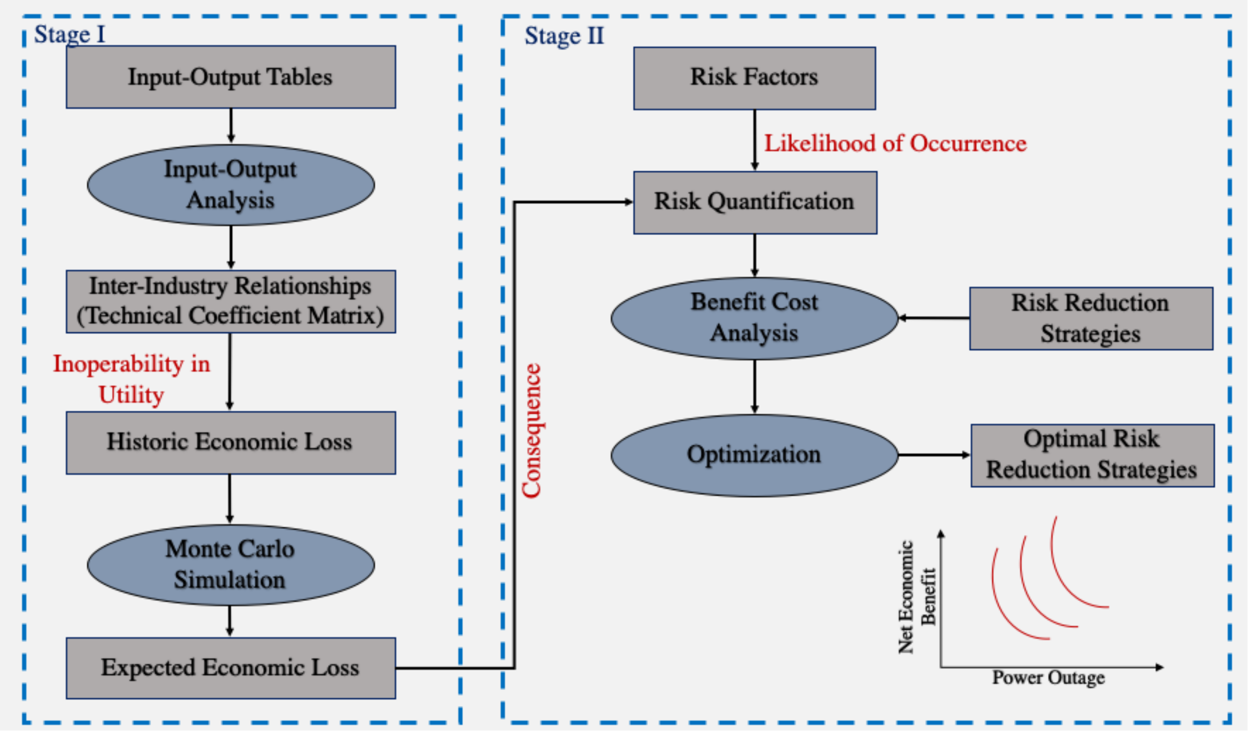


Figure 1.1 Research Methodology

The technical coefficient matrix derived in the step before has been used for Inoperability Input-Output Model or IIM (Yacov Y. Haimes et al. 2005; Santos and Haimes 2004). IIM is the extension of Input-Output Analysis for assessing the economic impact when there is inoperability in production, demand or supply. The previous IIMs and the IIM which has been performed in this research have a fundamental difference. Previous IIMs calculate the impacts in terms of loss of production. In this research the IIM calculates the impacts in terms of loss of GDP as a result of loss in production due to inoperability in Utility sector. To understand the economic impact of inoperability in Utility sector, Leontief's equilibrium equation has been extended for a post disaster situation and a new equation has been derived to calculate the economic loss when there is perturbation in the utility sector in terms of loss of GDP. In this research, the economic impact of inoperability in the Utility sector is expressed in terms of loss of GDP. In should be noted that there can be plethora of other reasons for GDP loss which are beyond the scope of this research.

With the new equation and the historic data between 1997 and 2016, the historic losses were calculated and used to perform a Monte Carlo Simulation. The Outcome of the simulation is the expected economic loss due to severe weather induced power outages. In should be mentioned that although the perturbation is in the production side, the loss is calculated in terms of loss of final demand, which is the GDP. The exercise has been performed at both national and state level. To bring the national level loss down to state level, state level multipliers have been produced using the data from Bureau of Labor Statistics. The method which has been suggested in the research for generating the state level multipliers can be effectively used for generating the multipliers for all the states in the U.S. Therefore, the economic loss assessment can be performed for any state. However, this research has shown the application for the state of Indiana only.

The objective of the second stage of the research is to develop the risk-based framework that will yield optimal strategies (and associated scope of work) to minimize the economic loss from weather-related power outages. First, the vulnerabilities in the electricity grids have been identified from the existing literature. Once the vulnerabilities have been identified, the possible causes of the power outages or the Risk Factors and their relative proportions were also investigated. In the next part, the risk reduction strategies were identified to mitigate the impacts of Risk Factors.

Furthermore, a framework has been produced to identify the optimal risk reduction strategies. The framework uses a Benefit Cost Analysis (BCA) first, to identify the threshold scope of the work for any risk reduction strategy that will keep the Benefit to Cost Ratio (BCR) more than 1. This step ensures that the decision maker will always be on the profitable side after implementing any strategy whose scope of work is higher than what is derived from BCA. Then optimization can be performed so that the optimal scope of work for different risk reduction strategies can be calculated under different budget conditions. The objective function of the optimization is to minimize the economic impact due to weather related power outages or to maximize the benefit obtained from implementing the risk reduction strategies.

The framework also considers the risk appetite of the decision makers. Five levels of risk appetite have been defined in the research. Any decision maker who is making the decision about investment related to resilience based on the assumption that for any given year the expected power outages will be less than what has been seen before is considered as risk seeking. A risk averse decision maker is the one who is making the decision based on the assumption that for any given year the expected power outages will be greater than what has been observed before. It is imperative that for a risk seeking decision maker, the scope of work for the risk reduction strategies will be less than that for a risk averse decision maker. First the decision maker finalizes the extent of power outages against which he or she will implement risk reduction strategies. Next, a probability is calculated for the event that for any given year the expected power outage will be less than or equal to the assumed power outage. Risk is quantified as a function of scenario, likelihood and consequence (Garrick 2008). The likelihood is the probability and the consequence is the economic loss from the assumed power outages. For any risk seeking decision maker, the probability value and the economic impact of the power outages will be lower. In other terms the quantified risk will be lower than normal. This risk value is used as a cost component in the BCA. A lesser cost component in the BCA will yield a lesser threshold scope of work to keep the BCR greater than 1. Therefore, the scope of work for any risk reduction strategy will be less for a risk seeking decision maker than that for a risk averse decision maker.

1.6 Expected Outcomes

This research is expected to have multiple outcomes which are interlinked.

- The first outcome is the economic impact of severe weather induced power outages in terms of loss of GDP at the national level.
- The second outcome is the state level multipliers to measure the economic impact of severe weather induced power outages at state level. In this research, the methodology will be explained for the state of Indiana. But the same procedure can be followed for any other state in the U.S.

- The third outcome will be the risk-based framework for identifying the optimal risk reduction strategies for minimizing the economic impact of severe weather induced power outages under different budget situations. The framework will have the flexibility to accommodate the risk appetite of the decision makers.

The framework which is proposed in the research can be used by the utility companies to answer the three key questions which were raised in the research: (1) where to invest and (2) how much to invest and (3) how to justify the investment. The framework can be used by the State Utility Regulatory Commissions to assess the importance of the risk reduction projects undertaken by the utilities for safeguarding the state's economy. The framework can be applied to other industries while considering associated risk factors.

1.7 Thesis Organization

The thesis is organized in 5 chapters. Chapter 1 introduces the background, research needs and the objectives of the research. It also includes the research scope, methodology and the expected outcomes from the research.

Chapter 2 consists of the literatures reviewed by the researcher. The scope of the research required extensive literature review. The reviewed literatures covered many research domains. They are infrastructure interdependencies, trends of weather-related power outages, cost of weather-related power outages, Input-Output Analysis, Inoperability Input-Output Model, vulnerabilities of electricity grids, risk factors associated to weather related power outages, risk reduction strategies and risk-based decision-making.

Chapter 3 illustrates the economic impact assessment of severe weather induced power outages at the national level. The chapter includes mapping inter-industry relationships, deriving the equation for economic loss estimation in terms of loss of GDP, measuring the historical loss between 1997 and 2016, simulating for the expected economic loss.

Chapter 4 is about the risk-based decision-making framework for identifying the optimal risk reduction strategies to minimize the economic loss due to severe weather induced power outages. The chapter includes derivation of state level multipliers, economic impact assessment at state level, risk factor identification, risk reduction strategies and a benefit cost analysis-based optimization process for identifying the optimal risk reduction strategies.

Chapter 5 will conclude the research by stating the summary of the work, its contributions, its limitations and recommendations for future research.

The chapter 3 and section 4.3 of chapter 4 encompasses the scope of Stage I. The rest of chapter 4 covers Stage II of the research.

2. LITERATURE REVIEW

The objective of the research is to develop a framework that can effectively identify the optimal risk reduction strategies to minimize the economic impact of severe weather induced power outages. Before the objectives can be fulfilled it is essential to understand the current state of art. This has been achieved through the review of existing literature. The scope of the research required vast amount of literature review. The reviewed literature circumscribes multiple domains of research, which are: (1) Trends of Power Outages (2) Infrastructure Interdependencies (3) Input-Output Model (4) Cost of Severe Weather Induced Power Outages (5) Inoperability Input-Output Model (6) Vulnerabilities in the Electricity Grid (7) Risk Factors Causing Severe Weather Induced Power Outages (8) Risk Reduction Strategies and (9) Risk based Decision Making. This chapter will briefly explain the current state of art in the domains mentioned above.

2.1 Trends of Power Outages

Every year power outages cost billions of dollars and affect millions of people. Previous researchers have analyzed the trends in power outages in the U.S. and it has been found that severe weather is a leading cause for the power outages which happen every year (Climate Central 2014; Mukherjee, Nateghi, and Hastak 2018a, 2018b). The report published by Climate Central in 2014 highlighted the increase of severe weather induced power outages over the years. They analyzed 28 years of power outage data and have observed that major power outages have increased by ten times between mid 1980s and 2012. Figure 2.1 shows the results. They have also said that 80 percent of all outages were caused due to severe weather events in between 2003-2012. Between 2003 and 2012, among the states in the U.S. Michigan reported the highest number of power outages followed by Texas, Ohio, Pennsylvania, Virginia, Maryland, North Carolina, California. The report concluded by forecasting that climate change will continue to strain the aging and vulnerable electrical infrastructure.

The U.S. Department of Energy (DoE) requires the utilities to report any power outage during which at least 50,000 customers were affected for at least an hour, there was a power supply disturbance more than 500 megawatt, or the demand exceeded by at least 100 megawatts. Every utility is supposed to submit this the incident report satisfying the abovementioned criteria to the DoE by filling out a survey form (https://www.oe.netl.doe.gov/oe417.aspx, accessed on March 16, 2020). Form OE-417 is an emergency reporting mechanism.

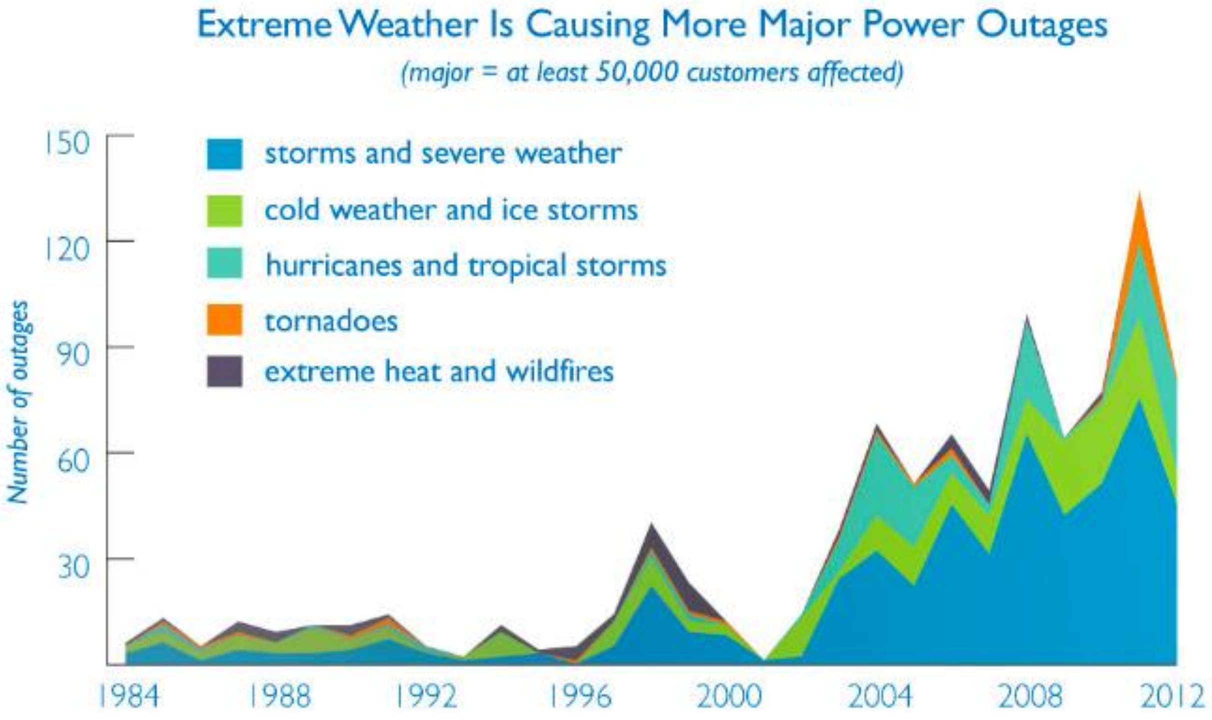


Figure 2.1 Analysis of 28 Years of Power Outage Data (Climate Central, 2014)

The data from OE-417 have been compiled with data from various other sources in Mukherjee, Nateghi, and Hastak (2018b). This article serves as a valuable asset for analyzing the pattern of severe weather induced power outages. The data has been subsequently used in Mukherjee, Nateghi, and Hastak (2018a) and they found that between 2000 and 2016 52.9% of the major reported outages were caused by weather related events, followed by intentional attacks (22.9%), system operability disruption (10.3%), outages due to public appeal (4.2%), equipment failure (4%) and system islanding (2.6%). They have also found that the frequency of these events is increasing over time. Another important finding includes the predominance of single state outages over multiple state outages.

A report published by the Executive Office of the President in 2013 has also shown the increasing pattern of severe weather induced power outages since 1992. Campbell (2012) have also highlighted the ascending trend of weather-related power outage events. Like DoE, North American Reliability Corporation (NERC) also requires utilities to report major power outages. Hines, Apt, and Talukdar (2008) used the information between 1984 and 2006 and found that on average 782,695 customers were affected from power outages due to hurricanes. For ice storms the number is reduced to 343,448 and for equipment failure the number is 57,140.

Therefore, it can be concluded by saying that for the last 4 decades severe weather-related events have remained the single most predominant cause of power outages, their intensity is increasing over time due to climate change and aging of electricity infrastructures and this trend is likely to continue.

2.2 Infrastructure Interdependencies

Infrastructures are the backbone of a nation. The Presidential Policy Directive 21 or PPD 21 has defined 16 critical infrastructure sectors "whose assets, systems, and networks, whether physical or virtual, are considered so vital to the United States that their incapacitation or destruction would have a debilitating effect on security, national economic security, national public health or safety, or any combination thereof" (https://www.cisa.gov/critical-infrastructure-sectors, accessed on April 26, 2020). Natural disasters affect critical infrastructures, which in turn affects industries and communities (Oh, Deshmukh, and Hastak 2013). These critical infrastructures are connected between themselves and their connections create a complex network of infrastructures.

Rinaldi, Peerenboom, and Kelly (2001) have defined 4 types of interdependencies between critical infrastructures. They are Physical, Geographic, Cyber and Logical. Physical interdependency exists when product of one infrastructure is used by another one. In this research physical interdependencies have been considered as the only interdependency. When, there is any disruption in the service of one type of infrastructures, due to interdependencies other infrastructures, industries and communities are also affected. This impact has been explained by a basic cell model in (Hastak et al. 2009; Oh and Hastak 2008). The model is shown in Figure 2.2. The model considers two folded impacts of a natural disaster which are primary and secondary. The primary impact is the direct impact of the natural disaster on the infrastructure. For example, the impact could be power outages for electricity infrastructure, collapse for buildings, roads, bridges. The secondary impact is due to the interdependencies. Therefore, to effectively understand the overall impact of a natural disaster, the understanding of the existing interrelations between infrastructures and industries is essential. This modeling of infrastructure interdependencies can be performed is various ways.

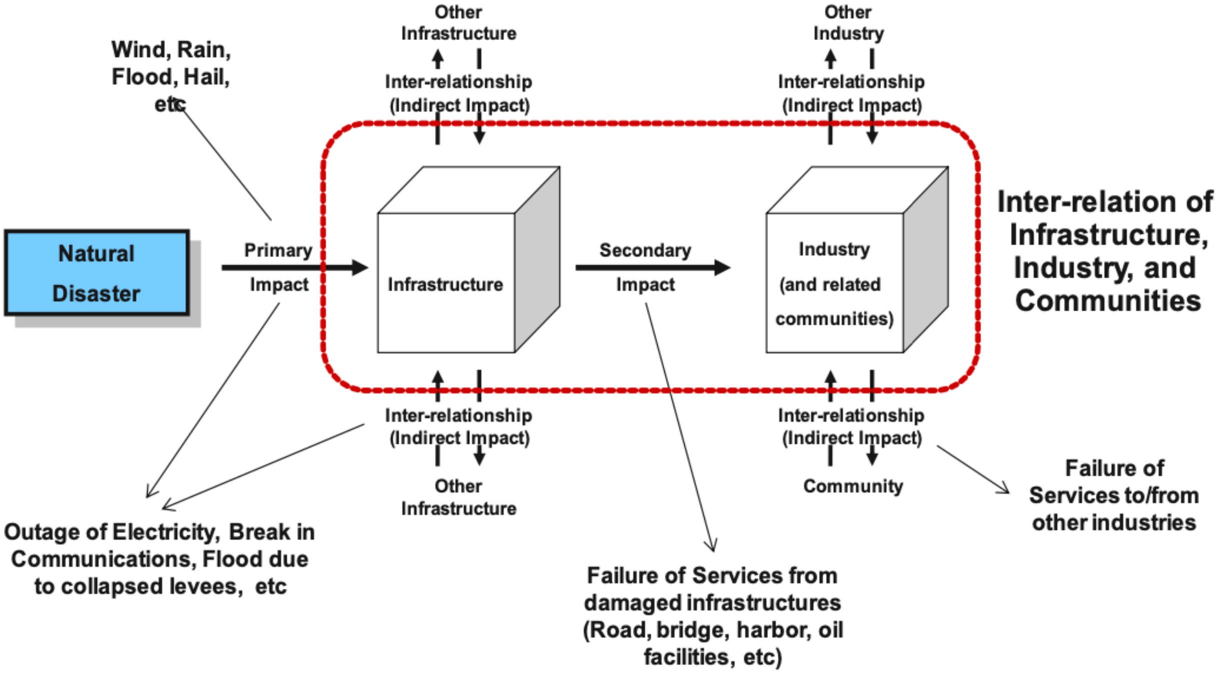


Figure 2.2 Basic Cell Model (Oh and Hastak 2008)

The first one is simulation based. System Dynamics (SD) is popular among the simulation techniques. It is a process to study the time based behavior of a complex system over (Kirkwood 1998). Arboleda et al. (2009) have used a system dynamics simulation to show the operational vulnerabilities for a healthcare facility. They have used the simulation to map the impact of the disruption in the service of external infrastructures: water, power and transportation. Oh, Deshmukh, and Hastak (2010) have applied system dynamics simulations to understand the vulnerabilities of critical infrastructures and associated industries and communities. Min et al. (2007) have also used system dynamics simulations to develop a framework to study the entire system of physical and economic infrastructures. Other examples of system dynamics simulation in the domain of infrastructure interdependencies can be found in Conrad et al. (2006), LeClaire and O’Reilly (2005). Some researchers have also used agent-based modeling (ABM) for interdependency analysis of critical infrastructures. In ABM, critical infrastructures behave like complex adaptive systems (Heracleous et al. 2017), which can interact between themselves. The interdependencies usually emerge from the interaction between different agents. Examples of ABM can be found in Dudenhoeffer, Permann, and Manic (2006), Kaegi, Mock, and Kröger (2009).

The next popular approach to analyze infrastructure interdependencies is to use the concept of graph theory. A graph can be represented by a set of nodes and edges between them. In this approach, the nodes are represented as the infrastructures and the edges between them are the interdependencies. Wang, Hong, and Chen (2012) have used graph theory in their research to develop a framework to analyze the vulnerability of interdependent infrastructures. They have used the example of power and water systems of a major city in China and studied the performance of the network by removing the nodes from the network. Ouyang and Wang (2015) have applied the concept of graph theory for deriving the structural and functional vulnerability of interdependent power and gas network. Other classical examples can be found in Svendsen and Wolthusen (2007), Hernandez-Fajardo and Dueñas-Osorio (2013).

The third popular approach is the use of Input-Output (I-O) Model. I-O model was proposed by Wassily Leontief a Russian-American economist. I-O models capture the interdependence between several producing and consuming sectors (Planting 2006). The interdependence is based on the equilibrium between the production and consumption of different industries. Interdependency analysis with the use of I-O model can be found in Y. Y. Haimes and Jiang (2001), Santos (2006), Setola, De Porcellinis, and Sforna (2009), Wei, Dong, and Sun (2010), Oliva, Panzieri, and Setola (2011).

Other than these three, there are more techniques available to analyze the interrelationships between different infrastructures. Eusgeld, Nan, and Dietz (2011) have used the concepts of "System of Systems" to understand the interdependence of critical infrastructures. Again, Gursesli and Desrochers (2003) have used Petri Nets to model infrastructure interdependencies.

2.3 Input-Output Model

Wassily Leontief, a Russian-American economist developed the framework of Input-Output (I-O) Model. He studied the economic transactions of the U.S. between 1919 and 1939 and came up with the framework in 1930s and 1940s, which was first published in 1951 (Leontief 1951). Later the U.S. adopted the I-O framework for national accounts. Presently I-O accounts are the primary constituents of the U.S. economic system (Planting 2006).

Leontief (1986) has defined I-O tables to describe the flow of goods and services between multiple sectors of a national economy. Leontief's technical coefficient matrix establishes the interrelationships between different producing and consuming sectors. According to him the economy can be divided into (n+1) sectors, n industries that are producing sectors and (n+1)th final demand sector. If x_i is the total output of sector i and x_{ij} is the amount of product produced by sector i, which is being consumed by sector j as an input, then one element of the technical coefficient matrix a_{ij} can be defined as

$$a_{ij} = \frac{x_{ij}}{x_i}$$

If A is the technical coefficient matrix and X and C are the matrices for the output of all sectors and the output going to the final users from all sectors respectively, then there exists a balance between the 3 variables, which can be expressed as

$$X = A * X + C$$

$$(I - A) * X = C$$

$$X = (I - A)^{-1} * C$$

Pissarenko (2009) explained the I-O table in 4 components. It is shown in figure 2.3. The first quadrant is the intermediate demand, which are produced by industries and also consumed by industries in the process of producing commodities. This flow is the inter-industry flow or intermediate demand.

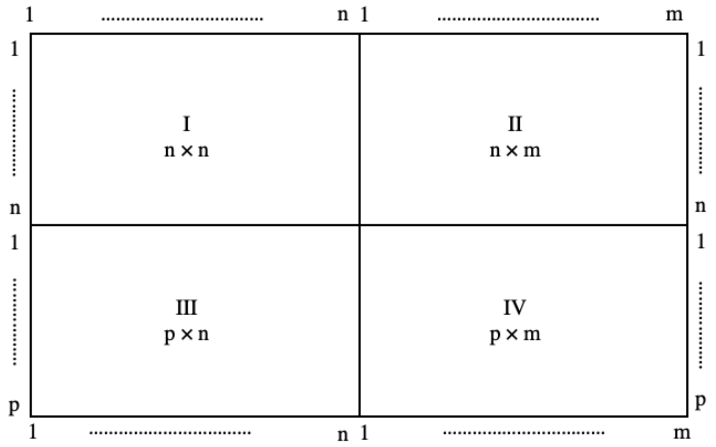


Figure 2.3 General Structure of I-O Table (Pissarenko 2009)

Quadrant II represents the final demand of the outputs of each producing industry. These are the demands from the households, governments and exports. This is the demand of the goods which are not consumed by industries. Quadrant III is the inputs to producing industries like raw materials which are not produced by any industries like imported raw material. The final quadrant is the inputs which are directly consumed i.e. they are not used to produce any commodity (like imported electricity).

Since the inception of I-O model, it has gone through a development process. Guo, Lawson, and Planting (2002) have highlighted the development of I-O models over time. They classified I-O models in two types. The first was formulated by Leontief, for which he received Nobel Prize in Economics in 1973. This model assumes that each industry produces only one product and each product is produced by one industry. This makes the I-O table symmetric. But in reality, industries produce more than one product. In 1968, The United Nations (U.N.) proposed the second model, which expands upon the I-O model proposed by Leontief. The modified I-O model suggested by the U.N. considers all the products produced by the various industries (United Nations 1968). Since then there have been ongoing discussions about ways to translate the asymmetric I-O tables into symmetric one. Two popular assumptions exist in this regard: Industry-Technology Assumption (ITA) and Commodity-Technology Assumption (CTA). The ITA assumption states that all commodities produced by an industry share the same input structure whereas, the CTA proposes each commodity has a unique input structure which is independent of the producing industry. Guo, Lawson, and Planting (2002) have explained how the Bureau of Economic Analysis (BEA) have used a mixed approach to create symmetric tables. The method involves a two-step process. In the first step, the secondary products are moved by hand to the industries where they are primary products. This process is called the process of Redefinition. This process basically follows the assumptions of CTA. In the next step, the all remaining secondary products are assumed to have identical input structures to those of the primary products of their producing industries. The ITA method is used to transfer them mechanically because it is considered to be the most preferred choice. They have also compared the coefficient matrices derived from the two sets of input data: before redefinition and after redefinition using BEA's 1992 benchmark I-O data. They found the difference is between -0.5% to 0.5% for three-fourth of the multipliers. They have also suggested that the difference could be significant when the secondary production contributes to a large share of a commodities total output or a large share of an industry's total output.

Planting (2006) has listed three fundamental principles behind the I-O model or I-O analysis. They are:

- Principle of Homogeneity which states that each industry's output requires a unique set of inputs. Because, industries produce different products and they might require substantially different inputs, it is almost impossible to achieve homogeneity.
- Principle of Proportionality which states that each input to one unit of output remain the same over a wide range of output levels. This means there is no economy of scale
- Principle of Consistency which states that the economic statistics should be organized and presented in a consistent manner. The use of a common classification system is therefore beneficial for the effective comparison of data across different spectrum of U.S. economic statistics.

The core of U.S. input-output accounts consists of two tables: Make and Use Tables. Planting (2006) has provided a detailed guideline about how the two mentioned tables can be used to develop the inter-industry relationships.

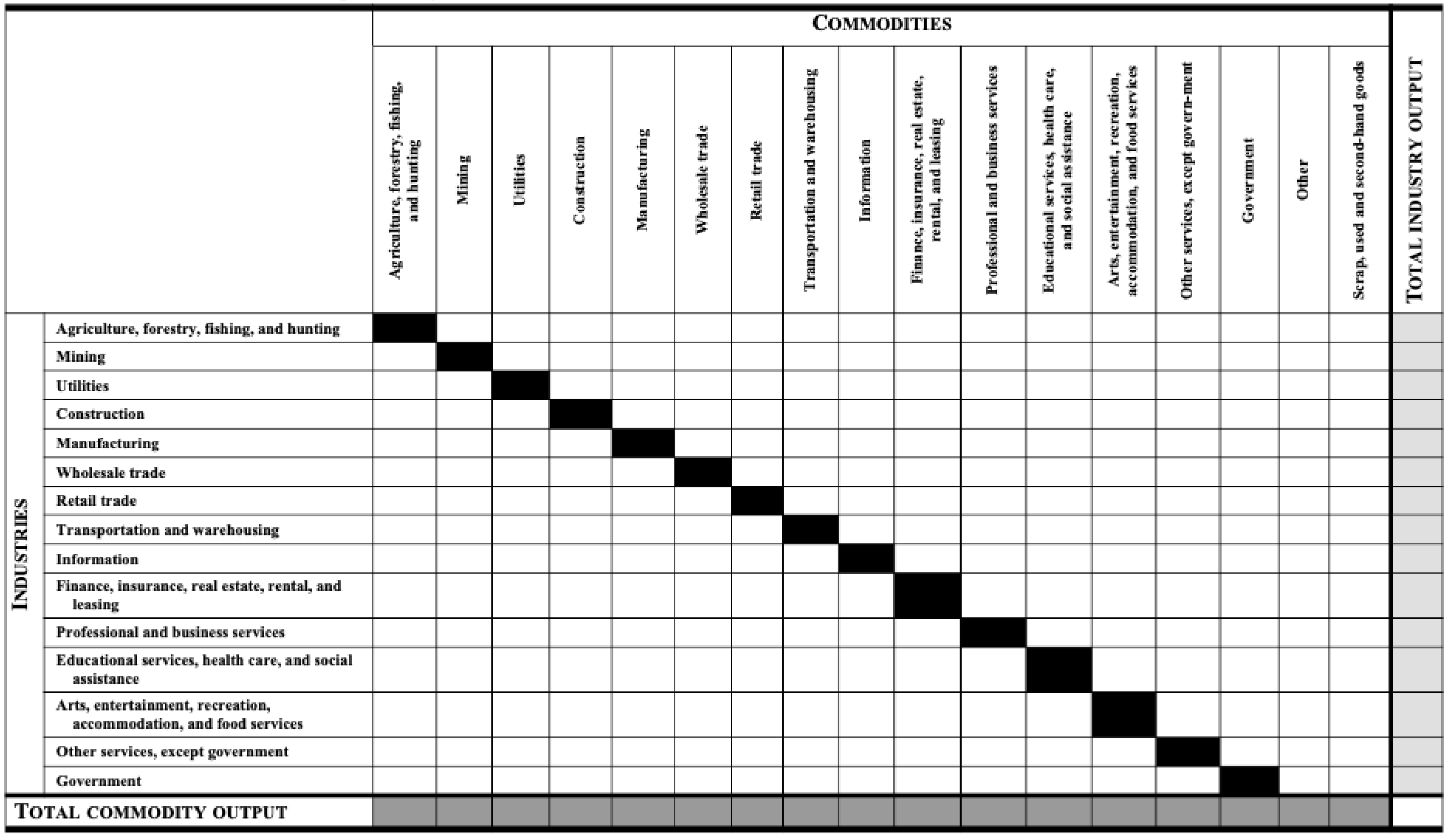
Make Tables show the production of different commodities by industries. The rows in the Make tables represent the industries and the columns represent the commodities. Looking along a row all commodities produced by an industry can be found which add up to the total industry output for that particular industry. Again, looking across a column all industries producing that particular commodity can be found and the sum of the column will be the output of that commodity. Figure 2.4 shows an example of a Make Table. It should be noted that each industry produces some amount of scrap. But no industry produces scrap on purpose or on demand, but it is a byproduct of the original productions.

The Use Tables shows the consumption of the produced commodities by different industries and end users. The rows of the Use tables represent the commodities whereas, the columns represent the industries. Looking across a row, the consumption of a commodity by different industries and the end users can be found. Therefore, the sum of all elements along a row is the total output of that commodity. The portion of the production consumed by the industries is called the intermediate demand and the portion of the production consumed by the end users is called the final demand. The entries along a column represents the consumption of different commodities by that industry and the "Value Added" components which are basically the compensation of employees, taxes on production and imports less subsidies and gross operating surplus. The sum of the value added of all industries represent the GDP of the nation (Planting 2006). The sum of all elements across the column is the total industry output of that industry. Figure 2.5 shows the Use Table.

Planting (2006) has also described the process of deriving the coefficient matrix from the Make and Use tables. It is as follows:

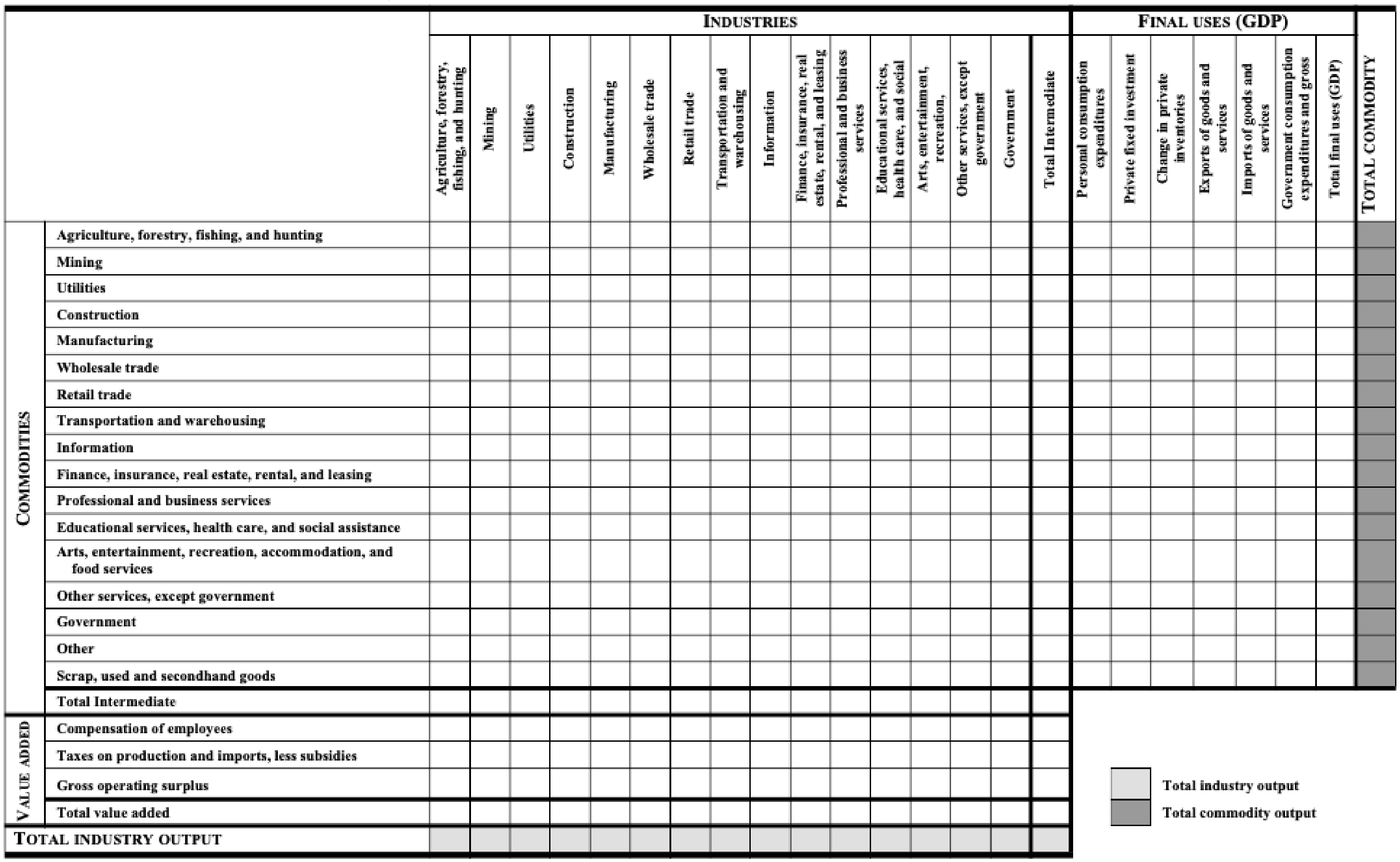
- Step 1 is to derive the Direct Requirement Matrix from the Use table. The industry inputs of the Use table are divided by that industry's total output which is the sum of all elements of that column. This is basically column-wise normalization of the Use table.
- Step 2 is to derive the Market Share matrix from the Make table, which shows the proportion of commodity output produced by different industries. This is done by column-wise normalizing the Make table.
- Step 3 is to make adjustments for the scrap which is not intentionally produced by the industries. In order to make the I-O model work in the intended way, that is, not requiring the industries to produce scrap because of demand, it is necessary to perform the scrap adjustment. To do this, first the ratio of non-scrap is calculated for all industries. The non-scrap ratio for an industry is the ratio of that industry's output excluding scrap and that industry's output including scrap (or total industry output). Once, the non-scrap ratio is derived for all industries, the elements of the market share matrix (derived in step 2) is divided by the non-scrap ratios. In a market share matrix, the rows represent the industries. Therefore, all the elements across a row of a market share matrix should be divided by the non-scrap ratio derived for that particular industry. After this step, the modified matrix is called Transformation Matrix.
- Step 4 is to multiply the Transformation matrix with Direct Requirement Matrix to generate industry by industry technical coefficient matrix.

Once, the technical coefficient matrix is derived, Leontief's equilibrium equation can be used to validate the correctness of the matrix.



		COMMODITIES																	
		Agriculture, forestry, fishing, and hunting	Mining	Utilities	Construction	Manufacturing	Wholesale trade	Retail trade	Transportation and warehousing	Information	Finance, insurance, real estate, rental, and leasing	Professional and business services	Educational services, health care, and social assistance	Arts, entertainment, recreation, accommodation, and food services	Other services, except govern-ment	Government	Other	Scrap, used and second-hand goods	TOTAL INDUSTRY OUTPUT
INDUSTRIES	Agriculture, forestry, fishing, and hunting	■																	▨
	Mining		■																▨
	Utilities			■															▨
	Construction				■														▨
	Manufacturing					■													▨
	Wholesale trade						■												▨
	Retail trade							■											▨
	Transportation and warehousing								■										▨
	Information									■									▨
	Finance, insurance, real estate, rental, and leasing										■								▨
	Professional and business services											■							▨
	Educational services, health care, and social assistance												■						▨
	Arts, entertainment, recreation, accommodation, and food services													■					▨
	Other services, except government														■				▨
	Government															■			▨
TOTAL COMMODITY OUTPUT		▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	

Figure 2.4 Make Table (Planting 2006)



		INDUSTRIES															FINAL USES (GDP)							TOTAL COMMODITY
		Agriculture, forestry, fishing, and hunting	Mining	Utilities	Construction	Manufacturing	Wholesale trade	Retail trade	Transportation and warehousing	Information	Finance, insurance, real estate, rental, and leasing	Professional and business services	Educational services, health care, and social	Arts, entertainment, recreation,	Other services, except government	Government	Total Intermediate	Personal consumption expenditures	Private fixed investment	Change in private inventories	Exports of goods and services	Imports of goods and services	Government consumption expenditures and gross	Total final uses (GDP)	
COMMODITIES	Agriculture, forestry, fishing, and hunting																								▓
	Mining																								▓
	Utilities																								▓
	Construction																								▓
	Manufacturing																								▓
	Wholesale trade																								▓
	Retail trade																								▓
	Transportation and warehousing																								▓
	Information																								▓
	Finance, insurance, real estate, rental, and leasing																								▓
	Professional and business services																								▓
	Educational services, health care, and social assistance																								▓
	Arts, entertainment, recreation, accommodation, and food services																								▓
	Other services, except government																								▓
	Government																								▓
	Other																								▓
	Scrap, used and secondhand goods																								▓
	Total Intermediate																								
VALUE ADDED	Compensation of employees																								
	Taxes on production and imports, less subsidies																								
	Gross operating surplus																								
	Total value added																								
TOTAL INDUSTRY OUTPUT		▒	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒								

▒ Total industry output
▓ Total commodity output

Figure 2.5 Use Table (Planting 2006)

2.4 Cost of Severe Weather Induced Power Outages

There have been multiple efforts to understand the economic impact of power outages by previous researchers. Clemmensen (1993) estimated the cost of power quality to be $26 billion per year in the U.S. However, quality is only a subset of reliability related events. Thus, it does not reflect the overall cost. In 2000, Electric Power and Research Institute (EPRI) estimated the cost of power interruption to be $50 billion per year (Douglas 2000).

Lawton et al. (2003) have estimated the cost of power outage for different types of customers. In their study they gathered data for 13 years from eight utilities who conducted the Value of Electric Service (VOS). In their study they calculated the cost of power outage for three types of customers: large commercial and industrial, small-medium commercial and industrial and residential customers. Their calculation of economic loss was based on the Customer Damage Function (CDF) defined by Goel and Billinton (1994). The general form of CDF can be expressed as a function of three variables: outage attributes, customer characteristics and geographical attributes. Based on this CDF function they calculated the average cost experienced by an average customer for a single summer afternoon outage for an hour is approximately $3 for residential sector, $1,200 for small-medium commercial and industrial sector and $82,000 for large commercial and industrial sector in 2002 Consumer Price Index (CPI) weighted dollars. The cost of the outage increases substantially following a non-linear pattern as the duration of the outage increases. The cost of outage is more in winter than in summer.

LaCommare and Eto (2006) has used a bottom-up approach to estimate the cost of power interruption and power quality to electricity customers. They developed a formula based on four factors: number of electricity customers, frequency of reliability events, cost of reliability events and vulnerability of the customers to reliability events. Based on these factors they have estimated the cost to be $79 billion (in 2002 CPI-weighted dollars). They found that 72% of the loss is suffered by the commercial customers. Moreover, cost of momentary interruptions contributes 67% of the total cost. They concluded that the cost of the interruptions can be as low as $22 billions and as high as $135 billion based on the assumptions.

Campbell (2012) estimated the annual cost of power outages to be between $20 billion to $55 billion. The Office of Executive President (2013) have estimated that the weather-related outages cost an inflation adjusted annual average of $18 billion to $33 billion to the U.S. economy. The annual cost changes based on the extent of severe weather events. In 2008, during the year of

Hurricane Ike, the cost was between \$40 billion to \$75 billion and in 2012 during super storm Sandy, the cost was between \$27 billion to \$70 billion. These estimates account for numerous costs like lost outputs, lost wages, spoiled inventory, inconvenience, cost of restarting industrial operations. The study also estimated that 20% to 25% of the annual cost of the weather-related power outages are attributed to lost output.

Feldman (2015) has estimated the cost of power outages in 2013 to be \$112 billion, whereas in that year the end use retail customers paid some \$364 billion to their suppliers for the electricity service. LaCommare et al. (2018) in the recent study again estimated the cost of sustained power outages and found that the cost has increased from their study in 2006 by 25 percent and the new cost is \$44 billion (2015 dollars). They found that 97% of the total cost is attributed to commercial and industrial sector and rest 3% is attributed to residential sector. Alam, Eren Tokgoz, and Hwang (2019) have also established an equation for assessing the economic loss in terms of revenue loss for the utilities from power outages. They have considered four factors in their estimation: time to restore power, number of customers without power, the average power consumption per customer and the unit price of electric power. The loss of revenue is the product of the four factors.

To the best knowledge of the author, none of the studies mentioned above, have captured the cascading impact of a natural disaster which has been explained in Oh and Hastak (2008). Therefore, this research has developed a methodology which can incorporate the ripple effect of severe weather induced power outages.

2.5 Inoperability Input-Output Model

Inoperability Input-Output Model or IIM has been explained by Santos and Haimes (2004) for interdependency analysis to estimate the direct and indirect economic impacts of terrorism on different sectors of U.S. Similar to the I-O model proposed by Leontief, this model is also based on an equilibrium equation:

$$q = A^{*}q + C^{*}$$

Where, C_* is demand-side perturbation vector calculated as the reduction in final demand per unit as-planned production. A_* is the interdependency matrix which represents the level of coupling between different sectors and q is the inoperability vector which can be calculated as the reduction in production (as-planned production minus reduced level of production) per unit as-planned production. They have explained the applications of IIM by two illustrative examples. The first example illustrated the impacts of air transportation perturbation on 12 representative national level sectors. They calculated the impact of 10% reduction in the demand of air transportation. Due to interdependencies the 10% reduction in demand induces reduction in demand in other sectors as well as on itself and the total loss is calculated as the loss of production. The outcome shows that an initial inoperability of 10% in the air transportation sector can cause a final inoperability of 10.02% in the air transportation sector. This extra 0.02% inoperability is induced due to the existing interdependencies between different sectors. The same study was repeated for 483 sectors (which includes all intermediate sectors) again. When, the outcomes were compared they found that the resultant inoperability in the air transportation sector for the second case study was 10.22% which is 0.2% percent more than the inoperability derived in first case study. Therefore, they concluded that pre-selection can lead to under estimation of inoperability. In this research they have also shown how the Regional I-O Multiplier System (RIMS II) published by BEA can be integrated with IIM to assess the regional economic impacts. They have used the location quotients to derive regional technical coefficient matrix, which is used to derive the regional loss.

The location quotients (LQ) compare the relative importance of an industry for a regional economy and national economy. The U.S. Bureau of Labor Statistics (BLS) has defined the location quotients as: “ratios that allow an area's distribution of employment by industry, ownership, and size class to be compared to a reference area's distribution.” (https://www.bls.gov/cew/about-data/location-quotients-explained.htm, accessed on April 30, 2020). LQ calculation for an industry “i” for a specific region “s” is based on employments created by that industry in that region. BLS has formulated LQ as:

$$LQ = \frac{\dfrac{Employment\ created\ by\ industry\ "i"\ in\ the\ region\ "s"}{All\ employment\ in\ the\ region\ "s"}}{\dfrac{Employment\ created\ by\ industry\ "i"\ at\ national\ level}{All\ employment\ created\ at\ national\ level}}$$

Haimes et al. (2005) have explained the extensions of the concepts of IIM for different applications. The physical based IIM; initially proposed by Haimes and Jiang (2001) considers physical inputs to infrastructures rather than the monetary inputs proposed by Leontief. The demand reduction IIM captures the impacts of reduction of demand on different other sectors. The dynamic IIM captures the temporal dimensions and can be used for modeling economic recovery. They have also derived a coefficient for measuring the resilience of industries.

Crowther and Haimes (2005) have examined the applications of IIM for risk assessment and management of interdependent infrastructures. They have explained how system engineers can adopt IIM for understanding vulnerabilities in the system using three illustrative case studies. The case studies consider inoperability in power infrastructure. The first case study elaborates the first step of the risk assessment which is to understand what can go wrong. They have incorporated the IIM for understanding the consequence of what can go wrong. The first case study uses a supply-side IIM. For that they have derived a new technical coefficient matrix: supply-side technical coefficient matrix. The supply-side technical coefficient matrix is related to (transpose of) the demand-side interdependency matrix (A^*). It assumes a 10% reduction of value added in the production process and the established loss equation can estimate the loss in terms of unrealized production. The second case study uses IIM to assess the impact of risk management policies. The last case study shows how the optimal risk management decisions can be made by integrating a sectors cost recovery model with IIM. First, they have developed a quadratic model that can represent the customers recovered as function of cost of recovery or recovery investment. Then they integrated that with IIM to calculate the Pareto-Optimal frontier for minimizing two objectives: production loss and recovery budget.

Santos (2006) has highlighted the importance of assessing the economic interdependencies to determine the most vulnerable sectors in the economy. He has used IIM to analyze the impact of demand-side perturbations of air transportation and accommodation industry on other sectors due to 9/11 catastrophe. The impacts have been measured in two metrics: inoperability and economic loss. Based on the two metrics industries can be ranked to understand their vulnerabilities. But the resulting rank produced by the two metrics can differ. Therefore, it is important to perform multi-criteria decision making before making the call.

Leung, Haimes, and Santos (2007) have extended the concept of demand-side perturbations to supply-side perturbations and output-side perturbations. The supply-side perturbation is a price model, which assesses the impact of increase of price of value added such as labor wages in terms of inoperability in production output. The output-side IIM measures the impacts of direct perturbations on the output of a sector. They have explained two sets of models: output-demand mixed model and output-supply mixed model. The output-demand mixed model calculates the impact of output perturbations in terms of loss of final demand for the industries suffering the output perturbations and loss of production for the rest of the industries in the economy. The output-supply mixed model estimates the impacts of a direct change in a sector's output prices. There have been multiple other works applying IIM for analyzing problems associated with the vulnerability of interconnected infrastructure systems. They can be found in (Guo and Hou 2019; Haggerty, Santos, and Haimes 2008; Jung, Santos, and Haimes 2009; Niknejad and Petrovic 2016; Xu et al. 2012).

BEA has published a detailed guideline about the use of RIIMS II multipliers (BEA 2013). 3 major ranges of applications have been noted: (1) Federal, state and local governments use RIIMS II multipliers to study impact of government regulations on local industries and to assess the local impact of transportation projects. (2) Economic development organizations apply the multipliers to understand the local impacts of economic events. (3) Businesses use the multipliers to estimate the impacts of wide range of investment project such as construction of a new hotel or expansion of a large factory. They have emphasized that the multipliers are only useful for assessing the outcome of a final demand change in a region. The final demands consist of a number of transactions: purchases by consumers outside the region, investment projects, purchases by governments, purchases by households. These are the inputs for the applications of RIMS II multipliers. There are two types of RIMS II multipliers: type I multipliers only considers industry impacts whereas type II multipliers consider industry and household expenditure impacts. Type II multipliers are more widely used. There are total 6 types of type II multipliers. They are shown in Table 2.1

Table 2.1 RIMS II Multipliers: Definition and Application

Multipliers	Definition	Application
Final Demand Output	Total Industry Output per $1 Change in Final Demand	Total Output Impact = Change in Final Demand * Multipliers
Final Demand Earnings	Total Household Earnings per $1 Change in Final Demand	Total Earning Impact = Change in Final Demand * Multipliers
Final Demand Employment	Total Number of Jobs per $1 Change in Final Demand	Total Job Impact = Change in Final Demand * Multipliers
Final Demand Value Added	Total Value-Added per $1 Change in Final Demand	Total Value-Added Impact = Change in Final Demand * Multipliers
Direct Effect Earnings	Total Household Earnings per $1 Initial Change in Household Earnings	Total Earning Impact = Change in Household Earnings * Multipliers
Direct Effect Employment	Total Number of Jobs per $1 Initial Change in Household Earnings	Total Job Impact = Change in Household Earnings * Multipliers

The applications of the multipliers can be explained with the help of a simple example. Suppose, the local government is interested in understanding the job impact of a $20 million investment project on the region of interest. Let the final demand employment multiplier for the region is 15. This implies that for every million-dollar investment project, 15 jobs will be created. Therefore, an investment project of $20 million will create 20 multiplied by 15 i.e. 300 total jobs.

2.6 Vulnerabilities in the Electricity Grid

To understand the vulnerabilities in the electricity grid, it is essential to understand how the grid is operated. The U.S. electric power infrastructure is a highly complex socio-technical system with multiple degrees of connectivity and redundancy, which is expanded over a vast geographical area (Mukherjee, Nateghi, and Hastak 2018a). It is comprised of a vast and connected interlocked components. The grid connects 5,800 major power plants and includes 450,000 miles of high voltage power transmission lines (American Society of Civil Engineers 2011). The electricity is produced at generation facilities: power plants, then the voltage is stepped up by step up transformer and transported to population center through high voltage transmission lines. After arriving at the population center, the voltage is reduced at the substations by step down transformers and electricity enters the distribution system. In distribution system it travels through series of low voltage lines before reaching the customer locations. Before delivering to the consumers, voltage is further reduced by transformers. Therefore, the grid can be considered to be comprised of three major components: Generation, Transmission and Distribution. Figure 2.6 shows the grid structure and major components.

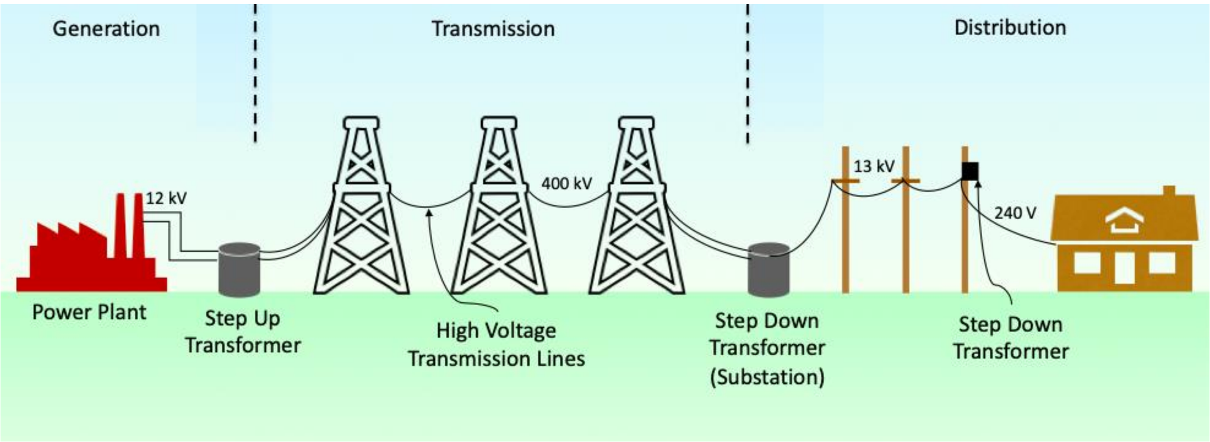
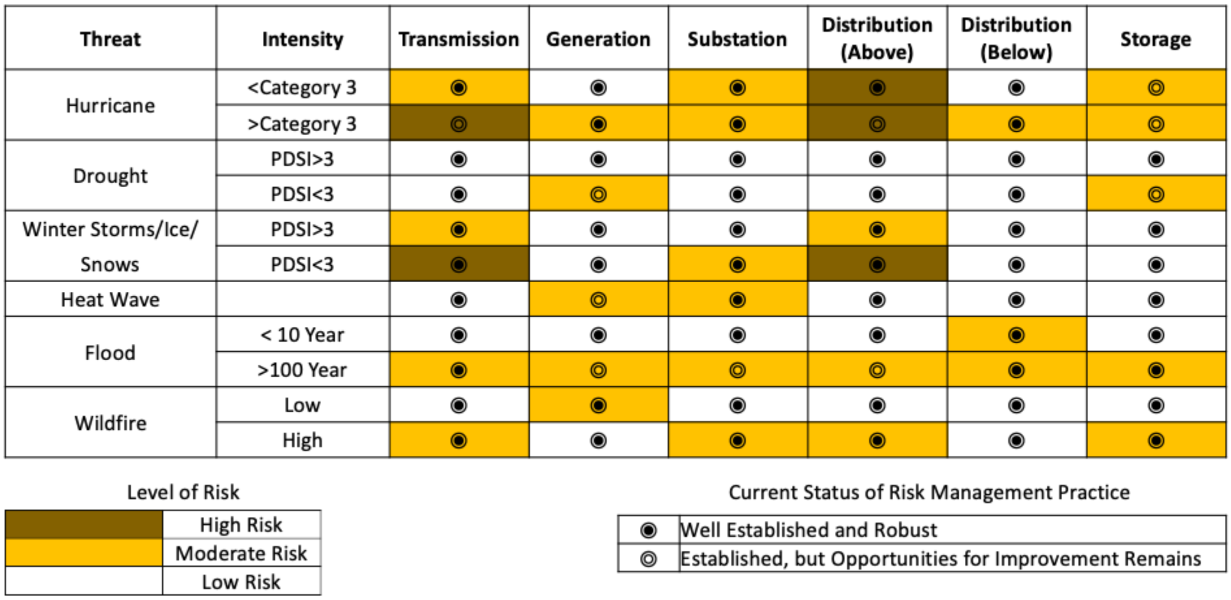


Figure 2.6 Structure of Electricity Grid

Vulnerability of the electricity grid can be associated with the vulnerability of the major components. During a natural disaster a generation plant might fail, transmission lines might fail also distribution lines might fail. The failures can happen in combination as well. But some components tend to fail more than the others.

Zhou, Pahwa, and Yang (2006) stated that in relation to reliability issues, the overhead distribution lines distinguish themselves from the other components. They also mentioned that the overhead distribution lines are the most vulnerable component in the distribution system. NEI Electric Power Engineering (2009) have also mentioned that the distribution system is the most vulnerable in the grid. The said that transmission related failure only accounts for less than 2% of all outages. Silverstein (2011) have reiterated the fact that distribution lines cause more power outages. In that report, it has been mentioned that 90% of the customer outages minutes are due to failure in the distribution system. The rest 10% belongs to generation and transmission system. But these are big outage events. However, Kenward and Raja (2014) have a different opinion about the vulnerable component of electricity grid. In their report, they have said that between 1984 and 2012, during severe weather events most of the outages came from the damage to large transmission lines and electric substations, as opposed to distribution systems. Again, Bhat and Meliopoulos (2016) have proposed a different thought. They said that presently, the transmission networks are built in such a way to withstand high wind speed. But distribution systems are very vulnerable. Therefore, they developed a tool that can identify the vulnerable areas and breakage points of the distribution networks. Eto (2016) has also repeated that distribution systems are the most vulnerable component of the grid system. He has reckoned that failures on the distribution systems during weather-related events are typically responsible for more than 90% of the electric power disruptions both in terms of durations and frequency of power outages. However, the infrequent damage on the transmission system can result in more wide-spread power outages. Qazi (2017) have said that events like hurricanes and earthquakes affect distribution system much more than the generation and transmission system.

The U.S. Department of Energy in their Quadrennial Energy Report (U.S. Department of Energy 2017) has conducted an integrated assessment of risks to the electricity sectors resilience from the current threats. The current threats comprise of natural or environmental events like hurricanes, winter storm, flood, wildfire, earthquake etc. and human threats like physical, cyber etc. For different threats, they have assessed the level of risk, resilience and current status of risk management practice of different system components of the grid. The summary of the report in shown in figure 2.7. The figure states that the overhead distribution system is at the most risk from hurricanes and winter storms or ice or snows followed by the transmission system. Also, the overhead distribution systems under extreme severe weather events like hurricanes (>category 3) or floods (>100 year) have the opportunity to improve their risk management practices.



Threat	Intensity	Transmission	Generation	Substation	Distribution (Above)	Distribution (Below)	Storage
Hurricane	<Category 3	🟨 ◉	◉	🟨 ◉	🟫 ◉	◉	🟨 ◎
	>Category 3	🟫 ◎	🟨 ◉	🟨 ◉	🟫 ◎	🟨 ◉	🟨 ◎
Drought	PDSI>3	◉	◉	◉	◉	◉	◉
	PDSI<3	◉	🟨 ◎	◉	◉	◉	🟨 ◎
Winter Storms/Ice/ Snows	PDSI>3	🟨 ◉	◉	◉	🟨 ◉	◉	◉
	PDSI<3	🟫 ◉	◉	🟨 ◉	🟫 ◉	◉	◉
Heat Wave		◉	🟨 ◎	🟨 ◉	◉	◉	◉
Flood	< 10 Year	◉	◉	◉	◉	🟨 ◉	◉
	>100 Year	🟨 ◉	🟨 ◎	🟨 ◎	🟨 ◎	🟨 ◉	🟨 ◉
Wildfire	Low	◉	🟨 ◉	◉	◉	◉	◉
	High	🟨 ◉	◉	🟨 ◉	🟨 ◉	◉	🟨 ◉

Level of Risk

🟫	High Risk
🟨	Moderate Risk
⬜	Low Risk

Current Status of Risk Management Practice

◉	Well Established and Robust
◎	Established, but Opportunities for Improvement Remains

Figure 2.7 Risk Assessment of Electricity Sector (U.S. Department of Energy 2017)

2.7 Risk Factors Causing Severe Weather Induced Power Outages

The risk factors are the primary causes of severe weather induced power outages. There is a plethora of research articles available that tried to find the causes of power outages but very few of them focused explicitly on the severe weather induced power outages. The summary is captured in Table 2.2.

Table 2.2 Risk Factors causing Power Outages

Sl. No.	Author	Risk Factors
1	Mukherjee, Nateghi, and Hastak (2018a)	1. Types of Severe Weather Events 2. Area of overhead transmission and distribution lines 3. Investment in Regular Operation and Maintenance 4. Topology of Power Distribution in Rural Region 5. Extent of Metropolitan Area in the State
2	Nateghi (2018)	1. Number of Customers Served 2. Tree Trimming Frequency 3. Developed Open Spaces 4. Soil Moisture 5. Wind Speed
3	Taylor (2015)	1. Vegetation 2. Equipment Failure 3. Inconclusive Investigations 4. Lockout without Permanent Fault 5. Pole Failures 6. Improper Installation 7. Mid Span Fault 8. Accident, Public Vehicle
4	Qazi 2017	1. Sagging of Lines into Vegetations 2. Falling Tree 3. Shorting of Line by Lighting 4. Lack of Monitoring 5. Overheating of Lines due to Imbalance between Power Generation and Load 6. Flooding 7. Snow & Ice
5	Wang 2016	1. External Factors (Burglar, Construction, Fire etc.) 2. Natural Factors (Lightning, Typhoon/Hurricane, geologic hazards, flood/earthquake, snow/rain) 3. Improper Maintenance (Tree, Animal etc.) 4. Improper Installation 5. Equipment Failure 6. Customer Cause
6	Alhelou, Hamedani-Golshan, Njenda and Siano, 2019	1. Weather/Trees 2. Faulty Equipment/Human Error 3. Vehicle/Accidents 4. Animals 5. Over Demand
7	National Emergency Crisis and Disaster Management Authority, UAE, 2014	1. Emergency breakdowns in power stations 2. Failure in electricity lines 3. Short circuit 4. Overload of electric grid 5. Human error

Mukherjee, Nateghi, and Hastak (2018a) have used historical data to develop a 2-stage hybrid risk estimation model. The model has identified risk factors for outage durations and number of customers affected based on historical data between 2000 and 2016. The research has segregated the intensity of outages (outage duration and number of customers affected) in 3 levels. The first level: minor; is those who belong to the bracket less than 1st quartile. The intensities which fall in between 1st and 3rd quartile is moderate and those which are beyond 3rd quartile are level 3 or extreme events. Risk factors are different for the three levels of severe weather induced power outages.

The historical power outage data of different states were analyzed using advanced machine learning algorithms. The research shows that for level 3 or extreme events the 5 most predominant risk factors (in terms of durations of power outage) for a state are: Types of Severe Weather Events, Area of overhead transmission and distribution lines, Investment in Regular Operation and Maintenance, Topology of Power Distribution in Rural Region, Extent of Metropolitan Area in the State.

Nateghi (2018) has proposed a data driven multivariate analysis to model the complex interplay between stochastic hazards, system topology and topology of the region to approximate multidimensional resilience of electricity grid. The research has used data from a utility based in the gulf of Mexico region. Tree based algorithms have been used to identify the most influencing variables for number of customers affected, outage duration and outage counts. The results show that for predicting outage duration, the 5 most influencing variables are: number of customers, tree trimming frequency, open space, soil moisture and wind speed.

Taylor (2015) has analyzed Duke Energy's outage data during major events. Each of these events were verified by a field engineer. The dataset contained 2 years of data and 906 data points. The results show that almost 72% of the outages were caused due to vegetation related incidents, 9% due to equipment failures and 2% due to pole failures. There are various other causes like: protective device malfunctioning, accident, mid span fault etc. The Electric Power Research Institute in their technical report on "Distribution Grid Resiliency: Overhead Structures" (EPRI 2015a) have mentioned that for Eversource utility between 2008 and 2015, approximately 91% of the outages during hurricanes were caused due to vegetation, the number goes down to 74% for tropical storms and 66% for tornadoes. Evidently, vegetation is one of the major causes of severe weather induced power outages.

Qazi (2017) has also identified that causes of severe weather induced power outages. He has listed Sagging of Lines into Vegetations, Falling Tree, Shorting of Line by Lighting, Lack of Monitoring, Overheating of Lines due to Imbalance between Power Generation and Load, Flooding, Snow & Ice are they primary causes of power outages. Wang (2016) have mentioned External Factors (Burglar, Construction, Vehicle, Fire etc.), Natural Factors (Lightning, Typhoon/Hurricane, geologic hazards, flood/earthquake, snow/rain), Improper Maintenance (Tree, Animal, Untimely Defect Elimination/Maintenance, Over Voltage etc.), Improper Installation, Equipment Failure, Customer Causes are the probable causes of power outages. Alhelou et al. (2019) have analyzed 66 major power outage data across the globe between 2011 and 2019. They found that 50% of the outages are caused due to weather or trees, followed by faulty equipment, accident, animals and over demand.

Department of Energy’s form OE-417 which is filed by the utilities in the aftermath of a major power outage recognizes various causes of power outages. They are physical attack, vandalism, theft, cyber event, fuel supply emergency, generator loss, transmission equipment failure, failure at substation, weather or natural disaster, operator action, unknown and others.

The shortcomings of the outage data collection in the aftermath of a natural disaster has been highlighted by a number of researches. Utilities have a system of tracking outages in their system. However, the Electric Power and Research Institute (EPRI 2015b) in their report has mentioned that the limitations of the outage related data collection hinders benefit-cost analysis-based decision making process. The limitations can be attributed to the incompleteness of the data. Most of the data collected represents the activities during restoration period, because at that time utilities are immersed in restoring power as quickly as possible. The limitations highlighted in the research are: (1) the data is mainly comprised of large outages (2) much of the data covers only a few years (3) inconsistency in the type of data collected by various utilities making aggregation difficult (4) needed data is not collected (5) data is collected with insufficient granularity etc. They have said that gathering outage related data could be possible even after the restoration is completed. They have suggested a data collection format which will facilitate the benefit-cost analysis-based decision making. The suggested data collection format collects four types of information: basic information, construction details, operational details and vegetation details. It should be noted that the format suggested by EPRI (2015b) is intended to facilitate benefit-cost analysis-based decision making. For risk-based decision making, the format may not suffice the requirements.

National Academy of Sciences, Engineering, and Medicine (2017) have emphasized upon the fact that good data on the causes of power outages, their probabilities and spatial and temporal distribution of are essential for resilient operation of grid system. Therefore, government and other responsible parties should support strengthening the data collection activities. U.S. Department of Energy (2017) have reiterated the fact that information sharing can mitigate the threat to the risk.

2.8 Risk Reduction Strategies

Vugrin et al. (2010) have identified three types of system capacity requirements that make the system resilient. Those are: Absorptive, Adaptive and Restorative capacities. Absorptive capacity is the degree to which a system can absorb the impacts of system perturbation and minimize the consequence. It is an endogenous feature of the system. Adaptive capacity is the ability of the system to adapt endogenously throughout the recovery process. It is the capability of self-organization for the recovery of the system. The Restorative capacity is the ability to be repaired easily in the aftermath of a system disruption. This research has been focused on the strategies that enhance the absorptive capacities of the electricity grid i.e. the strategies that make the system more robust to natural disasters.

National Academy of Sciences, Engineering, and Medicine (2017) have identified multiple strategies to prepare for and mitigate the risk of large scale blackouts. They are component hardening, vegetation management, selective undergrounding, reinforcement of poles and towers, dead-end structures, water protection, smart grid initiatives such as distributed energy resources, utility-scale battery storage etc.

Out of the risk reduction strategies, selective undergrounding has been widely regarded by the researchers. Larsen (2016) has found that selective undergrounding of transmission and distribution lines can be beneficial for utilities. Although, it is claimed that the cost of such undertakings are more than benefits derived from it, he has found that the benefits from undergrounding can exceed the cost by reducing power outages. He has also stated that there are number of factors that can influence the dominance of this benefit over its cost like age of existing overhead structure, capital cost of undergrounding, assumed value of lost load to customers, degree to which reliability can be improved and a number of other factors. Warwick et al. (2016) have found that the cost of moving a mile of overhead distribution line to underground in concrete encased ducting can be three to four times costlier than the new overhead line construction. The cost comparison can be seen in figure 2.8

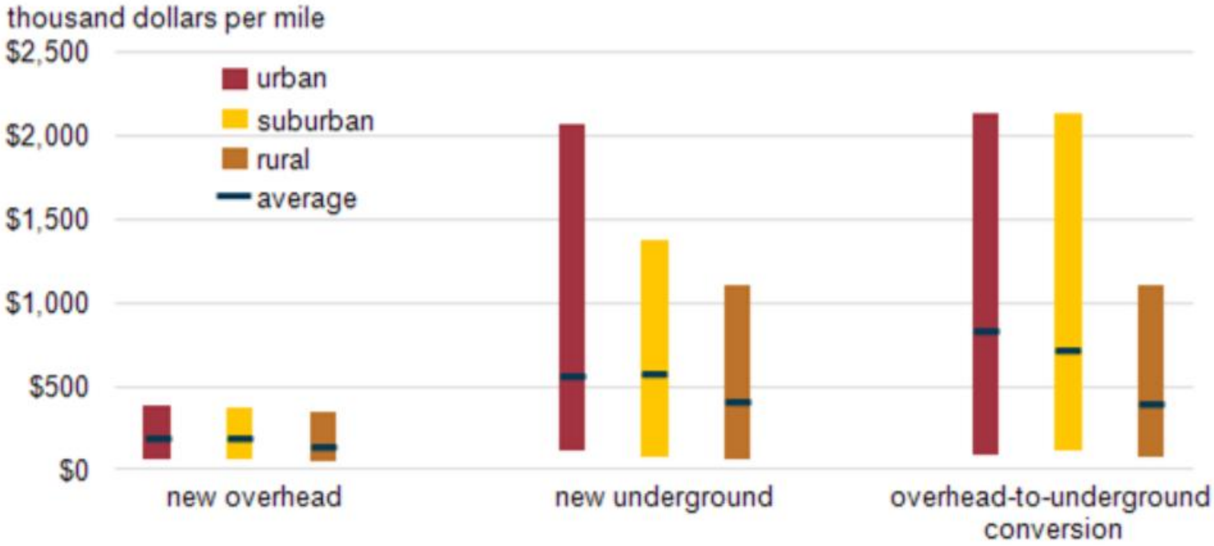


Figure 2.8 Cost per Mile for Constructing Distribution Lines: Overhead vs Underground (Warwick et al. 2016)

The research conducted by Electric Power and Research Institute (EPRI 2015c) has figured out that the cost per mile for undergrounding distribution lines in a function of the type of construction. For double circuit three-phase backbone (concrete encased duct) the average cost of construction per mile is $1.27 million, whereas double circuit three-phase backbone can cost $982 thousand per mile and three phase backbone can cost $630 thousand per mile. The cost is much lower for laterals. For three-phase lateral, average cost per mile is $456 thousand and for single-phase lateral the average cost is $266 thousand per mile. The research has also found that utilities usually spend 1.39% of their capital expense for underground distribution lines operations and maintenance.

Federal Emergency Management Agency (2008) has considered rerouting and providing more system redundancy as a major strategy to mitigate the impacts of system interruption from ice and wind related events. This measure is heavily dependent on the configuration of existing lines and their history of failures. An effective strategy can be rerouting the most vulnerable section of lines or introduce redundancy. In Midwest, there are many instances, where there is only one line and no redundancy. The rerouting or redundancy can be done by undergrounding as well as by new overhead line construction. The associated cost can be derived from figure 2.8.

Another major strategy to reduce the risk of vegetation related risks for overhead transmission and distribution lines is to implement enhanced vegetation management. The Electric Power and Research Institute (EPRI 2015d) has highlighted two key tasks for enhanced vegetation management. They are Enhanced Tree Trimming (ETT) and Hazard Tree Removal. The average tree trimming cycle for the utilities range between 3 to 5 years. The research found that the application of technology such as Light Detection and Ranging (LiDAR) can significantly improve utility's ability to detect the areas where ETT is required. Hazard trees are those that pose a risk to utility equipment because they are close enough to come in contact with the system if they were to fall. Identifying the hazard trees and removing them time to time is essential to mitigate the vegetation related risks. The importance of vegetation management has been highlighted in Appelt and Beard (2006). The research has provided six basic principles of effective vegetation management. They are: (1) taking long term and consistent approach (2) proactive actions for vegetation management (3) proper arboricultural practices (4) programs based on Integrated Vegetation Management (IVM) (5) proper record keeping and productivity measurement and (6) professional supervision and technical expertise. The IVM is recognized as the methodology that encompasses the industry best practices. It is therefore essential for an effective vegetation management program. Kuntz, Christie, and Venkata (2002) have developed an algorithm that can determine the optimal vegetation management scheduling for overhead distribution systems. It is shown that the algorithm can lower cost and find more reliable schedules compared to standard fixed interval schedules.

Component hardening is another popular strategy to make the distribution system more robust. Component hardening includes strengthening poles and lines, elevating substations for flood risk etc. For example, existing lines can be replaced by more heavier wires such as T-2. T-2 wires consist two wires, twisted together to form one strong wire. Strengthening wires and poles together can increase the strength of the distribution lines by 66% (Federal Emergency Management Agency 2008). The importance of component hardening is also listed in Jufri, Kim, and Jung (2017). The research has also suggested introducing hydrophobic coating on distribution lines to make it less susceptible to the snow and ice hazard. Common hardening technique to protect equipment from flood risk is by elevating the substations or relocating facilities to less flood prone areas (Office of Executive President 2013). The Narragansett Electric Company's Rhode Island flood mitigation plan (National Grid 2013) has enlisted the elevation plan of 8 substations within its territory to mitigate the flood risk. The height of elevation ranged between 2 feet to 6.5 feet. The total estimated cost of elevating the 8 vulnerable substation was approximately $23 million. EPRI (2015a) has suggested a number of measures for hardening of overhead structures. They have suggested the design to be done in such a way that the failure of components follows an order: conductor ties, conductors or splices, crossarms and then the pole. This is called Mechanical Coordination. They have also suggested use of larger poles to avoid pole breakage during storms. They estimated that moving to a class 2 equivalent pole top circumference along with the mechanical coordination can reduce breakage by 70% to 80%. They have also found that pole strength correlates with the pole top circumference. Pole top is the most important for storm performance. This option will enhance the same feature as upgrading the pole class but at a lower cost. Hardening of the system can be done by introducing dead-end structures as well. Dead ends are poles or transmission towers that stop the cascading effects. When a power line breaks the unbalanced force is significant to break a pole. The dead-end structures prevent the pole from bending. Dead-end structures are used for extra protection against extreme cases of ice and storm (Federal Emergency Management Agency 2008, Marne 2006).

Another strategy of improving the resilience of electricity grid is to implement the smart grid initiatives like micro grids, smart meters etc. Office of Executive President (2013) has highlighted that the ability of micro grids to separate and isolate itself from the utility seamlessly can improve the resilience of the overall grid. The introduction of smart technologies like smart meters can help the utilities to identify outages more rapidly, thus improving their situational awareness. However, Albasrawi et al. (2014) have said that smart grids can increase the vulnerability to accidental failures. Panteli et al. (2016) has also argued that defensive islanding can improve the resilience of power grid during extreme weather events.

2.9 Risk based Decision Making

Garrick (2008) has defined risk as a function of scenario, likelihood and consequence. Therefore, Risk can be written as

$$Risk = f(Scenario, Likelihood, Consequence)$$

The likelihood is the probability of a scenario and the consequence is the impact of the scenario occurring. From a severe weather induced power outage’s perspective consequence can be the economic impact of the power outages.

The calculation of probability can be based on classical probability theory or can be based on relative frequency of events. Winkler (1996) has said that for relative frequency approach, the real challenge is the availability of appropriate data set. He also stated that as long as the calculations are based on the assumptions of equally likely outcomes, the approach of relative frequency can be certainly utilized in the Probabilistic Risk Assessment (PRA).

Thompson and Graham (1996) have stated how efficiency can be incorporated in a risk control alternative. The efficiency of a risk reduction strategy is the percentage reduction of risk due to the implementation of the strategy. This efficiency can be further used in cost effectiveness analysis. The research has also explained the application of risk in the Benefit-Cost analysis.

Khadam and Kaluarachchi (2003) have said that a rational public policy only considers a management plan if the benefit exceeds the cost. However, there are few shortcomings of Risk-Cost-Benefit (RCB) analysis. One of them is the improper representation of cost of failure. The failure cost can never be precisely estimated. Therefore, they have developed a framework for multi-criteria decision analysis to compare different alternatives for the management of contaminated ground water.

2.10 Conclusion

The scope of the research required reviewing literature of multiple domains. Throughout this chapter, the reviewed literatures have been precisely explained. The research methodology has been developed based on the reviewed literatures. This chapter has explained the interdependencies of the existing infrastructures and the methodologies to model their interdependencies. The research has used Input-Output model to develop the interdependencies of infrastructures and industries. The existing approaches of quantifying the economic impacts of weather-related power outages have also been explained.

This chapter has explained how Inoperability Input-Output Model (IIM) can be utilized to assess the impact of vulnerabilities in the infrastructure systems. It has been shown that IIM can quantify the impacts of demand-side, supply-side and output-side perturbations. This research has used IIM to assess the economic impacts of severe weather induced power outages in terms of the Gross Domestic Product (GDP) at both national and state level.

This chapter has identified the vulnerable components of the electricity grid structures in terms of their probability of failure. The probability of failures is triggered due the presence of certain risk factors which have been identified in this chapter. The chapter also explained which strategies can be implemented to reduce the vulnerabilities. The chapter has been concluded by briefly explaining the risk-based decision-making process, which has been used in the Stage II of the research.

Knowledge gained from the previous works which have been stated in this chapter will help to assess the impacts of severe weather induced power outages and develop the framework for identifying the optimal strategies to minimize the economic impacts.

3. ECONOMIC IMPACT ASSESSMENT OF SEVERE WEATHER INDUCED POWER OUTAGES IN THE U.S.

Abstract: Every year power outages cost billions of dollars and affect millions of people. Historical data shows that between 2000 and 2016, 75 percentage of the outages (in terms of durations) were caused due to severe weather events. Due to the climate changes, the severe weather events are becoming more frequent. The National Association of Regulatory Commissioners have recently emphasized on the importance of building electricity sectors resilience thus ensuring long term reliability and economic benefits for the stakeholders. But, before investment can be planned for resilience building, it is essential to understand the economic impacts of severe weather induced power outages. This research has established a disaster impact assessment model to understand the economic losses due to a severe weather induced power outage in terms of the nation's Gross Domestic Product (GDP). To develop the proposed model, extended version of Leontief's Input-Output Model has been adopted using historical data from Bureau of Economic Analysis between 1997 to 2016. The outcome of the research shows an estimated GDP loss of 16.4 billion dollars (in 2017 values) due to 1% inoperability in the utility sector. The proposed model can be used to (1) provide a range of investment (2) justify the need of investment required for long term resilience planning in the utility sector.

Author Keywords: Natural disasters, Power outages, Input-Output Model, Economic Loss

3.1 Introduction

Disasters due to natural hazards can cause severe damage to infrastructures, which in turn can significantly affect the society, economy and environment. In the United States, the Presidential Policy Directive (PPD -21) has identified 16 critical infrastructures, whose disruption can cause significant threat to the national security. One of those 16 critical infrastructures is Energy. The U.S. electric power infrastructure is a highly complex socio-technical system with multiple degrees of connectivity and redundancy, which is expanded over a vast geographical area (Mukherjee, Nateghi, and Hastak 2018a). It is comprised of a vast and connected interlocked components. The grid connects 5,800 major power plants and includes 450,000 miles of high voltage power transmission lines (American Society of Civil Engineers 2011).

The electricity grid is vulnerable to natural disasters (Kenward and Raja 2014; Mukherjee, Nateghi, and Hastak 2018a; Nateghi 2018; Yoon, Mukherjee, and Hastak 2019). In 2005, during Hurricane Katrina some 2.6 million customers in Louisiana, Mississippi, Florida, Alabama and Georgia reported power outages on August 30, 2005 (Hurricane Katrina Situation Report #11 https://www.oe.netl.doe.gov/docs/katrina/katrina_083005_1600.pdf accessed on May 3 2020). Again in 2012 super storm Sandy left over 8.5 million people without power across seven states (Kenward and Raja 2014; Mukherjee, Nateghi, and Hastak 2018a). The recent devastations of hurricane Harvey, Irma, Jose and Maria have had colossal effect on the communities in the U.S. and Caribbean islands. The power outages in the aftermath of hurricane Maria left much of islands of Puerto Rico without power and it is imperative that these events have dire consequences on economy, public health, social being (Nateghi 2018).

The U.S. Department of Energy (DoE) requires the utilities to report any power outage during which at least 50,000 customers were affected for at least an hour, there was a power supply disturbance more than 500 megawatt, or the demand exceeded by at least 100 megawatts. Figure 3.1 and 3.2 shows the extent of these power outages between 2000 and 2019. Every utility is supposed to submit this the incident report satisfying the abovementioned criteria to the DoE by filling out a survey form called OE-417 (https://www.oe.netl.doe.gov/oe417.aspx, accessed on March 16, 2020). This OE-417 form is an emergency reporting mechanism. This form: OE-417 has identified multiple causes of power outages such as: physical attack, vandalism, theft, cyber event, fuel supply emergency, generator loss, transmission equipment failure, failure at substation, weather or natural disaster, operator action, unknown and others.

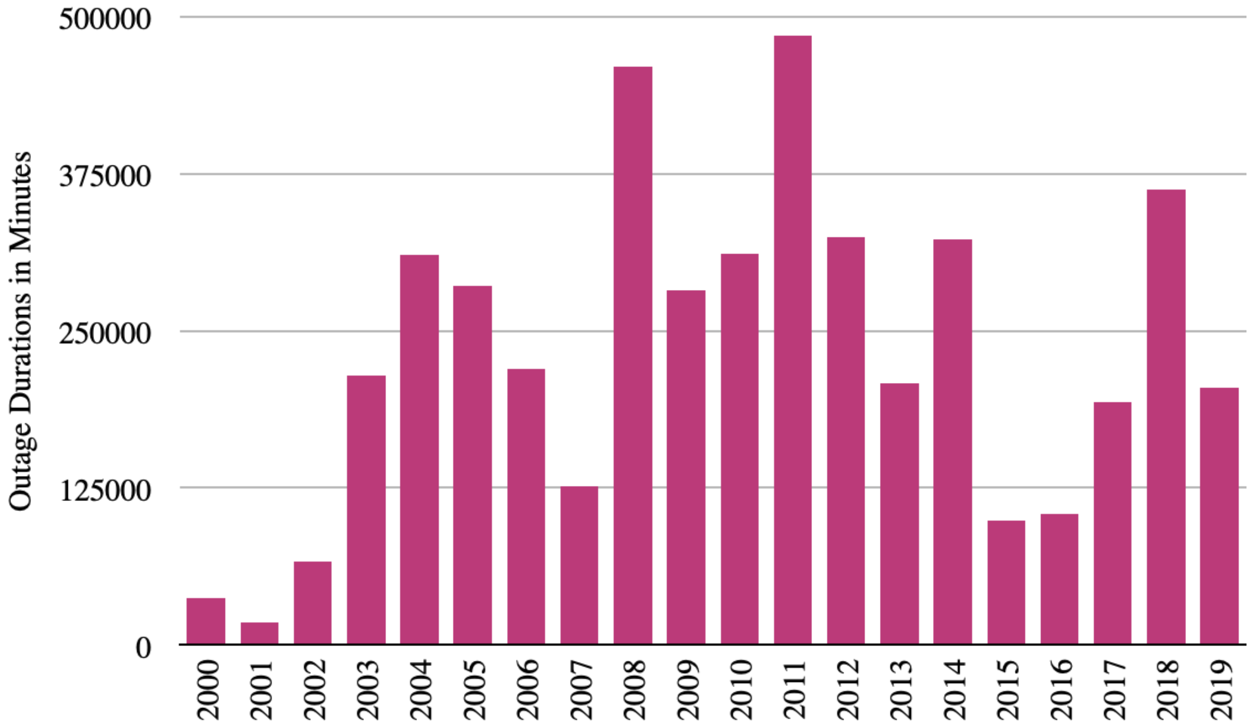


Figure 3.1 Duration of Power Outages between 2000 and 2019

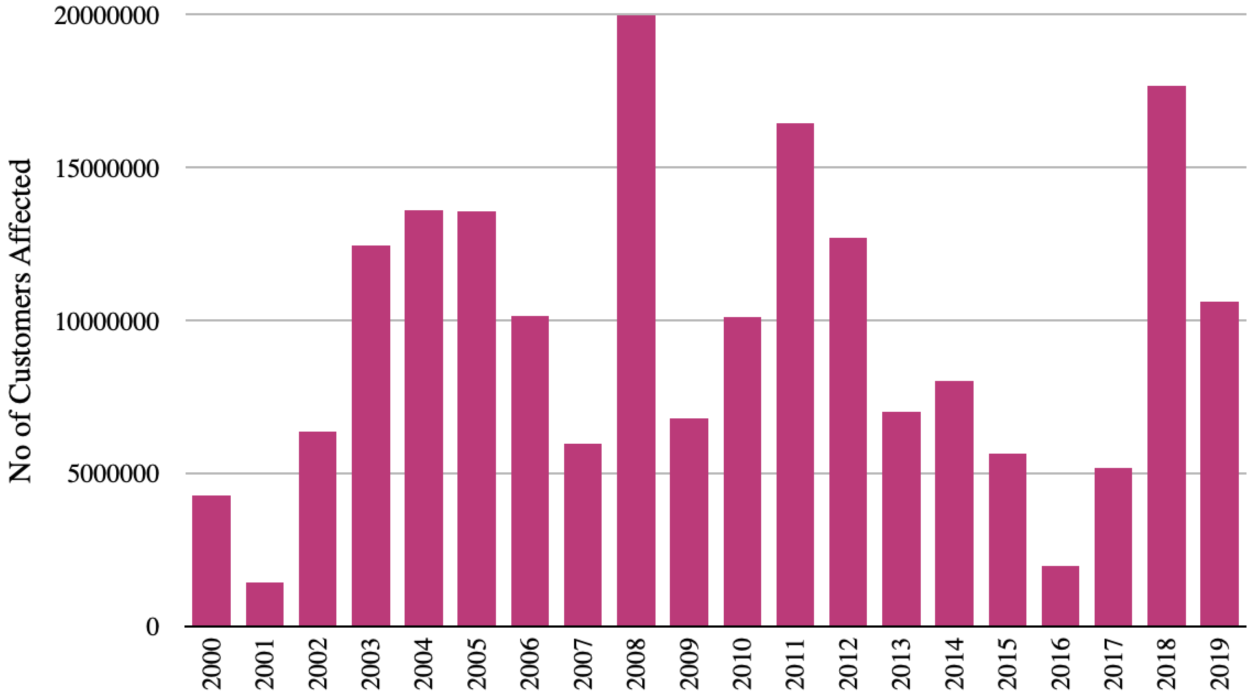


Figure 3.2 Number of Customers Affected due to Power Outages between 2000 and 2019

Historical data (Mukherjee, Nateghi, and Hastak 2018b) shows that between 2000 and 2016, 75% of the outages (in terms of durations) were caused due to severe weather events. During this period, out of the total number of customers affected, 86% were affected due to weather related incidents. Figure 3.3 shows the details. Hines, Apt, and Talukdar (2008) used the information between 1984 and 2006 and found that on average 782,695 customers were affected from power outages due to hurricanes. For ice storms the number is reduced to 343,448 and for equipment failure the number is 57,140.

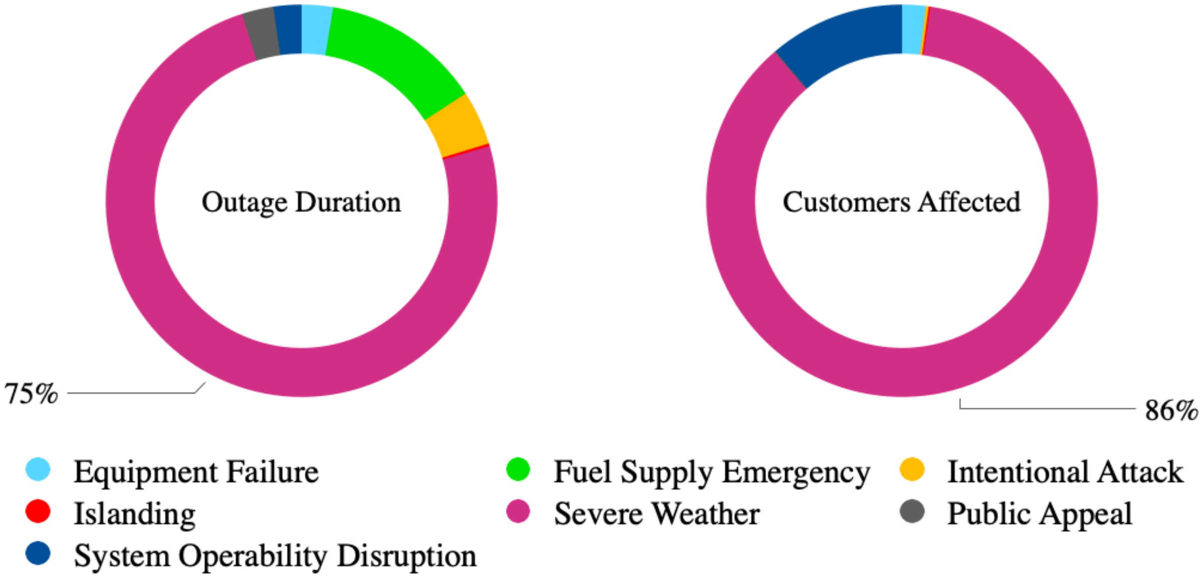


Figure 3.3 Causes of Power Outages

Due to climate changes, these incidents are becoming more frequent and that trend is likely to continue (Kenward and Raja 2014). Therefore, the utilities need to be prepared for these extreme situations. For that they need to invest to make the grid robust, reliable and resilient to the perturbation. The current practice to assess the benefit and cost of the investments to make the grid resilient grossly undermines the widespread economic impacts of the prolonged outages. In fact, the approval by the State Utility Regulatory Commissions for investments to improve the grid resilience can be biased (Keogh, Cody 2013). Before, investment can be planned it is important to understand the widespread impact of severe weather induced power outages. A report published by the Executive Office of The President (August 2013) estimated that between 2003 and 2012 weather related outage events have costed U.S. an inflated annual average of $18 billion to $33 billion. The annual cost fluctuated over the years and are maximum when any major hurricanes took place. In 2008 Hurricane Ike happened. The outages cost in 2008 was approximately $40 billion to $75 billion. In 2012 when super storm Sandy devastated the east coast, the said cost was approximately between $27 billion to $52 billion. Another Congressional Research (Campbell 2012) estimated the annual cost of power outages to be between $20 billion to $55 billion. But these studies have not considered the cascading economic impact of weather-related power outages. When a natural disaster happens, its impact is not limited to the infrastructure directly affected by the natural disaster. Due to existing interdependencies, other infrastructures also get affected (Hastak et al. 2009; Oh and Hastak 2008). For example, due to a sustained power outage, the industries which are dependent on the electricity might suffer production loss. This production loss can again affect other industries which are downstream in the supply chain. Therefore, the impact of power outages is not limited to utilities, but it is spread across the economy and the total loss is the sum of the losses suffered by each industry.

This research is intended to assess the cascading economic impacts due to severe weather induced power outages in terms of the loss of Gross Domestic Product (GDP) of the nation. To do that the research has adopted the extended version of Leontief's Input-Output model aka Inoperability Input-Output Model (Y. Y. Haimes and Jiang 2001; Yacov Y. Haimes et al. 2005; Santos and Haimes 2004) using the historical data between 1997 and 2016 from Bureau of Economic Analysis (BEA). The economic loss assessment can provide a feasible range of investment for resilience building projects in the utility sector. Moreover, the outcomes of the research can be used to understand the interdependencies between different industries and identify the most vulnerable industries at peril of severe weather induced power outages.

3.2 Literature Review

There have been multiple efforts to understand the economic impact of power outages by previous researchers. Lawton et al. (2003) have estimated the cost of power outage for different types of customers based on Value of Electric Service (VOS). Their calculation of economic loss was based on the Customer Damage Function (CDF) defined by Goel and Billinton (1994). The general form of CDF can be expressed as a function of three variables: outage attributes, customer characteristics and geographical attributes. Based on this CDF function they calculated the average cost experienced by an average customer for a single summer afternoon outage for an hour is approximately $3 for residential sector, $1,200 for small-medium commercial and industrial sector and $82,000 for large commercial and industrial sector in 2002 Consumer Price Index (CPI) weighted dollars. The cost of the outage increases substantially following a non-linear pattern as the duration of the outage increases. The cost of outage is more in winter than in summer. LaCommare and Eto (2006) has used a bottom-up approach to estimate the cost of power interruption and power quality to electricity customers. They developed a formula based on four factors: number of electricity customers, frequency of reliability events, cost of reliability events and vulnerability of the customers to reliability events. Based on these factors they have estimated the cost to be $79 billion (in 2002 CPI-weighted dollars). They found that 72% of the loss is suffered by the commercial customers. Campbell (2012) estimated the annual cost of power outages to be between $20 billion to $55 billion. The Office of Executive President (2013) have estimated that the weather-related outages cost the U.S. economy an inflation adjusted average of $18 billion to $33 billion. The annual cost changes based on the extent of severe weather events. In 2008, during the year of Hurricane Ike, the cost was between $40 billion to $75 billion and in 2012 during super storm Sandy, the cost was between $27 billion to $70 billion. These estimates account for numerous costs like lost outputs, lost wages, spoiled inventory, inconvenience, cost of restarting industrial operations. The study also estimated that 20% to 25% of the annual cost of the weather-related power outages are attributed to lost output. Feldman (2015) has estimated the cost of power outages in 2013 to be $112 billion, whereas in that year the retail customers paid some $364 billion to their suppliers for the electricity service. LaCommare et al. (2018) in the recent study again estimated the cost of sustained power outages and found that the cost has increased from their study in 2006 by 25 percent and the new cost is $44 billion (2015 dollars). To the best knowledge of the authors, none of these studies have considered the cascading impact of severe weather induced power outages on other industries. In other words, they have not incorporated the impacts due to existing interdependencies between different industries.

Natural disasters affect critical infrastructures, which in turn affects industries and communities (Oh, Deshmukh, and Hastak 2013). The Presidential Policy Directive 21 or PPD 21 has defined 16 critical infrastructure sectors “whose assets, systems, and networks, whether physical or virtual, are considered so vital to the United States that their incapacitation or destruction would have a debilitating effect on security, national economic security, national public health or safety, or any combination thereof" (https://www.cisa.gov/critical-infrastructure-sectors, accessed on April 26, 2020).

Rinaldi, Peerenboom, and Kelly (2001) have defined 4 types of interdependencies between critical infrastructures. They are Physical, Geographic, Cyber and Logical. Physical interdependency exists when product of one infrastructure is used by another one. In this research physical interdependencies have been considered as the only interdependency. When, there is any disruption in the service of one type of infrastructure, other infrastructures, industries and communities are also affected due to interdependencies. This impact has been explained by a basic cell model in (Hastak et al. 2009; Oh and Hastak 2008). The model considers two folded impacts of a natural disaster which are primary and secondary. The primary impact is the direct impact of the natural disaster on the infrastructure. For example, the impact could be power outages for electricity infrastructure, collapse for buildings, roads, bridges. The secondary impact is due to the interdependencies. Therefore, to effectively understand the overall impact of a natural disaster, the understanding of the existing interrelations between infrastructures and industries is essential. This modeling of infrastructure interdependencies can be performed is various ways.

The first one is simulation based. System Dynamics (SD) is popular among the simulation techniques. It is a process to study the time based behavior of a complex system over (Kirkwood 1998). Arboleda et al. (2009) have used a system dynamics simulation to show the operational vulnerabilities for a healthcare facility. Oh, Deshmukh, and Hastak (2010) have applied system dynamics simulations to understand the vulnerabilities of critical infrastructures and associated industries and communities. Min et al. (2007) have also used system dynamics simulations to develop a framework to study the entire system of physical and economic infrastructures. Other examples of system dynamics simulation in the domain of infrastructure interdependencies can be found in Conrad et al. (2006), LeClaire and O'Reilly (2005). Some researchers have also used agent-based modeling (ABM) for interdependency analysis of critical infrastructures. In ABM, critical infrastructures behave like complex adaptive systems (Heracleous et al. 2017), which can interact between themselves. The interdependencies usually emerge from the interaction between different agents. Examples of ABM can be found in Dudenhoeffer, Permann, and Manic (2006), Kaegi, Mock, and Kröger (2009).

The next popular approach to analyze infrastructure interdependencies is to use the concept of graph theory. A graph can be represented by a set of nodes and edges between them. In this approach, the nodes are represented as the infrastructures and the edges between them are the interdependencies. Wang, Hong, and Chen (2012) have used graph theory in their research to develop a framework to analyze the vulnerability of interdependent power and water systems of a major city in China. Ouyang and Wang (2015) have applied the concept of graph theory for deriving the structural and functional vulnerability of interdependent power and gas network. Other classical examples can be found in Svendsen and Wolthusen (2007), Hernandez-Fajardo and Dueñas-Osorio (2013).

The third popular approach is the use of Input-Output (I-O) Model. I-O model was proposed by Wassily Leontief a Russian-American economist (Leontief 1951, 1986). Leontief has defined I-O tables to describe the flow of goods and services between different sectors of a national economy. Leontief's technical coefficient matrix establishes the interrelationships between different producing and consuming sectors. According to him the economy can be divided into (n+1) sectors, n industries that are producing sectors and $(n+1)_{th}$ final demand sector and the total production output of a sector is the sum of the consumptions of producing sector and consumptions of end users. I-O models capture the interdependence between several producing and consuming sectors (Planting 2006). The interdependence is based on the equilibrium between the production and consumption of commodities produced by different industries. Interdependency analysis with the use of I-O model can be found in Y. Y. Haimes and Jiang (2001), Santos (2006), Setola, De Porcellinis, and Sforna (2009), Wei, Dong, and Sun (2010), Oliva, Panzieri, and Setola (2011).

The extension of I-O model aka Inoperability Input-Output Model or IIM has been explained by Santos and Haimes (2004) for analyzing inter-relationships to assess the direct and indirect economic impacts of terrorism through multiple sectors of U.S. Inoperability can be defined as the reduction in production (as-planned production minus degraded production) per unit as-planned production. Haimes et al. (2005) have explained the extensions of the concepts of IIM for different applications. The physical based IIM; initially proposed by Haimes and Jiang (2001) considers physical inputs to infrastructures rather than the monetary inputs proposed by Leontief. The demand reduction IIM captures the impacts of reduction of demand on different other sectors. The dynamic IIM captures the temporal dimensions and can be used for modeling economic recovery. They have also derived a coefficient for measuring the resilience of industries. Crowther and Haimes (2005) have examined the applications of IIM for risk assessment and management of interdependent infrastructures. They have explained how system engineers can adopt IIM for understanding vulnerabilities in the system using three illustrative case studies. Santos (2006) has highlighted the importance of assessing the economic interdependencies to determine the most vulnerable sectors in the economy. He has used IIM to analyze the impact of demand-side perturbations of air transportation and accommodation industry on other sectors due to 9/11 catastrophe. Leung, Haimes, and Santos (2007) have extended the concept of demand-side perturbations to supply-side perturbations and output-side perturbations. The supply-side perturbation is a price model, which assesses the impact of increase of price of value added such as labor wages in terms of inoperability in production output. The output-side IIM measures the impacts of direct perturbations on the output of a sector. There have been multiple other works applying IIM for analyzing problems associated with the vulnerability of interconnected infrastructure systems. They can be found in (Guo and Hou 2019; Haggerty, Santos, and Haimes 2008; Jung, Santos, and Haimes 2009; Niknejad and Petrovic 2016; Xu et al. 2012).

3.3 Disaster Impact Assessment Mechanism

The disaster impact assessment mechanism has been shown in figure 3.4. The figure highlights the cascading impacts of a natural disaster. During a natural disaster, civil infrastructures protect the communities from the physical risk (Choi, Deshmukh, and Hastak 2019). Again, during natural disasters, these civil infrastructures get damaged. Due to the damage to the infrastructures, their serviceability gets reduced. This reduction of serviceability of the infrastructures can be called the inoperability. As the infrastructures are dependent, the inoperability induced in one infrastructure due to natural disasters, affect the communities and the industries (Oh and Hastak 2008).

The primary impact of the natural disasters on utility sector in the power outage. When utility sector’s serviceability is compromised due to natural disasters, the impact is faced by communities and industries. This can be defined as the secondary impact. When an industry suffers from prolonged power outage, its production gets reduced. The reduced production of the affected industry further induces inoperability in the industries downstream in the supply chain. Therefore, the impact of power outage is not limited to utility sector only. The impact is widely spread across the economy and each industry which is dependent on the utility sector faces production loss and they also affect other industries. This loss in production causes reduced supply to the end users. The loss in consumption by the end users trigger the loss of GDP. Therefore, the total loss of GDP due to power outage is the sum of loss of GDP of all industries which are affected by the severe weather induced power outages.

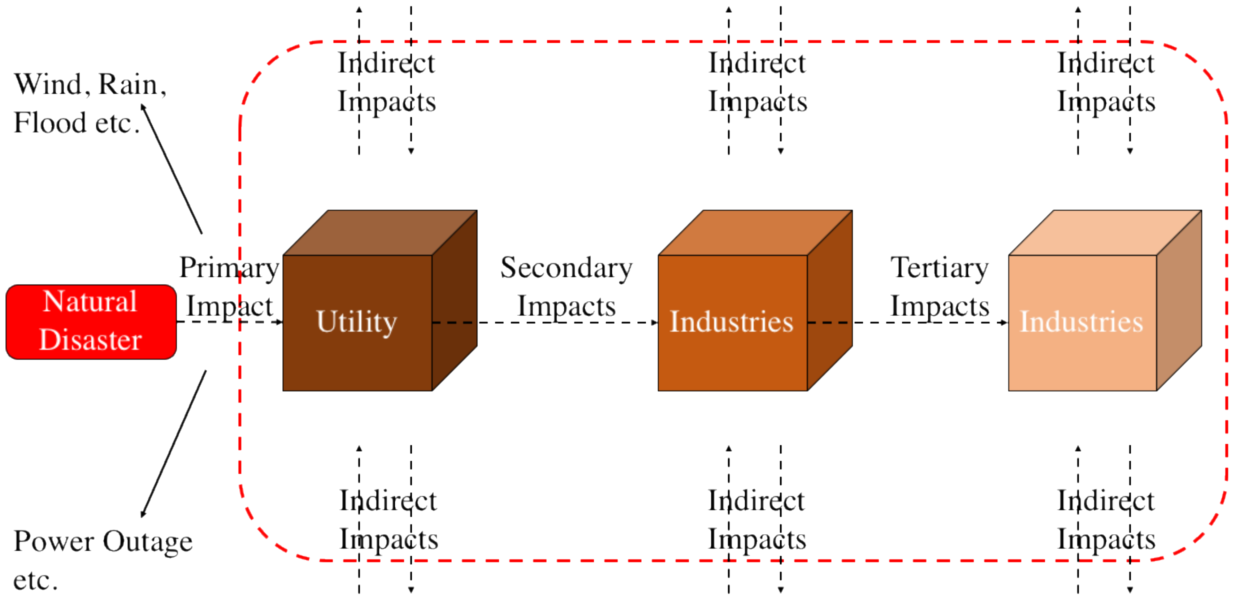


Figure 3.4 Disaster Impact Assessment Mechanism

This in the fundamental philosophy which has been followed in this research for assessing the economic impact of severe weather induced power outages. It is worth mentioning that the mechanism which has been shown in figure 3.4 is cyclic. This means that the affected industries increase the inoperability in the utility sector and the process continues. It can be explained with a simple example. Suppose, the inoperability in the utility sector affects the production of an industry "A" (for example Petroleum Products) and utility itself is dependent upon industry "A" for its normal operation. Then reduced production of industry "A" will increase the initial inoperability of utility sector which is induced directly due to natural disaster. The power outages due to natural disasters are primarily prolonged outages rather than momentary outage. The impacts of prolonged power outages may not get diminished in one cycle. Therefore, this research has considered two additional cycles for assessing the GDP loss. It is pertinent that each cycle increases the net economic impact of power outage.

There are two major assumptions relevant to the impact assessment mechanism. They are:

- *Equilibrium Assumption: This means that the balance between industry's production output and consumption of that output by industries (intermediate demand) and by end* *users (final demand) as suggested by Leontief (1951, 1986) still exists in a post disaster situation.*

- *Equal Impact Assumption: This means that the impact of the production loss is equally suffered by the industries and end users. So, if there is 1% reduction in production of an industry, the industries which are dependent on it will face a supply shortage of 1% and the end users of that industry will also face a supply shortage of 1%.*

Based on this mechanism the methodology of the research is developed. The methodology is shown in figure 3.5 and explained in the following sections.

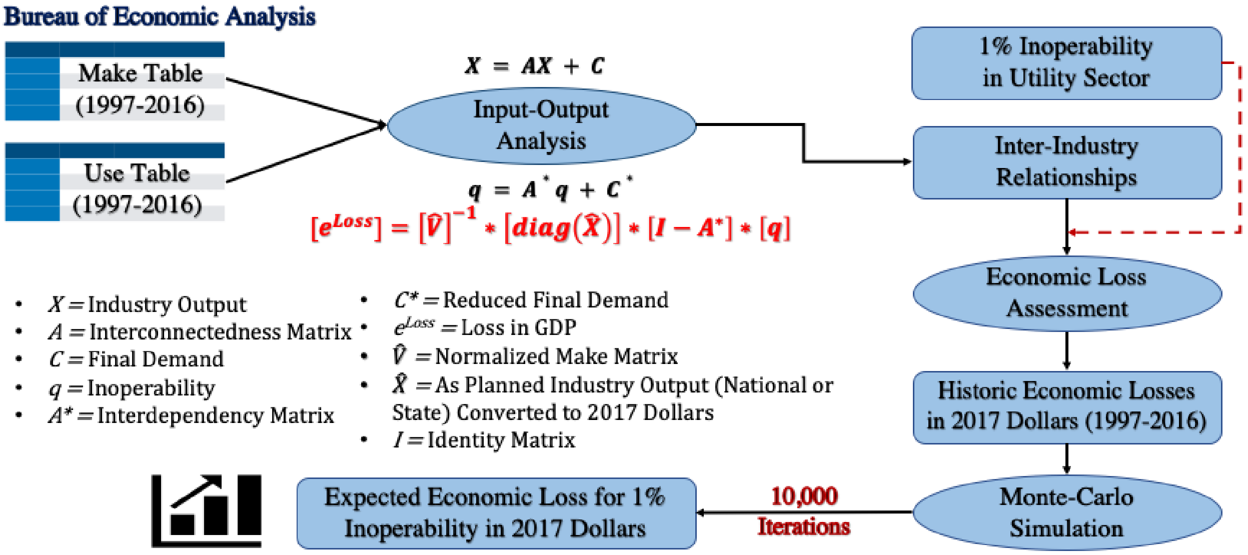


Figure 3.5 Research Methodology

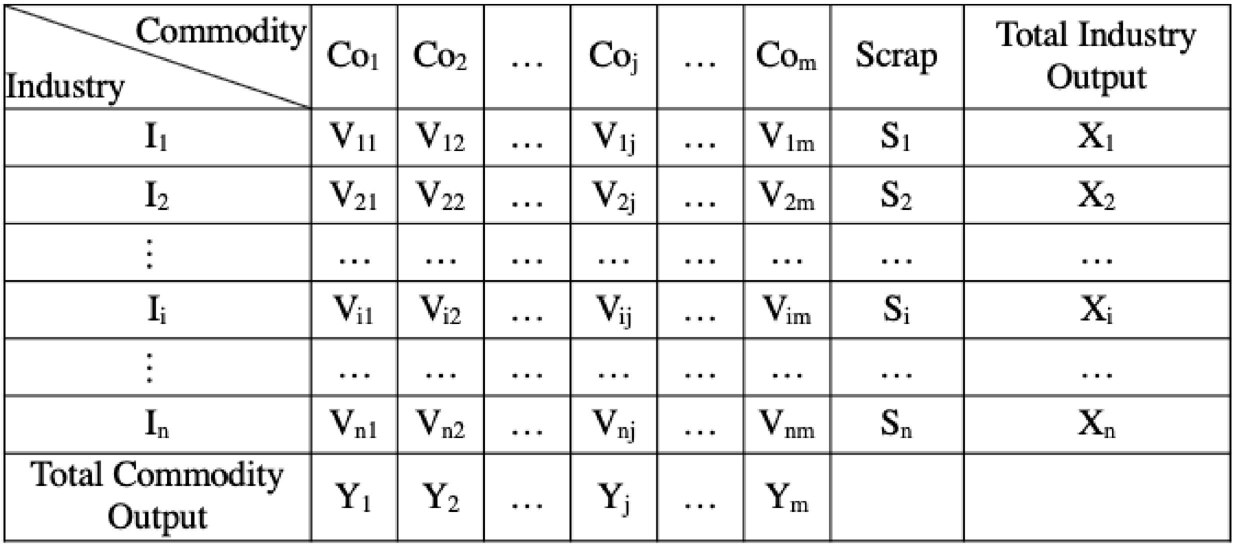
3.4 Input-Output Model

To assess the net GDP loss which is the sum of the GDP losses of all industries, it is essential to understand the inter-industry relationships. To establish the said relationship, this research has adopted the Input-Output model using the data from the BEA. Input-Output Model is an economic analysis tool used to develop the interdependence between different producing and consuming sectors. The fundamental principle behind the I-O model is the equilibrium of commodities produced by an industry and its consumption by different industries and end user. This equilibrium can be expressed as equation 1.

$$X = AX + C \tag{1}$$

Where, X is the total industry output, A is the technical coefficient matrix and C is the final demand. The technical coefficient matrix establishes the inter-industry relationships. The term AX represents the consumption of commodities by industries which is also called intermediate demand.

There are two primary components of the I-O model: Make and Use Tables. Make Tables show the production of different commodities by industries. Figure 3.6 shows an example of a Make Table. The rows in the Make tables represent the industries and the columns represent the commodities. Looking along a row all commodities produced by an industry can be found which add up to the total industry output for that particular industry. Again, looking along a column all industries producing that particular commodity can be found and the sum of the column will be the output of that commodity. It should be noted that each industry produces some amount of scrap. But no industry produces scrap on purpose or on demand, it is a byproduct of the original productions. All components of the Make table are expressed in Dollar values.



Commodity Industry	Co_1	Co_2	…	Co_j	…	Co_m	Scrap	Total Industry Output
I_1	V_{11}	V_{12}	…	V_{1j}	…	V_{1m}	S_1	X_1
I_2	V_{21}	V_{22}	…	V_{2j}	…	V_{2m}	S_2	X_2
⋮	…	…	…	…	…	…	…	…
I_i	V_{i1}	V_{i2}	…	V_{ij}	…	V_{im}	S_i	X_i
⋮	…	…	…	…	…	…	…	…
I_n	V_{n1}	V_{n2}	…	V_{nj}	…	V_{nm}	S_n	X_n
Total Commodity Output	Y_1	Y_2	…	Y_j	…	Y_m		

Figure 3.6 Structure of Make Table

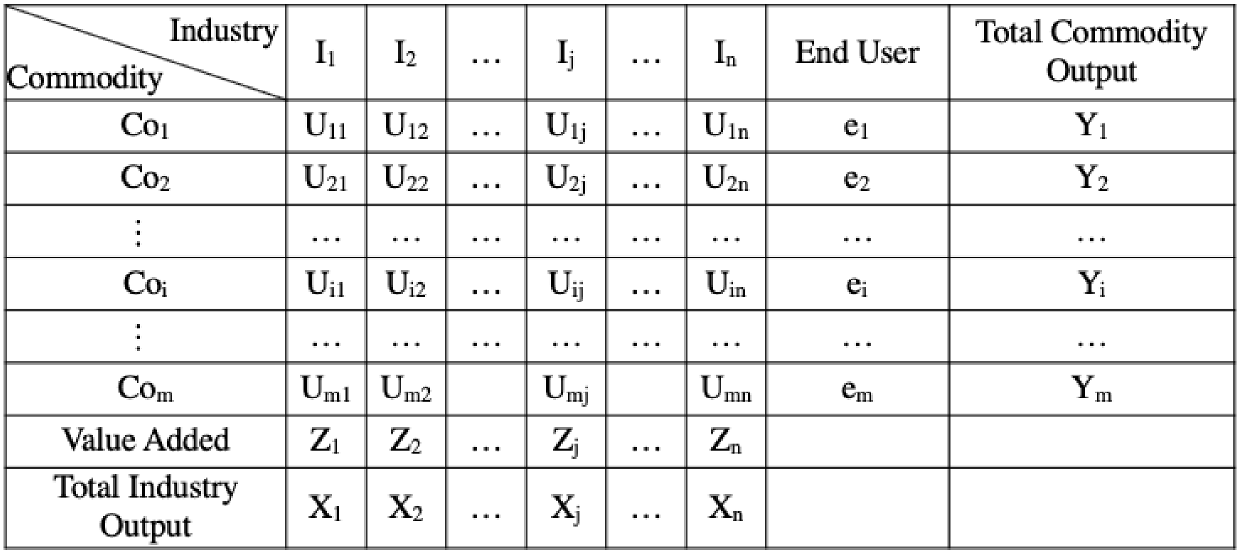
The sample make table has n industries which are producing m commodities. Industries are denoted by "I" and Commodities are denoted by "Co". V_{ij} represents the dollar value of commodity j produced by industry i. S_i represents the dollar value of scrap produced by industry i as a byproduct of its production operation. X_i is the dollar value of total output of industry i which contains the scrap S_i and Y_j is the dollar value of total output of commodity j. Therefore,

$$X_i = \sum_{j=1}^{m} V_{ij} + S_i \qquad 2$$

and

$$Y_j = \sum_{i=1}^{n} V_{ij} \qquad 3$$

The Use Tables shows the consumption of the produced commodities by different industries and end users. Figure 3.7 shows a sample Use Table. The rows of the Use tables represent the commodities whereas, the columns represent the industries. Looking across a row, the consumption of a commodity by different industries and the end users can be found. Therefore, the sum of all elements along a row is the total output of that commodity. The portion of the production consumed by the industries is called the intermediate demand and the portion of the production consumed by the end users is called the end user demand. The entries along a column represents the consumption of different commodities by that industry and the “Value Added” components which are basically the compensation of employees, taxes on production and imports less subsidies and gross operating surplus. The sum of the value added of all industries represent the GDP of the nation. The sum of all elements across the column is the total industry output of that industry. All components of the Use table are expressed in Dollar values.



Industry Commodity	I_1	I_2	…	I_j	…	I_n	End User	Total Commodity Output
Co_1	U_{11}	U_{12}	…	U_{1j}	…	U_{1n}	e_1	Y_1
Co_2	U_{21}	U_{22}	…	U_{2j}	…	U_{2n}	e_2	Y_2
⋮	…	…	…	…	…	…	…	…
Co_i	U_{i1}	U_{i2}	…	U_{ij}	…	U_{in}	e_i	Y_i
⋮	…	…	…	…	…	…	…	…
Co_m	U_{m1}	U_{m2}		U_{mj}		U_{mn}	e_m	Y_m
Value Added	Z_1	Z_2	…	Z_j	…	Z_n		
Total Industry Output	X_1	X_2	…	X_j	…	X_n		

Figure 3.7 Structure of Use Table

The sample use table has n industries which are consuming m commodities. An element, U_{ij} is the dollar value of industry j's consumption of commodity i, e_i is the dollar value of end user demand of commodity i, Z_j is the dollar value of the value added consumption by industry j. Y_i is the dollar value of total output of commodity i and X_j is the dollar value of the total output of industry j. Therefore,

$$X_j = \sum_{i=1}^{m} U_{ij} + Z_j \qquad 4$$

and

$$Y_i = \sum_{j=1}^{n} U_{ij} + e_i \qquad 5$$

This research has utilized historic Make and Use Tables between 1997 and 2016. There are three versions of Make and Use tables. In each version the number of industries and commodities are different. This research has used the tables in which secondary products adjustments are not performed (before redefinition) and which are comprised of 71 industries and 71 commodities.

These two tables were used to derive Leontief's technical coefficient matrix (A Matrix) following the process described in Planting (2006). The process of deriving the A matrix consists of 4 steps. Step 1 is to derive the Normalized Use table. The industry inputs of the Use table are divided by that industry's total output which is the sum of all elements of that column. This is basically column-wise normalization of the Use table.

$$\widehat{U} = U[Diag(X)]^{-1} \qquad 6$$

Where, U is the Use Matrix and $\widehat{U}$ is the Normalized Use Matrix. $\widehat{U}$ is a m×n matrix, containing m commodities along the rows and n industries along the columns.

$$X = \begin{bmatrix} X_1 = \sum_{i=1}^{m} U_{i1} + Z_1 \\ \vdots \\ X_j = \sum_{i=1}^{m} U_{ij} + Z_j \\ \vdots \\ X_n = \sum_{i=1}^{m} U_{in} + Z_n \end{bmatrix} \qquad 7$$

$$Diag(X) = Diag\begin{bmatrix} X_1 \\ \vdots \\ X_j \\ \vdots \\ X_n \end{bmatrix} = \begin{bmatrix} X_1 & 0 & 0 & 0 \\ 0 & X_2 & 0 & 0 \\ 0 & 0 & \ddots & 0 \\ 0 & 0 & 0 & X_n \end{bmatrix} \qquad 8$$

$$\widehat{U}_{ij} = \frac{U_{ij}}{X_j} \qquad 9$$

An element of $\widehat{U}$, $\widehat{U}_{ij}$ represents industry j's consumption of commodity i out of the total production input of industry j.

Step 2 is the normalization of Make table, which shows the proportion of a commodity output produced by different industries. This is done by column-wise normalizing the Make table.

$$\check{V} = V[Diag(Y)]^{-1} \qquad 10$$

Where, V is the Make Matrix and $\check{V}$ is the Normalized Make Matrix before Scrap Adjustment. $\check{V}$ is a n×m matrix, containing n industries along the rows and m commodities along the columns.

$$Y = \begin{bmatrix} Y_1 = \sum_{i=1}^{n} V_{i1} \\ \vdots \\ Y_j = \sum_{i=1}^{n} V_{ij} \\ \vdots \\ Y_m = \sum_{i=1}^{n} V_{im} \end{bmatrix} \qquad 11$$

$$Diag(Y) = Diag\begin{bmatrix} Y_1 \\ \vdots \\ Y_j \\ \vdots \\ Y_m \end{bmatrix} = \begin{bmatrix} Y_1 & 0 & 0 & 0 \\ 0 & Y_2 & 0 & 0 \\ 0 & 0 & \ddots & 0 \\ 0 & 0 & 0 & Y_m \end{bmatrix} \qquad 12$$

Step 3 is to make adjustment for the scrap which is not intentionally produced by the industries. In order to make the I-O model work perfectly, that is, not requiring the industries to produce scrap because of demand, it is necessary to perform the scrap adjustment. To do this, first the ratio of non-scrap is calculated for all industries. The non-scrap ratio for an industry is the ratio of that industry's output excluding scrap and that industry's output including scrap (or total industry output). The non-scrap ratio ρ_i for an industry i can be calculated as

$$\rho_i = \frac{X_i - S_i}{X_i} \qquad 13$$

Once, the non-scrap ratio is derived for all industries, the elements of the normalized make matrix before scrap adjustment ($\check{V}$) matrix (derived in step 2) is divided by the non-scrap ratios. In the $\check{V}$ matrix, the rows represent the industries. Therefore, all the elements across a row of a $\check{V}$ matrix should be divided by the non-scrap ratio derived for that particular industry. After this step, the modified matrix is called Normalized Make Matrix ($\hat{V}$).

$$\hat{V} = [Diag(\rho)]^{-1}\,\check{V} \qquad 14$$

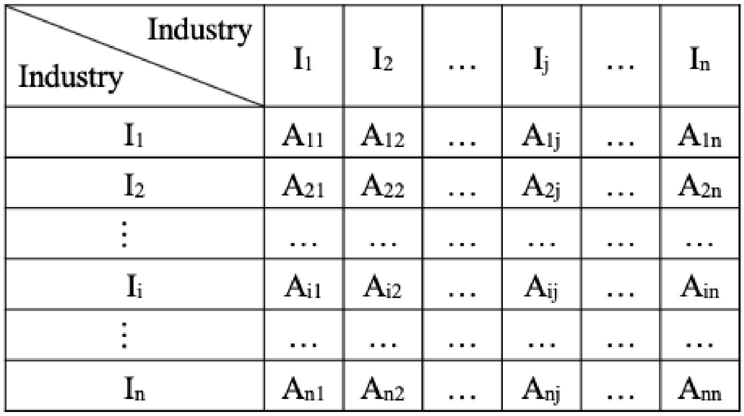
$$\rho = \begin{bmatrix} \rho_1 = \dfrac{X_1 - S_1}{X_1} \\ \vdots \\ \rho_i = \dfrac{X_i - S_i}{X_i} \\ \vdots \\ \rho_n = \dfrac{X_n - S_n}{X_n} \end{bmatrix} \qquad 15$$

$$Diag(\rho) = Diag\begin{bmatrix} \rho_1 \\ \vdots \\ \rho_i \\ \vdots \\ \rho_n \end{bmatrix} = \begin{bmatrix} \rho_1 & 0 & 0 & 0 \\ 0 & \rho_2 & 0 & 0 \\ 0 & 0 & \ddots & 0 \\ 0 & 0 & 0 & \rho_n \end{bmatrix} \qquad 16$$

$\hat{V}$ is a n×m matrix, containing n industries along the rows and m commodities along the columns. Step 4 is to multiply the normalized make matrix after scrap adjustment ($\hat{V}$) with normalized use Matrix ($\widehat{U}$) to generate industry by industry technical coefficient matrix (A).

$$A = \hat{V}\widehat{U} \qquad 17$$

Figure 3.8 shows the structure of an A matrix. A matrix is a n×n square matrix containing n industries along row as well as columns.



Industry Industry	I_1	I_2	…	I_j	…	I_n
I_1	A_{11}	A_{12}	…	A_{1j}	…	A_{1n}
I_2	A_{21}	A_{22}	…	A_{2j}	…	A_{2n}
⋮	…	…	…	…	…	…
I_i	A_{i1}	A_{i2}	…	A_{ij}	…	A_{in}
⋮	…	…	…	…	…	…
I_n	A_{n1}	A_{n2}	…	A_{nj}	…	A_{nn}

Figure 3.8 Structure of A Matrix

An element of this matrix A_{ij} represents the contribution of industry i to unit production input of industry j. This matrix represents the inter-industry relationships.

The formulation of the A matrix can be cross validated by using equation 1. The final demand vector C can be expressed as

$$C = \hat{V}e \tag{18}$$

Where e is the end user demand vector derived from use matrix.

$$\mathrm{e} = \begin{bmatrix} \mathrm{e}_1 \\ \vdots \\ \mathrm{e}_i \\ \vdots \\ \mathrm{e}_m \end{bmatrix} \tag{19}$$

The cross-validation can be performed using equation 1 rewritten as equation 20 by substituting equation 17 and 18:

$$X = \hat{V}\hat{U}X + \hat{V}e \tag{20}$$

The outcome of the I-O model is 20 71×71 matrices for each year between 1997 and 2016. These matrices have been used in IIM to assess the economic loss.

3.5 Inoperability Quantification in Utility Sector

Disaster impacted infrastructures have a reduced level of serviceability. This reduction of serviceability can be defined as the inoperability. Santos and Haimes (2004), Haimes et al. (2005) have defined inoperability as

$$Inoperability = \frac{As\ Planned\ Production\ - Reduced\ Level\ of\ Production}{As\ Planned\ Production} \qquad 21$$

For utility sector, Nateghi (2018) has defined inoperability as a multivariate non-linear function of hazard characteristics, system's topology, region's land cover and topography etc. Again, Yoon, Mukherjee, and Hastak (2019) have defined inoperability as

$$Inoperability = \frac{Annual\ Peak\ Demand\ Lost\ During\ an\ Outage}{Annual\ Peak\ Demand\ of\ the\ Region} \qquad 22$$

For this research, inoperability has to be defined in a way so that it can be used in the IIM. Because, the research intends to assess the economic impact of loss of production, the inoperability has to be associated with the loss of production. But, the planned production of equation 21, is not known, what is known, is the annual production which is basically the reduced level of production after all the production losses. Therefore, the equation 21can be rewritten as

$$Inoperability = \frac{Loss\ in\ Production\ in\ MWh}{Reduced\ Level\ of\ Production\ in\ MWh + Loss\ in\ Production\ in\ MWh} \qquad 23$$

It has been assumed here that the dollar value of the production output is proportional to the megawatt hour of electricity production. Clearly, the sum of reduced level of production and the production losses result in the as planned production.

The current form of outage data reporting does not capture the megawatt hour loss during a power outage. DoE's outage reporting form OE-417 asks the utilities to report the peak demand loss during the reported power outage but the reporting of the peak demand loss is not mandatory. For accurate estimation of the GDP loss due to severe weather induced power outages, it is essential to estimate the production loss during a power outage.

3.6 Inoperability Input-Output Model

The objective of the IIM is to assess the economic impact of the loss of production in the utility sector due to severe weather induced power outages. There are three main assumptions in the development of the IIM along with the two assumptions mentioned in the disaster impact assessment mechanism. They are:

- *Inoperability Assumption: It is assumed that failure of the components of the grids such as transmission lines, distribution lines, substations etc. prompts the utilities to reduce the* *production. In other words, the reduction of demand due to failure of grid components engenders the utilities to reduce the production.*

- *Data Availability Assumption: It is assumed that the loss of production can be quantified by the utilities following the equation 24.*
- *Cumulative Impact Assumption: It is assumed that the economic impact of n numbers of severe weather induced power outages is equivalent to the economic impact of 1 power outage whose duration is equal to the sum of the durations of those n individual power outages.*

$$Economic\ Impact\ of\ \{Outage\ 1 + Outage\ 2 + \cdots + Outage\ n\} = Economic\ Impact\ of\ 1\ Outage\ with\ duration\ equal\ to\ \sum_{i=1}^{n} Duration\ of\ Outage\ i \qquad 24$$

Based on these assumptions the equation for the GDP loss estimation is derived. It is important to understand that the estimated GDP loss is only attributed to the inoperability in the Utility sector. There can be many additional reasons for GDP loss which are beyond the scope of this work. The outcome of the loss of production is found in terms of the loss of final demand, which is GDP.

In pre-disaster situation, let $\hat{X}$ be the as planned production and $\hat{e}$ be the as planned end user demand. The other notations are as explained before.

$$\hat{X} = A * \hat{X} + \hat{V} * \hat{e} \qquad 25$$

The equilibrium assumption assumes that the balance between the production and consumption of commodities exist in a post disaster situation. Let $\tilde{X}$ be the reduced level of production and $\tilde{e}$ be the reduced level of final demand. Then according to equilibrium assumption,

$$\tilde{X} = A * \tilde{X} + \hat{V} * \tilde{e} \qquad 26$$

By subtracting equation 26 from equation 25, the balance between the reduction in production and the reduction in final demand due to reduction in production can be found.

$$\hat{X} - \tilde{X} = A * \left[\hat{X} - \tilde{X}\right] + \hat{V} * [\hat{e} - \tilde{e}] \qquad 27$$

To derive the unit reduction in production the equation 28 is derived.

$$[diag(\hat{X})]^{-1} * [(\hat{X}) - (\tilde{X})] \\ = [diag(\hat{X})]^{-1} * [A] * [(\hat{X}) - (\tilde{X})] + [diag(\hat{X})]^{-1} * [\hat{V}] * [(\hat{e}) - (\tilde{e})] \tag{28}$$

Equation 28 can be rewritten as equation 29

$$[diag(\hat{X})]^{-1} * [(\hat{X}) - (\tilde{X})] \\ = [diag(\hat{X})]^{-1} * [A] * [diag(\hat{X})] * [diag(\hat{X})]^{-1} * [(\hat{X}) - (\tilde{X})] \\ + [diag(\hat{X})]^{-1} * [\hat{V}] * [(\hat{e}) - (\tilde{e})] \tag{29}$$

The left hand side of the equation 29 is the inoperability vector based on equation 21 defined by Santos and Haimes (2004), Haimes et al. (2005). They have also defined a new matrix (A^*) which also captures the interindustry relationships.

$$[q] = [diag(\hat{X})]^{-1} * [(\hat{X}) - (\tilde{X})] \tag{30}$$

And,

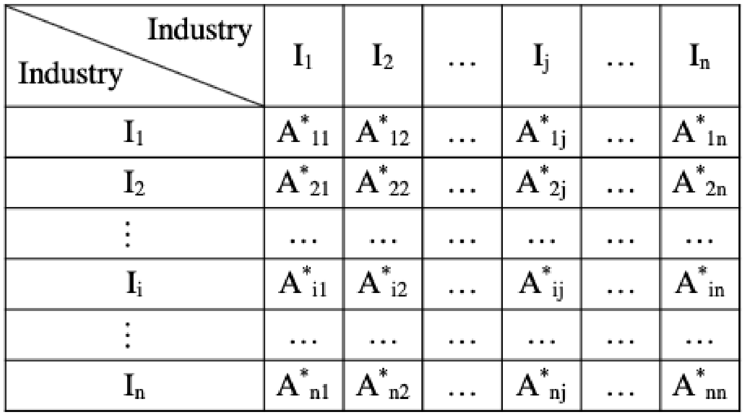
$$[A^*] = [diag(\hat{X})]^{-1} * [A] * [diag(\hat{X})] \tag{31}$$

If $\hat{X}_i$ and $\tilde{X}_i$ be the as planned production and reduced level of production of industry i respectively, then

$$Diag(\hat{X}) = Diag\begin{bmatrix} \hat{X}_1 \\ \vdots \\ \hat{X}_i \\ \vdots \\ \hat{X}_n \end{bmatrix} = \begin{bmatrix} \hat{X}_1 & 0 & 0 & 0 \\ 0 & \hat{X}_2 & 0 & 0 \\ 0 & 0 & \ddots & 0 \\ 0 & 0 & 0 & \hat{X}_n \end{bmatrix} \tag{32}$$

$$q = \begin{bmatrix} q_1 = \dfrac{\hat{X}_1 - \tilde{X}_1}{\hat{X}_1} \\ \vdots \\ q_i = \dfrac{\hat{X}_i - \tilde{X}_i}{\hat{X}_i} \\ \vdots \\ q_n = \dfrac{\hat{X}_n - \tilde{X}_n}{\hat{X}_n} \end{bmatrix} \tag{33}$$

Figure 3.9 shows the structure of the A^* matrix. A^* matrix is a n×n square matrix, where each row represents an industry and each column represents an industry. An element of the A^* matrix or A^*_{ij} represents the proportion of the total output of industry i which is being consumed by industry j.



Industry Industry	I_1	I_2	…	I_j	…	I_n
I_1	A^*_{11}	A^*_{12}	…	A^*_{1j}	…	A^*_{1n}
I_2	A^*_{21}	A^*_{22}	…	A^*_{2j}	…	A^*_{2n}
⋮	…	…	…	…	…	…
I_i	A^*_{i1}	A^*_{i2}	…	A^*_{ij}	…	A^*_{in}
⋮	…	…	…	…	…	…
I_n	A^*_{n1}	A^*_{n2}	…	A^*_{nj}	…	A^*_{nn}

Figure 3.9 Structure of A_* Matrix

When, equation 30 and 31 are replaced in equation 29, it becomes

$$[q] = [A^*] * [q] + \left[diag\left(\hat{X}\right)\right]^{-1} * [\hat{V}] * [(\hat{e}) - (\tilde{e})] \qquad 34$$

Equation 34 can be further simplified as equation 35, 36 and finally 37

$$\left[diag\left(\hat{X}\right)\right]^{-1} * \left[\hat{V}\right] * [(\hat{e}) - (\tilde{e})] = [I - A^*] * [q] \qquad 35$$

$$[(\hat{e}) - (\tilde{e})] = \left[\hat{V}\right]^{-1} * \left[diag\left(\hat{X}\right)\right] * [I - A^*] * [q] \qquad 36$$

$$[e^{Loss}] = \left[\hat{V}\right]^{-1} * \left[diag\left(\hat{X}\right)\right] * [I - A^*] * [q] \qquad 37$$

Where,

$$[e^{Loss}] = \begin{bmatrix} e_1^{Loss} \\ \vdots \\ e_i^{Loss} \\ \vdots \\ e_n^{Loss} \end{bmatrix} \qquad 38$$

The equation 37 has been used for calculating the GDP loss due to severe weather induced power outages for all years between 1997 and 2016. The production output of each industry was converted into 2017 dollars before using them in the GDP loss equation. The discount rates used for the conversion were derived from Federal Reserve Bank Database (https://fred.stlouisfed.org/series/INTDSRUSM193N, accessed on February 3, 2020). The database had discount rates since 2003. Therefore, for all the years before 2003, the discount rate of 2003 has been used. The term e_{Loss} is the GDP loss vector in which an element e_i^{Loss} represents the GDP loss suffered by industry i. The GDP loss calculated from equation 37 is not a real GDP loss for that year. It is the expected GDP loss, had there been an inoperability represented by vector q and it is based on the economic transactions between all the industries during the specified year. It can be said that had there been an inoperability which can be quantified by the q vector, then due to the economic relationships between industries during that year, industry i would have suffered a GDP loss of e_i^{Loss}. The loss is calculated as the reduction of end user demand which is calculated by subtracting reduced end user demand from the as planned end user demand. The net GDP loss is the sum of the GDP losses of each individual industry.

$$Net\ GDP\ Loss = \sum_{i=1}^{n} e_i^{Loss} \qquad 39$$

It should be noted that the equation which has been derived is a linear equation and the only variable in the equation is the q vector. The other terms are constant for a given year. Because, the equation is linear, the expected GDP loss has been calculated for an initial inoperability of 1% in the utility sector. The GDP loss for 2% inoperability will be twice that of 1% and so on so forth. It has been explained earlier that due to the interdependencies, the initial 1% inoperability in the utility sector produces further inoperability in other industries and this process is cyclic. Therefore, the net inoperability due to an initial inoperability of 1% in the utility sector is an inoperability vector, in which all industries will have their corresponding inoperability values.

The process of deriving the inoperability vector from the initial 1% inoperability is shown in figure 3.10. The process starts with an inoperability of 1% in industry i (or utility). Therefore, the first vector has only one nonzero component which is the inoperability of industry i. There is no inoperability in the other industries. When, there is 1% inoperability in industry i, the supply of its commodities is reduced by 1% to all industries as well as to the end users. Due to the equal impact assumption, the impact to industries and end user has been kept the same. So, there is no prioritization scheme considered. The reduction of supply from industry i has been propagated through A matrix and C vector. Then, the modified A matrix and C vector has been used to derive the reduced level of production based on equation 1. Once, the reduced level of production is derived, the inoperability vector is calculated based on equation 30. This is the inoperability vector after cycle 1. It has been explained before, that the research has considered two additional cycles to realize the impacts of sustained power outages. The inoperability vector derived after cycle 1 has been used to derive inoperability vector 2 which has been used again to derive inoperability vector 3 following the same procedure. The final inoperability vector has been used in equation 37 to calculate the expected GDP loss vector for a particular year. It should be noted that for each year there are different inoperability vector for an initial 1% inoperability. This happened because the vectors are calculated from A matrix and C vector which changed for each year between 1997 and 2016.

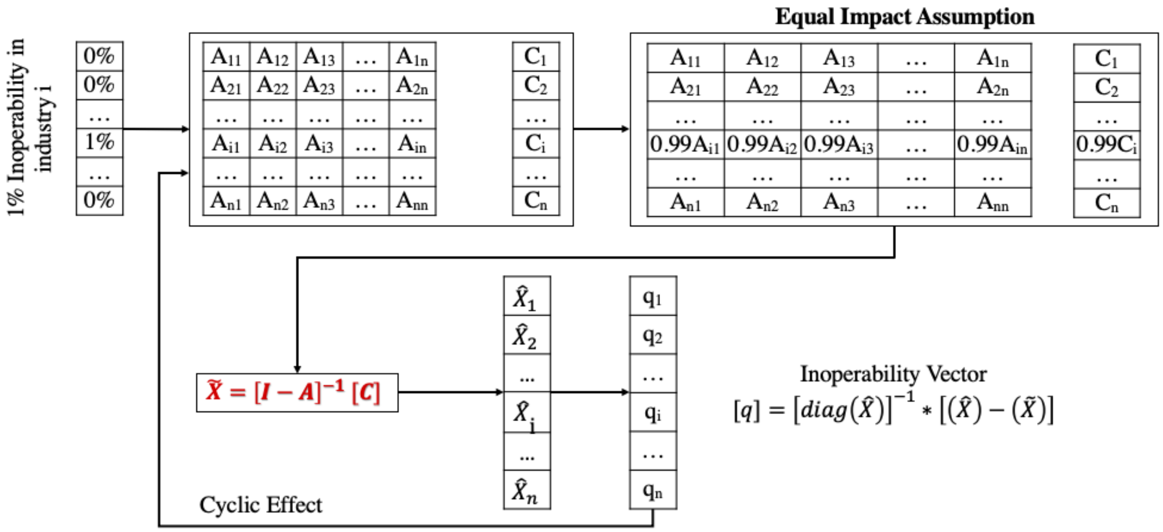


Figure 3.10 Procedure of Deriving Inoperability Vector

The same procedure has been repeated for 20 years between 1997 and 2016. For each year, there were different $\hat{V}$ matrix, $diag(\hat{X})$ matrix, A_* matrix and q vector. Therefore, there were 20 e_{Loss} vectors for each year between 1997 and 2016. The values of the GDP loss vector for a given year is driven by the economic transactions between different industries. Figure 3.11 shows the structure of the combined GDP loss vectors from all years between 1997 and 2016 for all industries. Each industry had 20 GDP loss values for each one of the 20 years of calculation.

Year Industry	1997	1998	...	...	...	2015	2016
Industry 1	$e_1^{Loss-1997}$	$e_1^{Loss-1998}$	...	...	...	$e_1^{Loss-2015}$	$e_1^{Loss-2016}$
...	...	...	...	...	...	...	...
Industry i	$e_i^{Loss-1997}$	$e_i^{Loss-1998}$	...	...	...	$e_i^{Loss-2015}$	$e_i^{Loss-2016}$
...	...	...	...	...	...	...	...
Industry n	$e_n^{Loss-1997}$	$e_n^{Loss-1998}$	...	...	...	$e_n^{Loss-2015}$	$e_n^{Loss-2016}$

Figure 3.11 Structure of the Combined GDP Vectors

Once, these vectors were derived, each industry was fitted into a triangular distribution. The selection of the distribution was based on the skewness of the data points. Each row of the matrix shown in figure 3.11 were fitted into the triangular distribution (Ahuja 1984; Chau 1995, Williams et al. 2008) based on its minimum, maximum and median values. Then a Monte Carlo Simulation (MCS) was performed for 10,000 iterations using equation 39. The test of convergence of the mean has been performed following the process suggested in Driels and Shin (2004). The outcome is shown is figure 3.12.

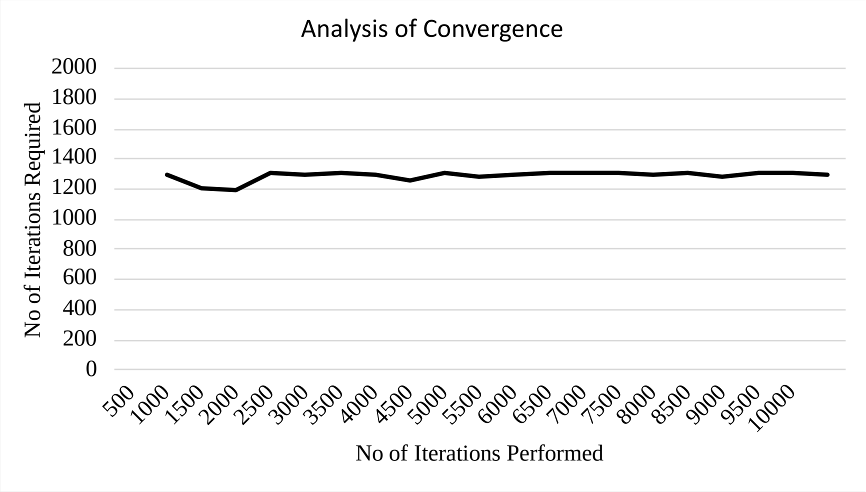


Figure 3.12 Analysis of Convergence for Monte Carlo Simulation

For 1% error on mean the numbers of iterations converged between 300 and 350. For 0.5% error on mean the numbers of iterations converged between 1200 and 1400. Thus, a sufficiently large number of 10,000 has been finalized for the number of iterations to minimize the error. The mean of the outcome of the MCS is the expected GDP loss in 2017 values for 1% inoperability in utility sector based on the historical economic transactions between industries.

3.7 Results

The research has utilized the historic make and use tables between 1997 and 2016. Both of the tables contained 71 industries and 71 commodities. Therefore, the outcome of the I-O model which is the technical coefficient matrix or A matrix for each year, contained 71 rows and 71 columns and both rows and columns represent an industry. The A matrix was used further to derive A^* matrix for each year. Once, the inoperability vector was derived as explained in the previous section, the historic GDP losses were calculated using equation 37. The historic losses for each industry were fitted into a triangular distribution and the sum of the 71 distributions were simulated for 10,000 times.

The outcome of the MCS is shown in figure 3.13. The average economic loss is $16.4 billion in 2017 values and the standard deviation is $1.5 billion in 2017 values. The outcome of the MCS is assumed to follow a normal distribution. Therefore the 95% confidence interval is calculated. The 95% confidence interval ranges from $13.4 billion to $19.4 billion in 2017 values.

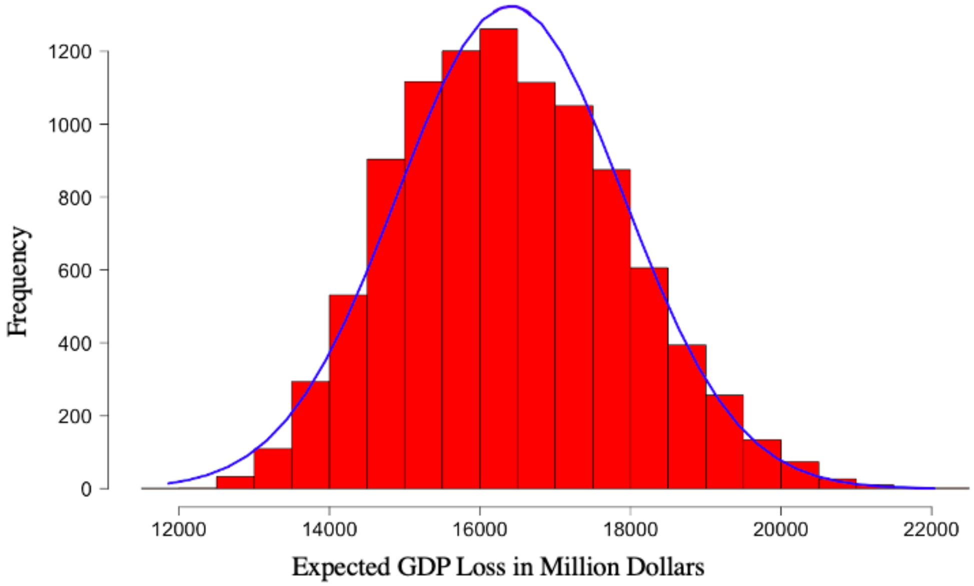


Figure 3.13 Histogram of Monte Carlo Simulation's Outcomes

It has been explained earlier, that the GDP loss estimation equation is a linear equation with only one variable which is the initial inoperability in the utility sector. Therefore, the economic loss for an initial 2% inoperability will be twice that of 1% and so on so forth. The final outcome of the research is shown in figure 3.14.

In figure 3.14 the average GDP loss is shown in red line and the lower bound (LB) and the upper bound (UB) of the 95% confidence interval is shown in black lines. It has been assumed that the expected GDP loss follows a normal distribution.

$$GDP\ Loss\ for\ 1\%\ Initial\ Inoperability \sim N(\$16.4\ Billion, \$1.5\ Billion^2) \qquad 40$$

The expected GDP loss for 2% is twice that of 1% follows linear transformation. Therefore,

$$GDP\ Loss\ for\ 2\%\ Initial\ Inoperability \sim N(\$32.8\ Billion, \$3.0\ Billion^2) \tag{41}$$

This is the reason of the expanding width of the confidence interval for higher inoperability.

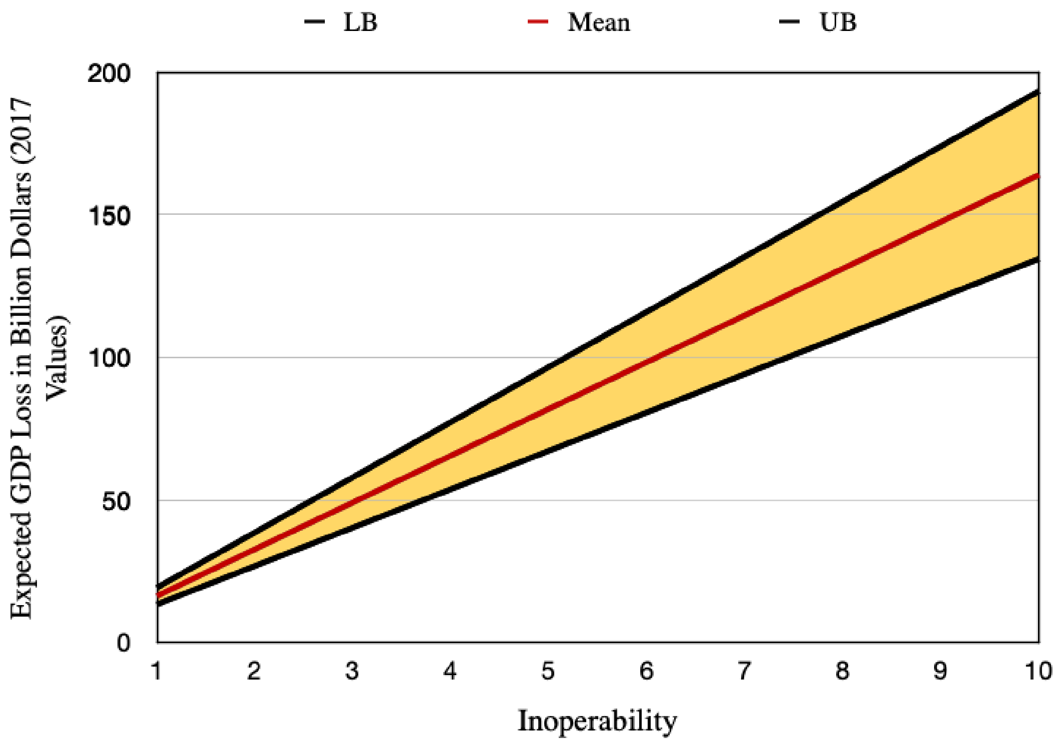


Figure 3.14 Expected GDP Loss vs Inoperability

3.8 Discussion

The net GDP loss is calculated as the sum of the GDP loss suffered by each of the 71 industries. The relative dependence on the utility sector is different for different industries. The industries which are heavily dependent on the utility are likely to incur more GDP loss and those which are less reliant are likely to suffer less loss.

Figure 3.15 shows the historic losses for all the industries. Because of the space constraint, the names of the industries in figure 3.15 have been replaced by the I-O codes of the industries. The I-O codes of all 71 industries can be found in the Appendix. The loss values are primarily influenced by the economic transaction during that year and the discount rate for that year. The average discount rates were derived from the Federal Reserve Bank database. The database shows that the year 2006 had the highest discount rate. As the total industry outputs were converted into 2017 dollars using this discount rates, this has surely influenced the historic GDP loss for that year.

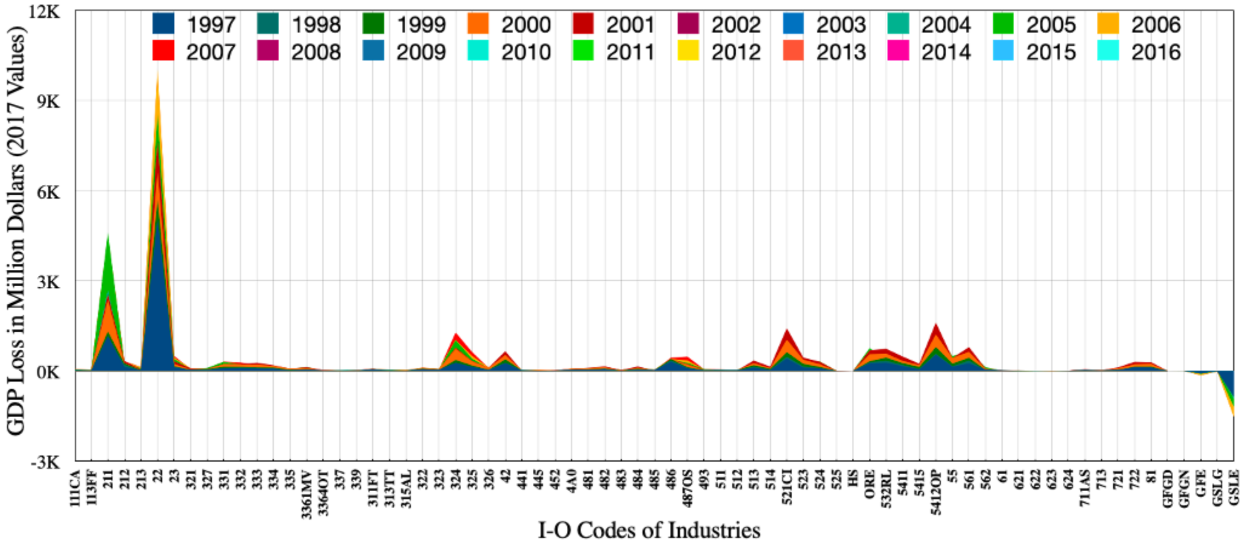


Figure 3.15 Historic GDP loss of All Industries

It can be seen from figure 3.15 that some industries have a negative GDP loss value. Three industries in particular have consistently shown negative GDP loss for all years between 1997 and 2016. They are Federal Government Enterprises (I-O Code GFE), State and Local General Government (I-O Code GSLG) and State and Local Government Enterprises (GSLE). Apparently, a negative GDP loss value indicates a gain in GDP. However, the negative GDP can be attributed to the reduction of imports by the 3 industries. The GDP or the end user demand has positive components like personal consumption expenditures, nonresidential private fixed investment in structures, residential private fixed investment, exports of goods and services etc. It also has negative component which is the imports of goods and service. The GDP of an industry is the sum of the positive and negative components. The two components can either increase, decrease or remain constant in a normal situation. In a natural disaster situation, it is more likely that the imports of some goods and service might be reduced. Therefore, the reduction of the negative component can lead to increase in GDP. However, the positive components might also increase. With the current set of data, it is not possible to explicitly mention which one of the two cases is actually happening. It might require additional information or situation specific data to conclude why some industries are having a gain in GDP when there is inoperability in utility sector.

Therefore, this research explains it as reduction of imports resulting in gain of GDP. As, the negative components are not neglected in the original GDP calculation, they have not been neglected in net GDP loss calculation in equation 39.

The industry which has faced the highest impact in terms of loss of GDP due to inoperability in utility sector is utility itself. In figure 3.15, utility (I-O Code 22) can be distinguished from all other industries. To determine the other vulnerable industries the average of the historic losses between 1997 and 2016 were calculated for each industry. Based on this average, they have been ranked. It can be seen in figure 3.16.

In figure 3.16, the industries are represented as bubbles. The bubbles which have higher diameters are the one with higher GDP losses. Utility sector has not been displayed in the figure. Other than Utility, Oil and Gas Extraction (I-O Code 211) has the highest impact followed by Miscellaneous Professional, Scientific and Technical Services (I-O Code 5412OP), Federal Reserve Banks, Credit Intermediation, and Related Activities (I-O Code 521CI), Petroleum and Coal Products (I-O Code 324), Administrative and Support Service (I-O Code 561) etc. These industries are likely to incur significant GDP loss, if there is inoperability in the utility sector.

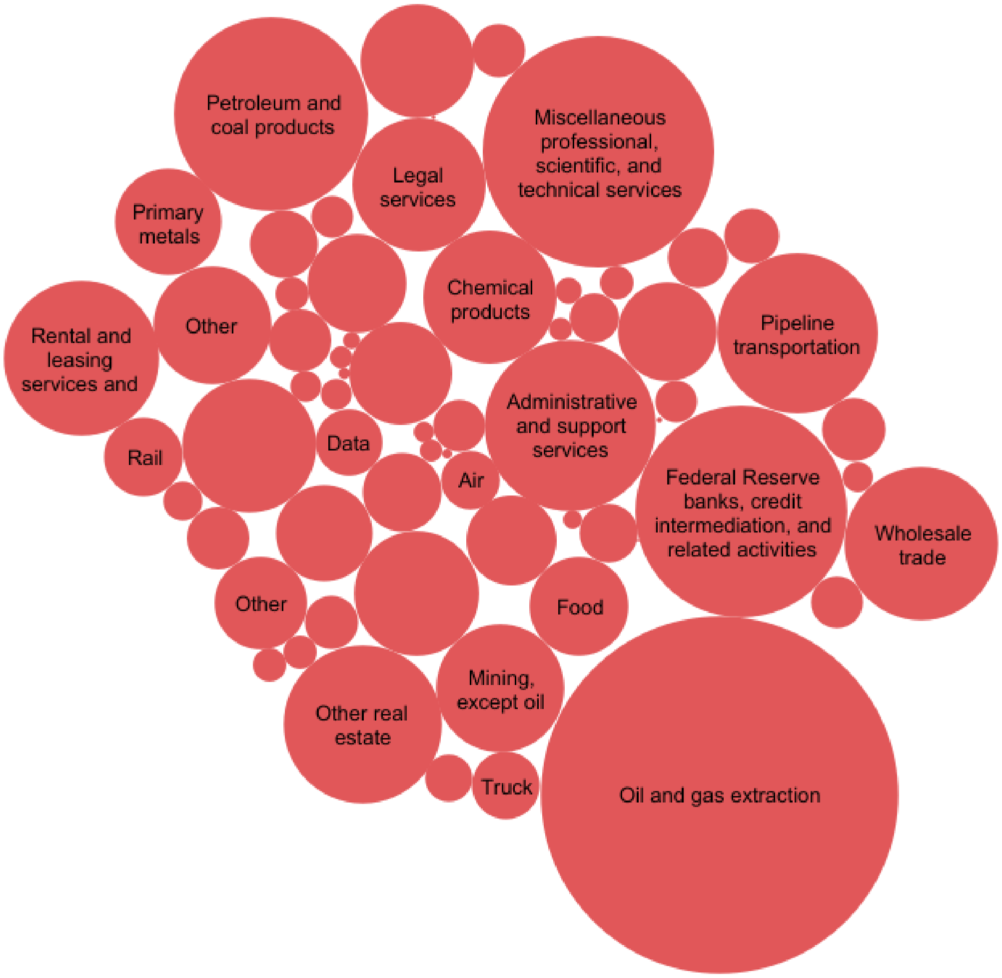


Figure 3.16 Vulnerable Industries

3.9 Conclusion

Due to climate changes and aging of electricity grid, severe weather induced power outages are getting more frequent and this trend is likely to continue. To overcome these challenges, utilities need to invest in making their system more resilient to ensure long term benefit to the stakeholders. But before investment can be planned, it is important to understand the impacts of severe weather induced power outages. This research has estimated the economic impact of weather-related power outages in terms of the nation's GDP. To achieve the objective the research has used historic data from the BEA between 1997 and 2016. The outcome of the research shows an average expected GDP loss of $16.4 billion in 2017 values for 1% inoperability in utility sector. Based on this research, it can be said that if there is an inoperability of 1% in the utility sector due to weather related incidents in a year, in 95% of the cases the expected GDP loss will be between $13.4 billion to $19.4 billion in 2017 values.

The research has developed a disaster impact assessment mechanism that considers the existing interdependencies between different infrastructures. To the best knowledge of the authors, the previous research is this domain of economic loss assessment from power outages have not considered the interdependencies between infrastructures. The power outages as an outcome of severe weather events are mostly prolonged power outages. Therefore, their impacts are not limited to utility only. All other industries which are dependent on utility also get affected. Based on this philosophy, the research has calculated the expected GDP loss due to severe weather induced power outages. The industries which are particularly vulnerable have also been identified. They are Oil and Gas Extraction (I-O Code 211), Miscellaneous Professional, Scientific and Technical Services (I-O Code 5412OP), Federal Reserve Banks, Credit Intermediation, and Related Activities (I-O Code 521CI), Petroleum and Coal Products (I-O Code 324) etc. Therefore, the outcomes of this research can be used by the decision makers for justifying the investment needs for resilience building projects in utility sector. The outcomes can also be used to plan auxiliary capacities in the industries which are more vulnerable from severe weather induced power outages. Thus, mitigating the cascading impacts.

There are certain limitations of the research. The loss calculated in this research does not contain the cost of physical damage, cost of restoration etc. It only calculates the cost associated with reduction of production output and its influence on other industries. The research has considered that the economic equilibrium between production and consumption of commodities exists in a post disaster situation which may not be true. The research has also assumed that if there is an inoperability in the utility sector, the impact is equally suffered by the industries and the end users. This may not be true. In a natural disaster situation, the power supply to essential services are often prioritized over the end users. Another limitation is related to the quantification of actual inoperability. The dataset which has been used for this research does not enlist electricity as a separate industry. It enlists utility as an industry which is comprised of electricity and two other industries: natural gas distribution industry and water, sewage and other industries. It is worth mentioning that Electricity is the single highest contributor of the three, contributing nearly 70% of the utility sectors production output. Therefore, for practical applications of the outcome of this research, this information should be kept in mind.

All the assumptions and limitations mentioned provide the setting for the future research. In future, research can be conducted by introducing different prioritization schemes in the post disaster situation and then calculating their respective economic loss. This might help in assessing different prioritization schemes. Also, research can be done to quantify the inoperability resulting from the severe weather events more effectively leveraging historical data.

3.10 Acknowledgement

Funding for this research was provided by the NSF Grant — #1728209 entitled Towards a Resilient Electric Power Grid: An Investment Prioritization Decision Framework Integrating Risks of Severe Weather- Induced Outages.

4. FRAMEWORK FOR IDENTIFYING OPTIMAL RISK REDUCTION STRATEGIES TO MINIMIZE THE ECONOMIC IMPACTS OF SEVERE WEATHER INDUCED POWER OUTAGES

Abstract: Every year power outages cost billions of dollars and affect millions of people. Historical data shows that between 2000 and 2016, 75 percentage of the outages (in terms of durations) were caused due to severe weather events. Due to the climate changes, these severe weather events are becoming more frequent. The National Association of Regulatory Commissioners have recently emphasized on the importance of building electricity sectors resilience thus ensuring long term reliability and economic benefits for the stakeholders. These severe weather events are often considered to be High Impact Low Frequency (HILF) events, which means that these events may not occur every year but when they happen the impact is likely to be debilitating. Therefore, it is imperative that the risk of power outages due to severe weather events and their economic impacts is persistent. To mitigate this risk, utilities need to invest heavily for building resilience so that the impact of these HILF events can be minimized. Under this situation, the utilities face three key questions (1) where to invest (2) how much to invest and (3) how to justify the investment. This research has established a framework for risk-based decision making for identifying optimal risk reduction strategies to minimize the economic impact of severe weather induced power outages. The risk-based decision-making framework proposed in the research has the flexibility to accommodate the risk appetite of the decision maker. The framework can be used by the investor owned utilities for rate approvals from the state utility regulatory commissions by justifying the importance of their resilience building projects to a state's economy.

4.1 Introduction

The U.S. electricity network is vast, complex socio-technical system with multiple degrees of connectivity and redundancy and it is expanded over vast geographic area (Mukherjee, Nateghi, and Hastak 2018a). The electricity grid consists of wide range of connected and interlocked components. The grid connects 5,800 major power plants and includes 450,000 high voltage power transmission lines (American Society of Civil Engineers 2011). Figure 4.1 shows the basic structure and major components of the electricity grid. The electricity is produced at generation facilities: power plants, then the voltage is stepped up by step up transformer and transported to population center through high voltage transmission lines. After arriving at the population center, the voltage is reduced at the substations by step down transformers and electricity enters the distribution system. In distribution system it travels through series of low voltage lines before reaching customer locations. Before delivering to the consumers, voltage is further reduced by transformers. Therefore, the grid can be considered to be comprised of three major components: Generation, Transmission and Distribution.

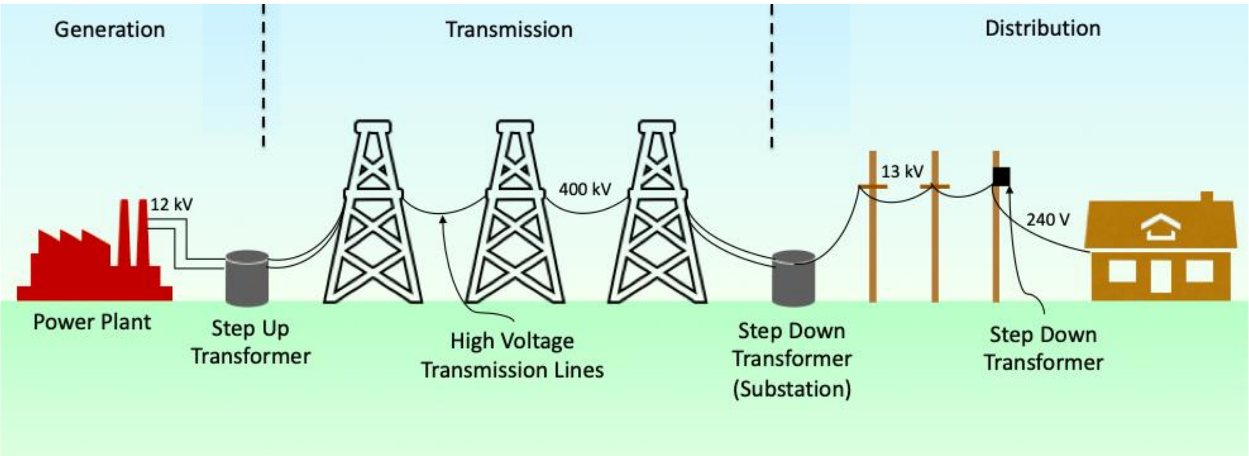


Figure 4.1 Basic Structure of Electricity Grid

The electricity grid is vulnerable to natural disasters (Kenward and Raja 2014; Mukherjee, Nateghi, and Hastak 2018a; Nateghi 2018; Yoon, Mukherjee, and Hastak 2019). In 2005, during Hurricane Katrina some 2.6 million customers in Louisiana, Mississippi, Florida, Alabama and Georgia reported power outages on August 30, 2005 (Hurricane Katrina Situation Report #11 https://www.oe.netl.doe.gov/docs/katrina/katrina_083005_1600.pdf accessed on May 3 2020). Again in 2012 super storm Sandy left over 8.5 million people without power across seven states (Kenward and Raja 2014; Mukherjee, Nateghi, and Hastak 2018a). The recent devastations of hurricane Harvey, Irma, Jose and Maria have had colossal effect on the communities in the U.S. and Caribbean islands. (Nateghi 2018). The U.S. Department of Energy (DoE) requires the utilities to report any major outage by in which at least 50,000 customers get affected for at least an hour or the power supply disturbance more than 500 megawatt or the demand exceeded by at least 100 megawatts by filling out a survey form called OE-417 (https://www.oe.netl.doe.gov/oe417.aspx, accessed on March 16, 2020). The historic data of such outages show that severe weather events are the predominant cause of major power outages. A report published by the Executive Office of The President (August 2013) estimated that between 2003 and 2012 weather related outage events have costed U.S. an inflated annual average of $18 billion to $33 billion. The annual cost fluctuated over the years and are maximum when any major hurricanes took place. In 2008 Hurricane Ike happened. The outages cost in 2008 was approximately $40 billion to $75 billion. In 2012 when super storm Sandy devastated the east coast, the said cost was approximately between $27 billion to $52 billion. Another Congressional Research (Campbell 2012) estimated the annual cost of power outages to be between $20 billion to $55 billion.

These severe weather events are called High Impact Low Frequency (HILF) events, which means these events may not occur every year but whenever it occurs the impact is likely to be catastrophic. Therefore, the risk due to these HILF events are ever present. Moreover, the climate changes are making these events more frequent and this trend is likely to continue (Kenward and Raja 2014). To overcome this challenge, utilities need to invest heavily in making their system robust, reliable and resilient to ensure long term economic benefit. The American Society of Civil Engineers in 2011 predicted an investment gap of $673 billion by 2020 in modernizing the grid (American Society of Civil Engineers 2011). The utility sector is highly regulated. Utilities need the approval from the state utility regulatory commissions for increasing the rate to recover the cost of capital projects. The state regulatory commissions are responsible to oversee the utilities' financial responsibility and approval of utility capital investments do not consider the risks of severe-weather induced power outage risks in their regulatory process (Regulatory Assistance Project 2011). In fact, the approval by the State Utility Regulatory Commissions for investments to improve the grid resilience can be biased (Keogh & Cody 2013). Under this situation, utilities face three key question (1) where to invest, (2) how much to invest and (3) how to justify the investment. This research is intended to answer the three key questions so that utilities can invest proactively in making their system robust, reliable and resilient and at the same time can smoothly get approval from the regulatory bodies.

This research has developed a framework that can use the impact of severe weather induced power outages on a State’s economy to identify the optimal risk reduction strategies under different budget situations so that the economic loss due to severe weather induced power outages can be minimized. The framework uses Inoperability Input-Output model to assess the economic impacts of severe weather induced power outages and uses that in a Benefit-Cost Analysis based optimization framework to find the optimal scope of different strategies. In the benefit cost analysis, the benefit is defined as the reduction of economic loss for a particular state. Therefore, economic loss due to power outage is calculated at the state level and it will change from one state to another state. Hence, the utilities need to recalculate the economic loss value for different states before applying it in the framework. The framework has the flexibility to incorporate the risk appetite of the decision makers. Five levels of risk appetites have been defined. The risk appetite determines the scope of the resilience building projects and the budget requirements. The framework can be used by the investor owned utilities for rate approvals from the state utility regulatory commissions by justifying the importance of their resilience building projects to the state’s economy.

4.2 Literature Review

Vulnerability of the electricity grid can be associated with the vulnerability of the major components. During a natural disaster a generation plant might fail, transmission lines might fail also distribution lines might fail. The failures can happen in combination as well. But some components tend to fail more than the others.

Zhou, Pahwa, and Yang (2006) stated that in relation to reliability issues, the overhead distribution lines distinguish themselves from the other components. They also mentioned that the overhead distribution lines are the most vulnerable component in the distribution system. NEI Electric Power Engineering (2009) have also mentioned that the distribution system is the most vulnerable in the grid. They said that transmission related failure only accounts for less than 2% of all outages. Silverstein (2011) have reiterated the fact that distribution lines cause more power outages. In that report, it has been mentioned that 90% of the customer outages minutes are due to failure in the distribution system. The rest 10% belongs to generation and transmission system. But these are big outage events. However, Kenward and Raja (2014) have a different opinion about the vulnerable component of electricity grid. In their report, they have said that between 1984 and 2012, during severe weather events most of the outages come from the damage to large transmission lines and electric substations, as opposed to distribution systems. Again, Bhat and Meliopoulos (2016) have proposed a different thought. They said that presently, the transmission networks are built in such a way to withstand high wind speed. But distribution systems are very vulnerable. Therefore, they developed a tool that can identify the vulnerable areas and breakage points of the distribution networks. Eto (2016) has also repeated that distribution systems are the most vulnerable component of the grid system. He has reckoned that failures on the distribution systems during weather-related events are typically responsible for more than 90% of the outages both in terms of durations and frequency. However, the infrequent damage on the transmission system can result in more wide-spread power outages. Qazi (2017) has said that events like hurricanes and earthquakes affect distribution system much more than the generation and transmission system. The U.S. Department of Energy in their Quadrennial Energy Report (U.S. Department of Energy 2017) states that the overhead distribution system is at the most risk during hurricanes and winter storms or ice or snows followed by the transmission system. Also, the overhead distribution systems under extreme severe weather events like hurricanes (>category 3) or floods (>100 year) have the opportunity to improve their risk management practices. Therefore, it has been concluded that distribution system is the most vulnerable portion of the electricity grid.

The risk factors are the primary causes of severe weather induced power outages. There are plethora of research articles available that tried to find the causes of power outages but very few of them focused explicitly on the severe weather induced power outages. Mukherjee, Nateghi, and Hastak (2018a) have used historical data to develop a 2-stage hybrid risk estimation model. The model has identified risk factors for outages durations and number of customers affected based on historical data between 2000 and 2016. The historical power outage data of different states were analyzed using advanced machine learning algorithms. The research shows that for extreme event, the 5 most predominant risk factors contributing to the durations of power outage for a state are: Types of Severe Weather Events, Area of overhead transmission and distribution lines, Investment in Regular Operation and Maintenance, Topology of Power Distribution in Rural Region, Extent of Metropolitan Area in the State. Nateghi (2018) has proposed a data driven multivariate analysis to model the complex interplay between stochastic hazards, system topology and topology of the region to approximate multidimensional resilience of electricity grid. The research has used data from a utility based in the gulf region. Tree based algorithms have been used to identify the most influencing variables for number of customers affected, outage duration and outage counts. The results show that for predicting outage duration, the 5 most influencing variables are: number of customers, tree trimming frequency, open space, soil moisture and wind speed. Taylor (2015) has analyzed Duke Energy's outage data during major events. Each of these events were verified by a field engineer. The dataset contained 2 years of data and 906 data points. The results show that almost 72% of the outages were caused due to vegetation related incidents, 9% due to equipment failures and 2% due to pole failures. There are various other causes like: protective device malfunctioning, accident, mid span fault etc. The Electric Power Research Institute (EPRI) in their technical report on "Distribution Grid Resiliency: Overhead Structures" (EPRI 2015a) have mentioned that for Eversource utility between 2008 and 2015, approximately 91% of the outages during hurricanes were caused due to vegetation, the number goes down to 74% for tropical storms and 66% for tornadoes. Evidently, vegetation is one of the major causes of severe weather induced power outages. Qazi (2017) has also identified that causes of severe weather induced power outages. He has listed Sagging of Lines into Vegetations, Falling Tree, Shorting of Line by Lighting, Lack of Monitoring, Overheating of Lines due to Imbalance between Power Generation and Load, Flooding, Snow & Ice are they primary causes of power outages. Wang (2016) have mentioned External Factors (Burglar, Construction, Vehicle, Fire etc.), Natural Factors (Lightning, Typhoon/Hurricane, geologic hazards, flood/earthquake, snow/rain), Improper Maintenance (Tree, Animal, Untimely Defect Elimination/Maintenance, Over Voltage etc.), Improper Installation, Equipment Failure, Customer Causes are the probable causes of power outages. Alhelou et al. (2019) have analyzed 66 major power outage data across the globe between 2011 and 2019. They found that 50% of the outages are caused due to weather or trees, followed by faulty equipment, accident, animals and over demand. Based on the above evidences, this research has considered three major risk factors: vegetation related risk, equipment failure and pole related incidents. It should be noted that the list of risk factors is not exhaustive. Utilities can identify risk factors based on historical data and use them for decision making.

For risk-based decision making it is essential to quantify the risk. Garrick (2008) has defined risk as a function of scenario, likelihood and consequence. The likelihood is the probability of a scenario and the consequence is the impact of the scenario occurring. From a severe weather induced power outage’s perspective consequence can be the economic impact of the power outages. The calculation of probability can be based on classical probability theory or can be based on relative frequency of events. Winkler (1996) has said that for relative frequency approach, the real challenge is the availability of appropriate data set. He also stated that as long as the calculations are based on the assumptions of equally likely outcomes, the approach of relative frequency can be certainly utilized in the Probabilistic Risk Assessment (PRA). Thompson and Graham (1996) have stated how efficiency can be incorporated in a risk control alternative. The efficiency of a risk reduction strategy is the percentage reduction of risk due to the implementation of the strategy. This efficiency can be further used in cost effectiveness analysis. The research has also explained the application of risk in the Benefit-Cost analysis. Khadam and Kaluarachchi (2003) have said that a rational public policy only considers a management plan if the benefit exceeds the cost. However, there are few shortcomings of Risk-Cost-Benefit (RCB) analysis. One of them is the improper representation of cost of failure. The failure cost can never be precisely estimated. Therefore, they have developed a framework for multi-criteria decision analysis to compare different alternatives for the management of contaminated ground water.

For risk-based decision making it is necessary that the data reflects the risk information. However, the current practice of data collection has some limitations which has been highlighted by the Electric Power and Research Institute (EPRI 2015b). In their report they have mentioned that the limitations of the outage related data collection hinder benefit-cost analysis-based decision-making process. The limitations can be attributed to the incompleteness of the data. Most of the data collected represents the activities during restoration period. Because at that time utilities are immersed in restoring power as quickly as possible, they fail to collect necessary data. They have suggested a data collection format which will facilitate the benefit-cost analysis-based decision making. The suggested data collection format collects four types of information: basic information, construction details, operational details and vegetation details. It should be noted that the format suggested by EPRI (2015b) is intended to facilitate benefit-cost analysis-based decision making. For risk-based decision making, the format may not suffice the requirements. National Academy of Sciences, Engineering, and Medicine (2017) have emphasized upon the fact that good data on the causes of power outages, their probabilities and spatial and temporal distribution are essential for resilient operation of grid system. Therefore, government and other responsible parties should support strengthening the data collection activities. U.S. Department of Energy (2017) have reiterated the fact that information sharing can mitigate the threat to the risk.

4.3 Economic Loss due to Severe Weather Induced Power Outages

The benefit cost analysis-based optimization framework proposed in this research requires the assessment of the economic loss due to severe weather induced power outages for a state. The framework quantifies the benefit from a strategy as the reduction of expected economic loss after implementation of the strategy. So, the economic loss assessment is required. In this research, the economic impact of severe weather induced power outages on a state's economy is expressed in terms of loss of Gross Domestic Product (GDP) for a state. For that Inoperability Input-Output Model (IIM) has been used (Haimes and Jiang 2001; Haimes et al. 2005; Santos and Haimes 2004). The reduction of serviceability of a disaster impacted infrastructure can be defined as the inoperability. For GDP loss assessment, cascading impacts of weather-related power outages have been considered. The power outages due to natural disasters are normally prolonged power outages. Therefore, the impact is not limited to the utility sector. When there is a sustained power outage, due to interdependencies between industries, other industries which are dependent upon utility sector also get affected. Those affected industries also affect other industries which are downstream in the supply chain. This impact is cyclic. This means that the affected industries increase the inoperability in the utility sector and the process continues. Therefore, to estimate the GDP loss it is essential to understand the interindustry relationships.

For developing the inter-industry relationships this research has used Input-Output Model (I-O Model) proposed by Wassily Leontief (Leontief 1951,1986). The fundamental principle behind the I-O model is the equilibrium of commodities produced by an industry and its consumption by different industries and end users. This equilibrium can be expressed as an equation:

$$X = AX + C \qquad 42$$

Where, A is Leontief's technical coefficient matrix which represents the relationship between different industries, X is the vector representing the production output of the industries in dollars and C is the final demand vector in dollars. The procedure of deriving the inter-industry relationships can be found in Planting (2006).

$$A = \hat{V}\hat{U} \tag{43}$$

$$C = \hat{V}e \tag{44}$$

Where, $\hat{V}$ is the normalized make matrix after scrap adjustment, $\hat{U}$ is the normalized use matrix and e is the end user demand vector.

It has been assumed that the interindustry relationships at a national level also holds true at state level. Hence, the inter-industry relationships were derived at national level using Bureau of Economic Analysis's 20 years of Make and Use Table between 1997 and 2016. The Make and Use table with 71 industries and 71 commodities were used in this research.

Once the A matrices are derived for 20 years, they have been used in IIM. The Inoperability in IIM has been defined as the percentage reduction in as-planned production (Haimes et al. 2005; Santos and Haimes 2004) and it is calculated on annual basis. For developing IIM, it has been assumed that the interindustry relationships exist in a post disaster situation and the impact of inoperability is equally shared by industries and end users.

In pre-disaster situation, let $\hat{X}$ be the as planned production and $\hat{e}$ be the as planned end user demand. Then, Leontief's balance equation states that,

$$\hat{X} = A * \hat{X} + \hat{V} * \hat{e} \tag{45}$$

It has been assumed that the balance between the production and consumption of commodities exists in a post disaster situation. Let $\tilde{X}$ be the reduced level of production and $\tilde{e}$ be the reduced level of end user demand. Then based on equilibrium assumption,

$$\tilde{X} = A * \tilde{X} + \hat{V} * \tilde{e} \tag{46}$$

By subtracting equation 46 from equation 45, the balance between the reduction in production and the reduction in final demand due to reduction in production can be found.

$$\hat{X} - \tilde{X} = A * \left[\hat{X} - \tilde{X}\right] + \hat{V} * [\hat{e} - \tilde{e}] \tag{47}$$

To derive the unit reduction in production the equation 48 is derived.

$$\begin{gathered}\left[diag\left(\hat{X}\right)\right]^{-1} * \left[\left(\hat{X}\right) - \left(\tilde{X}\right)\right] \\ = \left[diag\left(\hat{X}\right)\right]^{-1} * [A] * \left[\left(\hat{X}\right) - \left(\tilde{X}\right)\right] + \left[diag\left(\hat{X}\right)\right]^{-1} * [\hat{V}] * [(\hat{e}) - (\tilde{e})]\end{gathered} \tag{48}$$

The left hand side of the equation 48 is the inoperability vector defined by Santos and Haimes (2004), Haimes et al. (2005). They have also developed a new matrix (A_*) which also captures the interindustry relationships. The inoperability vector q can be defined as equation 49

$$[q] = \left[diag(\hat{X})\right]^{-1} * [(\hat{X}) - (\tilde{X})] \qquad 49$$

And,

$$[A^*] = \left[diag(\hat{X})\right]^{-1} * [A] * \left[diag(\hat{X})\right] \qquad 50$$

When, equation 49 and 50 are replaced in equation 48, it becomes

$$[q] = [A^*] * [q] + \left[diag(\hat{X})\right]^{-1} * [\hat{V}] * [(\hat{e}) - (\tilde{e})] \qquad 51$$

$$[(\hat{e}) - (\tilde{e})] = \left[\hat{V}\right]^{-1} * \left[diag(\hat{X})\right] * [I - A^*] * [q] \qquad 52$$

$$[e^{Loss}] = \left[\hat{V}\right]^{-1} * \left[diag(\hat{X})\right] * [I - A^*] * [q] \qquad 53$$

Equation 53 is a linear equation and the only variable in the equation is the q vector. The other terms are constant for a given year. Because, the equation is linear, the expected GDP loss has been calculated for an initial inoperability of 1% in the utility sector. The GDP loss for 2% inoperability will be twice that of 1% and so on so forth.

The process of deriving the inoperability vector from the initial 1% inoperability is shown in figure 4.2.

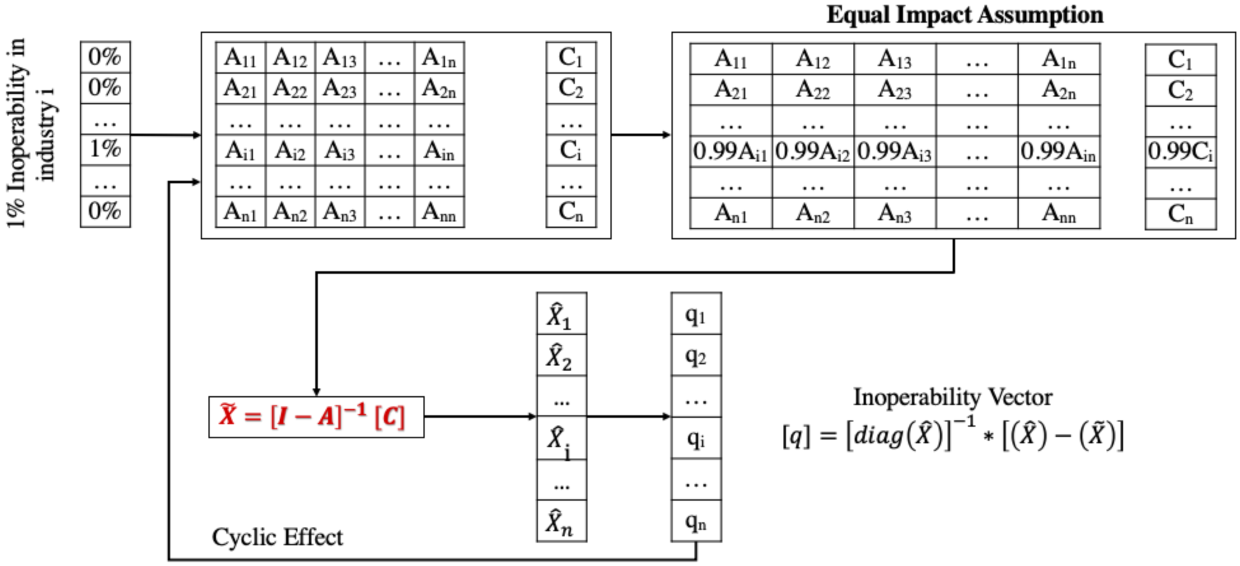


Figure 4.2 Procedure of Deriving Inoperability Vector

The process starts with an inoperability of 1% in industry i (or utility). In the first vector, only industry i has an initial inoperability of 1%. Therefore, the supply from industry i to all industries and end users is reduced by 1% (based on equal impact assumption). The modified A matrix and C vector were then used to calculate the $\tilde{X}$ vector based on equation 42. Once, $\tilde{X}$ vector is derived, it is further used to derive the inoperability vector q after cycle 1 using equation 49. To realize the impacts of sustained power outages, this research has considered two additional cycles. The inoperability vector derived after cycle 1 is used to derive inoperability vector 2 which is again used to derive the inoperability vector 3. The final vector after third cycle is used for GDP loss estimation.

The variables in equation 51 are calculated at national level. Therefore, this equation is used for calculating GDP loss at national level. To calculate the GDP loss at state level, the variables need to be brought down to the state of interest. It has been assumed that the inter-industry relationships derived at national level are true at state level. This can be explained with a simple example. Suppose at national level, out of the total production input of industry A, y% is coming from industry B. It is assumed that relationship is uniform across all states. So, if a state has the presence of industry A and industry B then the proportion in which industry B's product is consumed by A in that state is y%. Based on this assumption, the matrices $\hat{V}$ and A_* derived for national level analysis can be used for state level calculation. The inoperability vector is derived based on the inter-industry relationships. As the inter-industry relationships are same at both national and state level, the inoperability vector derived at national level is valid for state level. The only variable which needs to be calculated at state level is the production output of each industry. The production output of each industry will be different for different states. To calculate the production output of an industry at state level, state level multipliers are proposed. The derivation of state level multipliers is based on the assumption that the output of an industry in a state is proportional to the employment generated by that industry in that state. The information of employment created by an industry in a state is available at the Bureau of Labor Statistics (BLS). For deriving the state level multipliers, the state level and national level employment information of all 71 industries in the I-O tables (make and use tables) were collected for the year 2017 (https://data.bls.gov/cew/apps/data_views/data_views.htm#tab=Tables accessed on February 27 2020). The multiplier can be formulated as equation 54

$$Multiplier\ of\ Industry\ i\ for\ a\ State = \frac{Employment\ Created\ by\ Industry\ i\ in\ that\ State}{Employment\ Created\ by\ Industry\ i\ at\ the\ national\ level} \quad 54$$

For the state of interest, the multipliers are created for all 71 industries. The multipliers for all 71 industries together form the multiplier vector, which is used to calculate the state level production of industries.

$$\hat{X}_{State} = \hat{X}_{National} \times Multiplier\ Vector\ of\ a\ State \quad 55$$

Where, $\hat{X}_{State}\ and\ \hat{X}_{National}$ are the as planned production output vector at state and national level respectively. The multipliers were created using 2017's employment information. Thus, the production output of each industry at national level was converted into 2017 values before using them in equation 55. The discount rates used for the conversion were derived from Federal Reserve Bank Database (https://fred.stlouisfed.org/series/INTDSRUSM193N, accessed on February 3, 2020). The database had discount rates since 2003. Therefore, for all the years before 2003, the discount rate of 2003 has been used.

Finally, the GDP loss vector is derived as equation 56

$$[e^{Loss}] = [\hat{V}]^{-1} * [diag(\hat{X}_{State})] * [I - A^*] * [q] \quad 56$$

So, if the production of the industries is reduced, less amount of commodity will be delivered to the end users, which will cause loss of GDP for the State.

Where, $$[e^{Loss}] = \begin{bmatrix} e_1^{Loss} \\ \vdots \\ e_i^{Loss} \\ \vdots \\ e_n^{Loss} \end{bmatrix} \quad 57$$

The term e_i^{Loss} represents the GDP loss suffered by industry i. The GDP loss calculated from equation 56 is a not a real GDP loss for that year. It is the expected GDP loss, had there been an inoperability represented by vector q and it is based on the economic transactions between all the industries for a specific year. The net GDP loss is the sum of the GDP losses of each individual industry.

$$Net\ GDP\ Loss = \sum_{i=1}^{71} e_i^{Loss} \quad 58$$

The same procedure has been repeated for 20 years between 1997 and 2016. Therefore, there were 20 e_{Loss} vectors for each year between 1997 and 2016. The values of the GDP loss vector for a given year is driven by the economic transactions between different industries. Once, these vectors were derived, each industry was fitted into a triangular distribution (Ahuja 1984; Chau 1995, Williams et al. 2008). The selection of the distribution was based on the skewness of the data points. Then a Monte Carlo Simulation (MCS) was performed for 10,000 iterations using equation 58. The test of convergence of the mean has been performed following the process suggested in Driels and Shin (2004). The outcome is shown in figure 4.3.

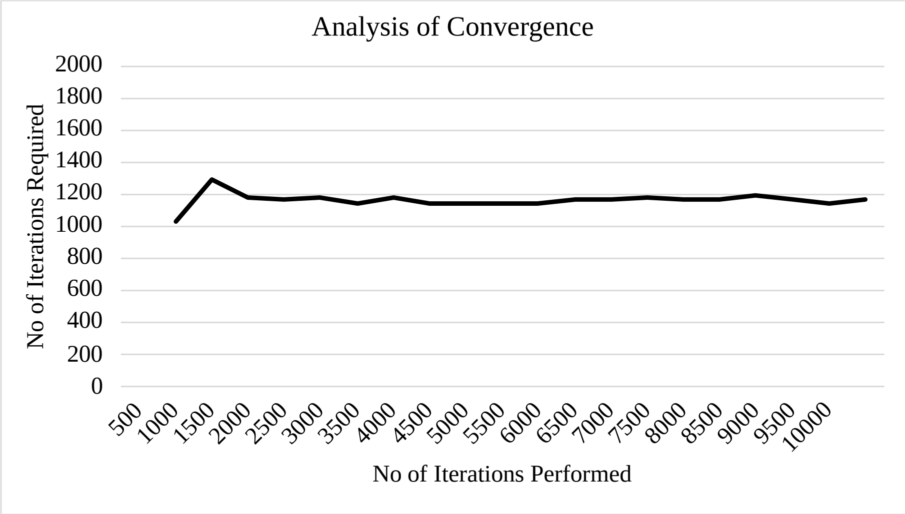


Figure 4.3 Analysis of Convergence for Monte Carlo Simulation

For 1% error on mean the numbers of iterations converged around 300. For 0.5% error on mean the numbers of iterations converged around 1200. Thus, a sufficiently large number of 10,000 has been finalized for the number of iterations to minimize the error. The mean of the outcome of the MCS is the expected GDP loss in 2017 values for 1% initial inoperability in utility sector based on the historical economic transactions between industries.

For the state of Indiana, the expected GDP loss for 1% inoperability in the utility sector is $274.5 million in 2017 values. The expected GDP loss is assumed to follow a normal distribution. Therefore, the 95% confidence interval ranges between $227.7 million and $321.2 million in 2017 values.

4.4 Risk Propagation Mechanism

The risk propagation mechanism is the fundamental principle for the framework. It is shown in figure 4.4. The hazards in figure 4.4 are the natural hazards like: hurricanes, severe storms, floods, snow, ice etc. The hazards will vary for different geographic locations. For example, in the Midwest natural hazards like snow and ice are predominant but for the states in gulf region snow and ice are not dominant.

During a natural disaster, the risk factors get triggered which in turn causes damage to the electricity grid. This can be explained by a simple example. Heavy wind during a hurricane or severe storm can engender trees to fall over the distribution lines and break the line which can cause power outage. Therefore, trees falling over distribution lines is a risk factor. Again, the flood in the aftermath of a major hurricane can inundate the electric substations. The inundation of electric substations by flood water can also cause power outage. So, the flooding of the substations or the equipment failure due to the flooding is another risk factor. It has been assumed in the mechanism that the risk factors are independent of each other. Therefore, the total impact of all risk factors is the sum of the individual impacts of each risk factor. This research has considered three risk factors: vegetation related failures, equipment failures, pole related failures. But this list of risk factors is not exhaustive. There can be several other risk factors. Utilities can add risk factors based on historic evidences.

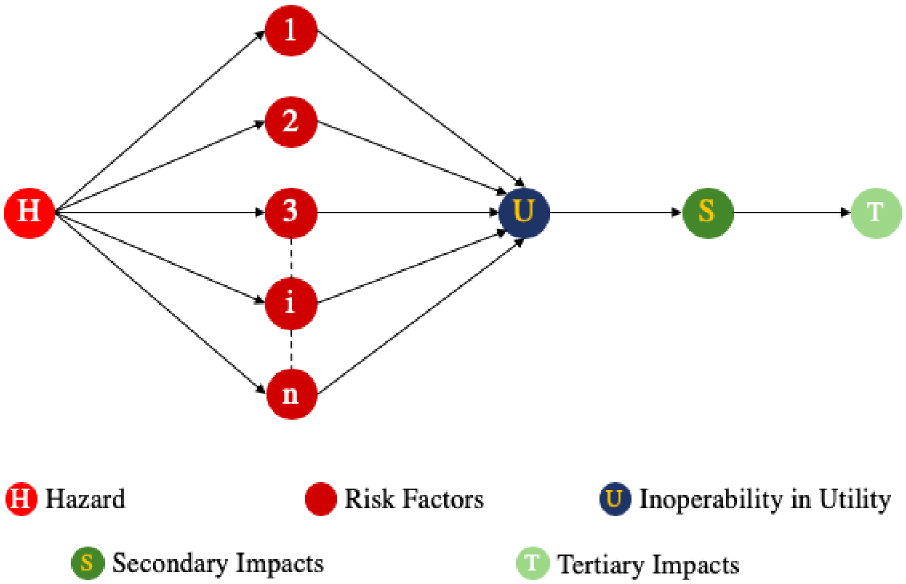


Figure 4.4 Risk Propagation Mechanism

The impact of the power outage can be quantified as the inoperability in the utility sector. Inoperability can be defined as

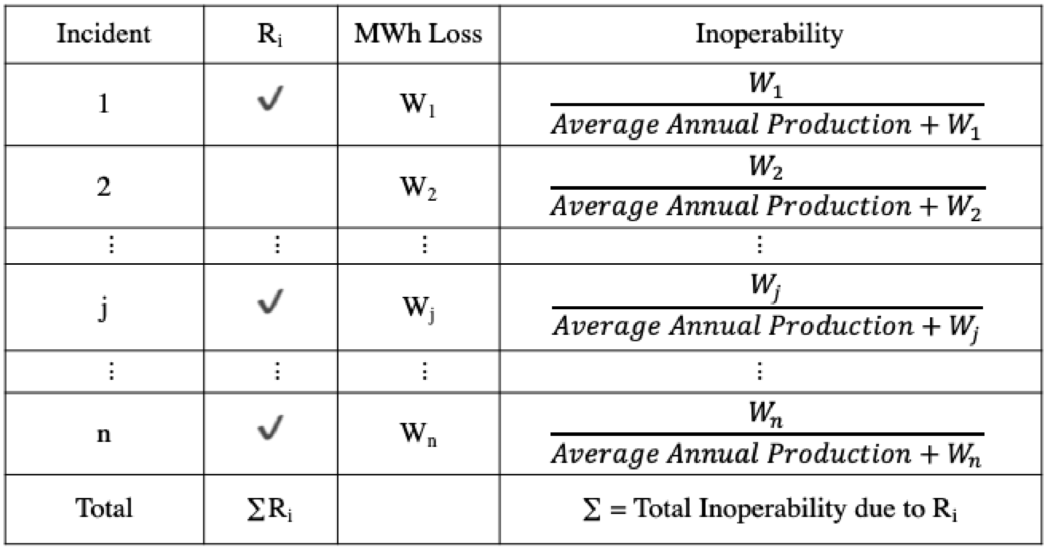
$$Inoperability = \frac{Loss\ in\ Production\ in\ MWh}{Reduced\ Level\ of\ Production\ in\ MWh + Loss\ in\ Production\ in\ MWh} \quad 59$$

Suppose, a state on an average produces 100 MWh of electricity annually. During a natural disaster, one particular utility faces a production loss of 0.5 MWh. Then, inoperability can be calculated as 0.5 divided by the sum of 100 and 0.5, which is 0.49%. The proposed framework is expected to be used by the utilities for planning optimal risk reduction strategies and getting them approved from their respective state utility regulatory commissions. Therefore, the analysis is done at state level. For different states, the calculation will be different, but the procedure will remain the same. Due to the interdependencies, the inoperability in utility sector induces inoperability in other industries, which again induces inoperability in industries which are downstream in the supply chain.

For risk-based analysis, it essential to collect risk data in a format that facilitates such analysis. The proposed framework has certain data requirements before it can be used. Thus, an annual database format has been suggested, for the effective application of the framework.

4.5 Annual Database Format

The database format helps the aggregation of data in such a way to facilitate the application of the proposed benefit cost analysis-based optimization framework. Data should be collected in the proposed format on annual basis. That is why it is called the annual database format. The database format is shown in figure 4.5. For the database, it has been assumed that the utilities can record the inoperability after a natural disaster event following equation 59. It has also been assumed that if there are m numbers of risk factors, their occurrence is independent of each other. Therefore, the net impact of m risk factors in a given year is the sum of the impacts from each risk factor in that year. The database has to be prepared for each individual risk factors. So, if there are m risk factors, then m databases as shown in figure 4.5 has to be prepared.



Incident	R_i	MWh Loss	Inoperability
1	✓	W_1	$\frac{W_1}{Average\ Annual\ Production + W_1}$
2		W_2	$\frac{W_2}{Average\ Annual\ Production + W_2}$
⋮	⋮	⋮	⋮
j	✓	W_j	$\frac{W_j}{Average\ Annual\ Production + W_j}$
⋮	⋮	⋮	⋮
n	✓	W_n	$\frac{W_n}{Average\ Annual\ Production + W_n}$
Total	$\sum R_i$		$\sum$ = Total Inoperability due to R_i

Figure 4.5 Annual Database Format

In the database, incidents are the severe weather events during which power outages were recorded. Utilities normally captures this information as Major Event Days (MED). A major event day can be defined as the day in which the daily system average interruption duration index (SAIDI) exceeds a threshold value (IEEE-1366 2012). A major event day might occur due to various reasons other than the severe weather events. But for this database, the incidents are the MEDs which are caused due to severe weather-related incidents only. In the database shown in figure 4.5, n numbers of such MEDs were recorded in a given year, which means that during the given year there were n numbers of distinct severe weather induced power outages.

The second column indicates occurrence of a risk factor i during the recorded MEDs in a given year. If falling of trees over distribution lines is a risk factor, then this column captures the number of times trees fell over distribution lines and caused power outages. The sum of this column gives the total number of occurrences of risk factor i in a given year.

The third column shows the power loss in MWh during each occurrence of the risk factor i. The current form of major power outage reporting of DoE (OE-417) requires utilities to report the peak demand loss during any major power outage. But this reporting of peak demand loss is not mandatory. For this database, it has been assumed that the utilities can collect this information effectively.

The final column of the database calculates the inoperability for each occurrence of risk factor i based on the equation 59. The average annual production of the utility in MWh is used in the denominator. Evidently, the average annual production is less than the As-Planned production because it contains the loss of production due to external disturbances. Therefore, the sum of the MWh loss and the average annual production leads to the As-Planned production of the utility. The sum of this column is the total inoperability due to the occurrence of risk factor i in a given year. In the same way, the database has to be prepared for the other risk factors.

Once, the database is prepared, it can be used to derive three parameters (1) the number of MEDs which were caused due to severe weather events in a given year (2) the percentage occurrence of risk factor i given the MEDs due to severe weather events in a given year and (3) the average inoperability as an outcome of the occurrence of risk factor i in a given year.

$$RF_i = \frac{\sum R_i}{MED} \tag{60}$$

$$q_{R_i} = \frac{Total\ Inoperability\ due\ to\ R_i}{\sum R_i} \tag{61}$$

Where, MED is the count of severe weather induced power outages in a given year, $\sum R_i$ is the total count of occurrence of risk factor i in a given year, RF_i is the percentage occurrence of risk factor i during severe weather induced power outages in a given year and q_{R_i} is the average inoperability as an outcome of the occurrence of risk factor i in a given year. For effective analysis, the database needs to be prepared for multiple years to derive the average values of the parameters.

It has been assumed that the risk factors are independent of each other. Therefore, the total inoperability in that year due to severe weather induced power outages is

$$q_{Total} = MED \times \sum_{i=1}^{m} RF_i \times q_{R_i} \tag{62}$$

Where, q_{Total} is the total inoperability in the year due to severe weather induced power outages and m is the number of independent risk factors.

In the previous section the net economic loss due to the severe weather induced power outages has been estimated for 1% annual inoperability in the utility sector. The economic loss has been estimated as the expected GDP loss for a state. The economic loss considers the existing interdependencies between industries in the state and calculates the cascading economic impact as an outcome of the production loss due to severe weather events. Equation 62 calculates the net annual inoperability for a utility. If the said utility contributes p% of the total annual electricity production of a state, then the expected economic loss due to the said utility's annual inoperability can be estimated as

$$Annual\ Economic\ Impact = MED \times \sum_{i=1}^{m} \left(RF_i \times q_{R_i}\right) \times p\% \times e_{1\%}^{Loss} \qquad 63$$

Where, $e_{1\%}^{Loss}$ is the expected GDP loss for the state due to 1% annual inoperability in the utility sector in that state. The equation 63 is the basis for the benefit cost analysis-based optimization framework.

4.6 Risk Reduction Strategies

Vugrin et al. (2010) have identified three types of system capacity requirements that make the system resilient. Those are: Absorptive, Adaptive and Restorative capacities. Absorptive capacity is the degree to which a system can absorb the impacts of system perturbation and minimize the consequence. It is an endogenous feature of the system. Adaptive capacity is the ability of the system to adapt endogenously throughout the recovery process. It is the capability of self-organization for the recovery of the system. The Restorative capacity is the ability to be repaired easily in the aftermath of a system disruption. This research has been focused on the strategies that enhance the absorptive capacities of the electricity grid i.e. the strategies that make the system more robust to natural disasters.

National Academy of Sciences, Engineering, and Medicine (2017) have identified multiple strategies to prepare for and mitigate risk of large-scale blackouts. They are component hardening, vegetation management, selective undergrounding, reinforcement of poles and towers, dead-end structures, water protection, smart grid initiatives such as distributed energy resources, utility-scale battery storage etc.

Out of the risk reduction strategies, selective undergrounding has been widely regarded by the researchers. Larsen (2016) has found that selective undergrounding of transmission and distribution lines can be beneficial for utilities. Although, it is claimed that the cost of such undertakings are more than benefits derived from it, he has found that the benefits from undergrounding can exceed the cost by reducing power outages. He has also stated that there are number of factors that can influence the dominance of this benefit over its cost like age of existing overhead structure, capital cost of undergrounding, assumed value of lost load to customers, degree to which reliability can be improved and a number of other factors. Warwick et al. (2016) have found that the cost of moving a mile of overhead distribution line to underground in concrete encased ducting can be three to four times costlier than the new overhead line construction. The cost comparison can be seen in figure 2.8

The research conducted by Electric Power and Research Institute (EPRI 2015c) has figured out that the cost per mile for undergrounding distribution lines is a function of the type of construction. For double circuit three-phase backbone (concrete encased duct) the average cost of construction per mile is $1.27 million, whereas double circuit three-phase backbone can cost $982 thousand per mile and three phase backbone can cost $630 thousand per mile. The cost is much lower for laterals. For three-phase lateral, average cost per mile is $456 thousand and for single-phase lateral the average cost is $266 thousand per mile. The research has also found that utilities usually spend 1.39% of their capital expense for underground distribution lines operations and maintenance.

Federal Emergency Management Agency (2008) has considered rerouting and providing more system redundancy as a major strategy to mitigate the impacts of system interruption from ice and wind related events. This measure is highly dependent on the configuration of existing lines and their history of failures. An effective strategy can be rerouting the most vulnerable section of lines or introduce redundancy. In Midwest, there are many instances, where there is only one line and no redundancy. The rerouting or redundancy can be done by undergrounding as well as by new overhead line construction. The associated cost can be derived from figure 2.8.

Another major strategy to reduce the risk of vegetation related risks for overhead transmission and distribution lines is to implement enhanced vegetation management. The Electric Power and Research Institute (EPRI 2015d) has highlighted two key tasks for enhanced vegetation management. They are Enhanced Tree Trimming (ETT) and Hazard Tree Removal. The average tree trimming cycle for the utilities range between 3 to 5 years. The research found that the application of technology such as Light Detection and Ranging (LiDAR) can significantly improve utility's ability to detect the areas where ETT is required. Hazard trees are those that pose a risk to utility equipment because they are close enough to come in contact with the system if they were to fall. Identifying the hazard trees and removing them time to time is essential to mitigate the vegetation related risks. The importance of vegetation management has been highlighted in Appelt and Beard (2006). The research has provided six basic principles of effective vegetation management. They are: (1) taking long term and consistent approach (2) proactive actions for vegetation management (3) proper arboricultural practices (4) programs based on Integrated

Vegetation Management (IVM) (5) proper record keeping and productivity measurement and (6) professional supervision and technical expertise. The IVM is recognized as the methodology that encompasses the industry best practices. It is therefore essential for an effective vegetation management program. Kuntz, Christie, and Venkata (2002) have developed an algorithm that can determine the optimal vegetation management scheduling for overhead distribution systems. It is shown that the algorithm can lower cost and find more reliable schedules compared to standard fixed interval schedules.

Component hardening is another popular strategy to make the distribution system more robust. Component hardening includes strengthening poles and lines, elevating substations for flood risk etc. For example, existing lines can be replaced by more heavier wires such as T-2. T-2 wires consist two wires, twisted together to form one strong wire. Strengthening wires and poles together can increase the strength of the distribution lines by 66% (Federal Emergency Management Agency 2008). The importance of component hardening is also listed in Jufri, Kim, and Jung (2017). The research has also suggested introducing hydrophobic coating on distribution lines to make it less susceptible to the snow and ice hazard. Common hardening technique to protect equipment from flood risk is by elevating the substations or relocating facilities to less flood prone areas (Office of Executive President 2013). The Narragansett Electric Company's Rhode Island flood mitigation plan (National Grid 2013) has enlisted the elevation plan of 8 substations within its territory to mitigate the flood risk. The height of elevation ranged between 2 feet to 6.5 feet. The total estimated cost of elevating the 8 vulnerable substation was approximately $23 million. EPRI (2015a) has suggested a number of measures for hardening of overhead structures. They have suggested the design to be done in such a way that the failure of components follows an order: conductor ties, conductors or splices, crossarms and then the pole. This is called Mechanical Coordination. They have also suggested use of larger poles to avoid pole breakage during storms. They estimated that moving to a class 2 equivalent pole top circumference along with the mechanical coordination can reduce breakage by 70% to 80%. They have also found that pole strength correlates with the pole top circumference. Pole top is the most important for storm performance. This option will enhance the same feature as upgrading the pole class but at a lower cost. Hardening of the system can be done by introducing dead-end structures as well. Dead ends are poles or transmission towers that stop the cascading effects. When a power line breaks the unbalanced force is significant to break a pole. The dead-end structures prevent the pole from bending. Dead-end structures are used for extra protection against extreme cases of ice and storm (Federal Emergency Management Agency 2008, Marne 2006).

Another strategy of improving the resilience of electricity grid is to implement the smart grid initiatives like micro grids, smart meters etc. Office of Executive President (2013) has highlighted that the ability of micro grids to separate and isolate itself from the utility seamlessly can improve the resilience of the overall grid. The introduction of smart technologies like smart meters can help the utilities to identify outages more rapidly, thus improving their situational awareness. However, Albasrawi et al. (2014) have said that smart grids can increase the vulnerability to accidental failures. Panteli et al. (2016) has also argued that defensive islanding can improve the resilience of power grid during extreme weather events.

4.7 Risk Quantification

The severe weather-related incidents are called high impact low frequency (HILF) events. These events may not occur every year but when they occur, the impact is likely to be catastrophic. Therefore, the risk of economic loss from the severe weather induced power outages are ever present. This research has quantified the risk from a decision-making perspective. The risk appetite of the decision maker governs the risk quantification which is subsequently used in the benefit cost analysis-based optimization framework to identify the optimal scope of different strategies which will minimize the economic loss of severe weather induced power outages.

The process of deriving the annual inoperability has been shown is equation 62. When the exercise is repeated for multiple years, the average annual inoperability (average observed inoperability) and the standard deviation can be calculated following the standard procedure. In the process of decision making related to the resilience building projects, a decision maker considers an inoperability against which the decision will be made. This can be called the design inoperability. Any decision maker who is making the decision about investment related to resilience based on the assumption that for any given year the expected power outages will be less than what has been observed before is considered as risk seeking. So, for a risk seeking decision maker, the design inoperability will be less than the average observed inoperability. A risk averse decision maker is one who is making the decision based on the assumption that for any given year the expected power outages will be greater than what has been observed before. For a risk averse decision maker, the design inoperability will be greater than average observed inoperability.

Five levels of risk appetite have been defined in this research. They are very high, high, moderate, low and very low. The risk appetites are based on the relationship between design inoperability and average observed inoperability. For risk quantification, it has been assumed that the average observed inoperability for a utility follows a normal distribution with a fixed mean and standard deviation. The classification of risk appetites is shown in Table 4.1.

Table 4.1 Risk Appetite Classification

Risk Appetite	**Design Inoperability Belongs to**
Very High	0 to 20 Percentile of Average Observed Inoperability
High	20 to 40 Percentile of Average Observed Inoperability
Moderate	40 to 60 Percentile of Average Observed Inoperability
Low	60 to 80 Percentile of Average Observed Inoperability
Very Low	80 to 100 Percentile of Average Observed Inoperability

This can be explained by a simple example. Suppose for a utility the average observed inoperability is 1% with a standard deviation of 0.5%. However, the decisions related to the resilience building projects were made based on a design inoperability of 0.8%, which is 34th percentile of the average observed inoperability. This means that for a future year there is 66% chance that the observed inoperability will be higher than the design inoperability. Based on the classification in Table 4.1, the risk is high.

Garrick (2008) has defined risk as a function of scenario, likelihood and consequence. This research has used that definition. Risk has been quantified as equation 64

$$Risk = P(q \leq q_{Design}) \times q_{Design} \times e_{1\%}^{Loss} \qquad 64$$

Where, q is the inoperability observed in a future year, q_{Design} is the design inoperability. For the simple example explained above, $P(q \leq q_{Design})$ is the probability that in a given year the observed inoperability will be less than the design inoperability which is 0.34 and the consequence is the expected GDP loss due to the design inoperability (0.8%). For the given example the risk can be calculated as

$$Risk = 0.34 \times 0.80\% \times p\% \times e_{1\%}^{Loss} \qquad 65$$

The notations are as explained before.

4.8 Benefit Cost Analysis

The benefit cost analysis (BCA) provides the lower threshold scope of the strategies that will keep the benefit to cost ratio (BCR) higher than 1. When the BCR is kept greater than 1, the decision maker will always be on the profitable side. This research uses the risk derived from equation 64 in the BCA. The risk quantified using equation 64 is the total quantified risk for the utility. It has been explained before that the risk factors are assumed to be independent. Therefore, the total quantified risk from equation 64 is the sum of risk due to each risk factor.

To derive the risk associated with each risk factor, this research proposes to quantify their relative contribution to the annual inoperability. The annual inoperability is calculated based on equation 62. But it is the total annual inoperability. The inoperability due a risk factor i can be derived as equation 66

$$q_i = MED \times RF_i \times q_{R_i} \tag{66}$$

Where, q_i is the inoperability due to risk factor i, other notations are as explained before. The relative contribution of risk factor i can be calculated as equation 67

$$\theta_{R_i} = \frac{MED \times RF_i \times q_{R_i}}{MED \times \sum_{i=1}^{m} RF_i \times q_{R_i}} \tag{67}$$

Where, θ_{R_i} is the relative contribution of risk factor i to the annual inoperability. The numerator in the equation the inoperability due to risk factor i and the denominator is the annual inoperability which is the sum of inoperability due to all risk factors. Once the relative contribution of each factor is derived it can be used to estimate the risk associated with risk factor i ($Risk_{R_i}$) using equation 68

$$Risk_{R_i} = \theta_{R_i} \times P(q \leq q_{Design}) \times q_{Design} \times e_{1\%}^{Loss} \tag{68}$$

The risk associated with risk factor i has been used in the BCA as a cost component. The BCA is performed for each risk reduction strategy. Now, there can be multiple risk reduction strategies to mitigate the impact of one risk factor. For example, to mitigate the vegetation related risk, some of the possible risk reduction strategies can be selective undergrounding, rerouting of the distribution lines, enhanced tree trimming along the vulnerable region etc. Hence, the risk derived for a risk factor has to be further distributed across the risk reduction strategies relevant to the risk factor. If there are n strategies planned for risk factor i, then the risk quantified for risk factor i or $Risk_{R_i}$ can be distributed among the n strategies. This research has distributed the risk equally among the strategies. So, the risk associated with a risk reduction strategy to mitigate the impact of risk factor i can be found using equation 69

$$Risk_{RR_i} = \frac{Risk_{R_i}}{n} \qquad 69$$

Where, $Risk_{RR_i}$ is the risk associated with a risk reduction strategy to mitigate the impact of risk factor i. The numerator is the risk associated with risk factor i as derived in equation 68. Once the risk for each strategy is calculated the BCA is performed. The cash flow diagram is shown is figure 4.6.

In the cash flow diagram, the construction period for the new projects has been considered for 5 years. So, for the first 5 years, the annual cost is the sum of the construction cost and the operation and maintenance (O&M) cost. Once the construction period is over, there will only be O&M cost for the rest of the design life. It should be noted that the O&M cost will gradually increase as construction progresses until the end of construction period. Once, the construction is over, the O&M cost will be estimated for the full scope of the reduction strategy. The risk derived from equation 69, is used as the cost component. The derived risk for each risk reduction strategy has been used consistently for all the years.

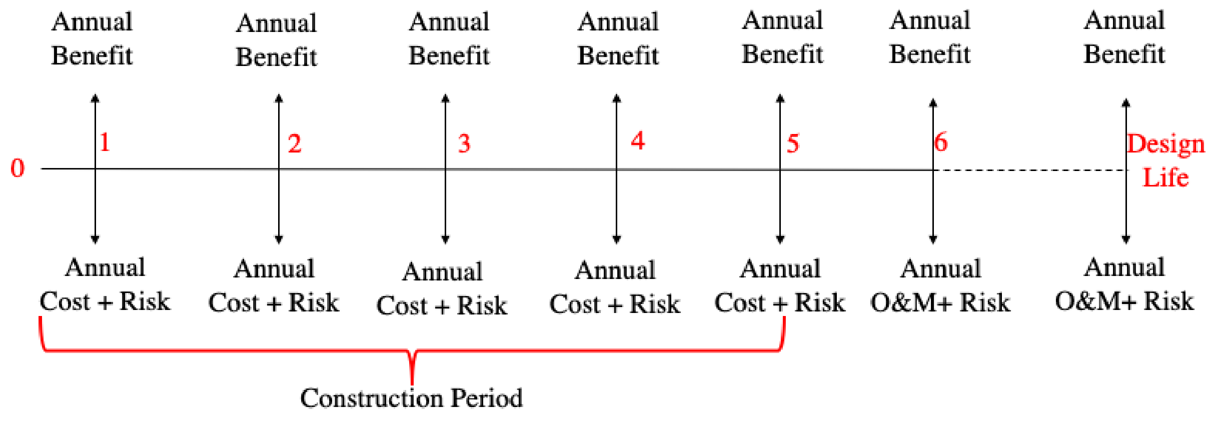


Figure 4.6 Cash Flow Diagram for Benefit Cost Analysis

For calculating the benefit, it is essential to know the vulnerability. For vegetation related risk, vulnerability can be in miles of vulnerable distribution line, for equipment related risk it can be the number of substations at risk of being flooded etc. For identifying vulnerability historic evidences of failure has to be used. In this research it has been assumed that the relationship between vulnerable components and annual economic loss is linear. The annual economic impact due to risk factor i can be found as

$$Annual\ Economic\ Impact\ due\ to\ R_i = MED \times RF_i \times q_{R_i} \times p\% \times e_{1\%}^{Loss} \tag{70}$$

If V is the vulnerable portion of the grid which is triggering risk factor i then the linearity assumption considers that each unit of V contributes equally to the annual economic impact. Therefore, if the strategy is planned for x unit, it will reduce the impact by x/V percentage. For example, let us assume that a utility has identified 100 miles of its distribution lines as vulnerable causing vegetation related risk. Suppose, the annual economic impact of vegetation related risk has been estimated using equation 70 to be $100 million a year. Therefore, based on the linearity assumption each mile of the vulnerable distribution line causes an economic loss of $1 million a year. Now, if the utility plans 10 miles of undergrounding, that will reduce the annual economic loss by $10 million a year. This reduction of economic loss has been considered as the benefit in the analysis. So, the equation for calculating the benefit can be written as equation 71

$$Annual\ Benefit = MED \times RF_i \times q_{R_i} \times p\% \times \frac{x}{V} \times e_{1\%}^{Loss} \tag{71}$$

Like the O&M cost, the benefit will also increase gradually as the construction progresses till the end of construction period. Once, the benefit is derived, the net present of value (NPV) of the benefit, cost and risk are calculated. The BCR is calculated as the ratio of NPV of benefit and sum of NPV of cost and risk.

$$BCR = \frac{NPV\ of\ Benefit}{NPV\ of\ Cost + NPV\ of\ Risk} \geq 1 \tag{72}$$

The inequation 72 yields the low threshold of x which will keep the BCR greater than 1. It should be noted that cost is a function of x, benefit is a function of x, but risk is not a function of x. As the risk appetite of decision maker changes from very high to very low, the risk value increases. As the risk increases, the risk associated with a risk factor and reduction strategies also increases. The increase in the risk in the denominator of the inequality 72, increases the lower threshold value of x. Therefore, it can be said that for a risk seeking decision maker the scope of work for any risk reduction strategy will be lower than a risk averse decision maker. The same procedure is repeated for all the risk reduction strategies to determine their minimum scope of work which will keep the BCR greater than 1. Once, the lower threshold scope of each strategy is determined, they are used in an optimization to find the optimal mix of different strategies which will minimize the economic impact.

4.9 Optimal Strategy Selection Process

The optimal strategy implies to the suite of different strategies which minimizes the economic loss due to severe weather induced power outages. The process is shown in figure 4.7. The process starts with the selection of design inoperability which determines the risk level: very high, high, moderate, low and very low. The risk value increases as the risk level changes from very high to very low. The derived risk is then used in the BCA to determine the lower threshold scope of all strategies. Once the minimum scope of all strategies is determined it is used in an optimization process. The objective function of the optimization process is to minimize the economic loss from severe weather induced power outages. To minimize the economic loss, the benefit from the strategies has to be maximized. For optimization, this research has maximized the benefit from the risk reduction strategies.

Objective Function: Maximize (the sum of NPV of benefits from all risk reduction strategies)

Subject to,

- Feasibility Constraint: Planned scope of work should be less than or equal to feasible scope of work or vulnerable portion of the system whichever is lower
- Budget Constraint: The cost of implementing all risk reduction strategies should be less than or equal to the budget allocated for the resilience building project
- BCR Constraint: The Scope of the work of all risk reduction strategies should keep their individual BCRs greater than or equal to 1
- Geographical Constraints: There should not be any overlapping in the geographic location of different risk reduction strategies relevant to a risk factor.

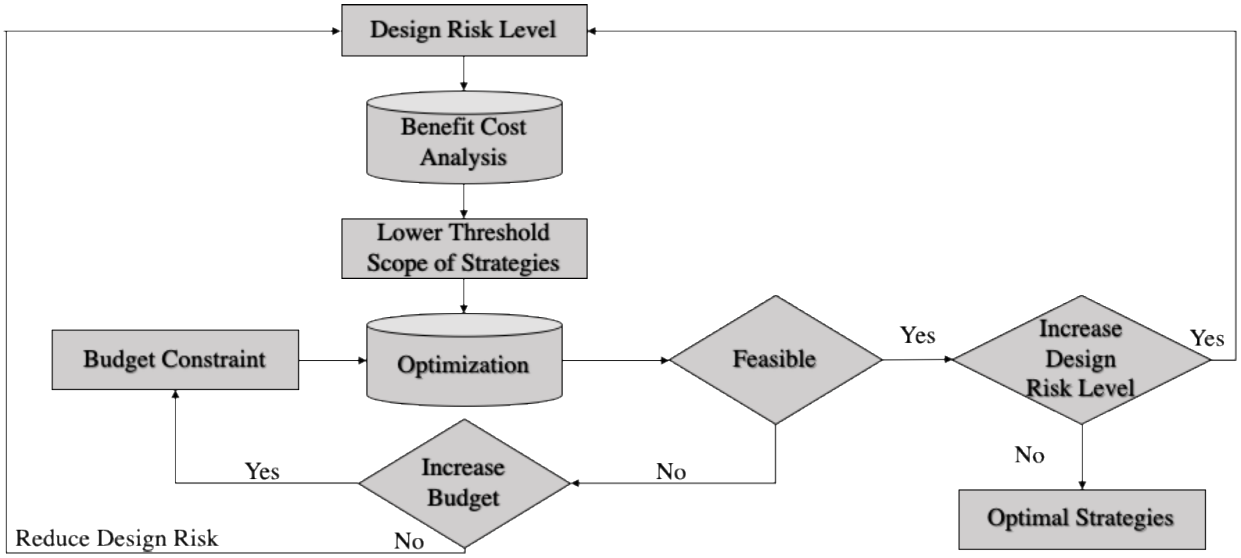


Figure 4.7 Optimal Strategy Selection Process

If the optimization is not feasible, the decision maker will have two options either to increase the budget or decrease the design risk level which will reduce the risk and threshold scope of strategies. If the optimization is feasible then the decision maker will have two options as well. First, he or she can increase the design risk level, and follow the same procedure or the process can be stopped. If the process is stopped, the outcome will the combination of optimal scope of different strategies which will minimize the economic loss of severe weather induced power outages.

The complete procedure can be explained by a simple example. Suppose, a utility (henceforth referred as UCo) located in Indiana contributes 15% to the state's total electricity production every year. UCo has 6000 miles of overhead distribution lines, 117 electric substations and 240,000 electric poles within its service territory. The outcome of the vulnerability analysis is shown is Table 4.2.

Table 4.2 Vulnerability of Components of Grid

	Overhead Distribution Line	**Substations**	**Poles**
Total Length	6000 Miles	117 Nos	240000 Nos
Vulnerability	1.00%	3.00%	1.00%
Vulnerable	60 Miles	4 Nos	2400 Nos

UCo has collected its historical weather-related power outages data following the database format and performed the analysis with the collected data. The historical data shows an average inoperability of 1% and a standard deviation of 0.2%. UCo has identified 3 risk factors: vegetation related (R_1), equipment related (R_2), and pole related (R_3). Suppose, the outcomes of the analysis with the historical data are as shown in table 4.3.

Table 4.3 Risk Factors

Risk Factor	**MED**	$\boldsymbol{RF_i}$	$\boldsymbol{q_{R_i}}$	**Relative Proportion**
R_1	3.4	0.72	0.0031	76%
R_2	3.4	0.09	0.0060	18%
R_3	3.4	0.02	0.0090	6%

The table shows that UCo has recorded an average of 3.4 MEDs per year due to severe weather events. Out of all MEDs vegetation related incidents occurred 72% of time and caused an average inoperability of 0.31%, equipment related incidents occurred 9% of time and caused an average of inoperability 0.60% and pole related incidents occurred 2% of time and caused an average of inoperability 0.90%. The relative proportion of the risk factors were calculated based on equation 67. The expected GDP loss for the state of Indiana due to 1% inoperability of the utility sector has been derived in section 4.3 and it is \$274.5 million in 2017 values. The expected GDP loss for the state of Indiana due to 1% inoperability in UCo can be calculated following equation 63

$$\begin{aligned} &Annual\ Economic\ Impact \\ &= 3.4 \times (0.72 \times 0.0031 + 0.09 \times 0.0060 + 0.02 \times 0.0090) \\ &\times 15\% \times \$274.5\ million \end{aligned} \tag{73}$$

The expected annual GDP loss due to 1% inoperability in UCo is \$41.3 million. UCo has identified 4 strategies to mitigate the risk of the annual economic loss. They are selective undergrounding, rerouting the distribution lines to avoid vulnerable zones, elevating the substations to mitigate flood risk and increasing pole strength to make them more robust. The projects are planned to be completed in 5 years and the design life is 20 years. The estimated unit cost of each strategy is shown in table 4.4

Table 4.4 Unit Cost of Strategies

Risk Factors	Strategy	Unit Cost of Construction	O&M Cost
Vegetation Related	Undergrounding	\$962,000 per Mile	1.39% of Capital Cost
	Rerouting	\$274,857 per Mile	4.77% of Capital Cost
Equipment Related	Elevating Substations	\$2,865,000 per No	1.39% of Capital Cost
Pole Related	Increasing Pole Strength	\$2,500 per No	4.77% of Capital Cost

UCo wants to find the optimal scope of all strategies which will minimize the economic impact of the power outages following the process shown in figure 4.7. It starts with a moderate risk level say 50th percentile. For 50th percentile, the design inoperability is 1%. It has been assumed that the average inoperability follows a normal distribution with mean 1% and standard deviation 0.2%. The risk can be quantified following equation 64.

$$Risk = P(q \leq 1\%) \times 1\% \times 15\% \times \$274.5\ Million \qquad 74$$

$P(q \leq 1\%)$ is equal to 0.5 as q follows a normal distribution with mean 1% and standard deviation 0.2%. The calculated risk is \$20.6 million. It has to be distributed across the risk factors and subsequently across the strategies. The relative proportions have already been estimated in table 4.3 and the number of strategies associated with each risk factor is shown in table 4.5. For example, the relative proportion of the vegetation related risk factor is 76% (Refer Table 4.3). So, the risk associated with vegetation related risk factor is 76% of the calculated risk of \$20.6 million which is \$15.6 million. Now to mitigate the vegetation related risk UCo has planned for 2 strategies: selective undergrounding and rerouting (Refer Table 4.4). Therefore, the \$15.6 million risk is equally distributed to each strategy. The same procedure is followed to estimate the risk associated with each risk reduction strategies. The results are shown in table 4.5.

Table 4.5 Risk Quantification

Risk Factors	**Strategy**	**Risk (in $M)**
Vegetation Related	Undergrounding	7.8
	Rerouting	7.8
Equipment Related	Elevating Substations	3.8
Pole Related	Increasing Pole Strength	1.3

The risk values shown in table 4.5 are used in BCA. For the sake of simplicity, it is assumed that UCo has planned for equal amount of work and budget for each year during construction. If x1, x2, x3 and x4 are the scope of work for each year for undergrounding, rerouting, elevating substations and increasing pole strength respectively, then the benefit from undergrounding x1 miles of distribution lines out of 60 miles of vulnerable line can be calculated as equation 71

$$Annual\ Benefit = 3.4 \times 72\% \times 0.31\% \times 15\% \times \frac{x1}{60} \times \$274.5\ Million \qquad 75$$

Which is equal to $520,781(x1). So, if undergrounding is planned for x1 miles the annual benefit derived from equation 75 is $520,781(x1). The cost of undergrounding x1 miles of existing distribution line is $962,000x1 and the O&M cost is 1.39% of the capital cost. The O&M cost and the benefit from undergrounding will gradually increase as construction progresses. At the end of 1st year, x1 miles will be undergrounded, so the O&M cost and benefit were calculated for x1 miles. At the end of 2nd year 2x1 miles will be undergrounded. So, the O&M cost and benefit will be twice. The process will continue till the construction ends. Then the O&M cost and benefit will be constant which will be for 5x1 miles. The cash flow diagram for undergrounding is shown in figure 4.8.

The NPV of benefit, cost and risk were calculated using a discount rate of 5%. The inequation 72, yielded a minimum scope of 4.3 miles of undergrounding per year for 5 years which will keep the BCR greater than 1. The same procedure is repeated for the other 3 strategies at all risk levels using the linearity assumption. The minimum scope of all strategies at different risk levels are shown in table 4.6. It can be seen from table 4.6 that as the risk level has increased, the minimum scope of work has also increased. With the minimum scope of strategies, the minimum budget requirements for each risk level can be determined using the unit cost shown in table 4.4.

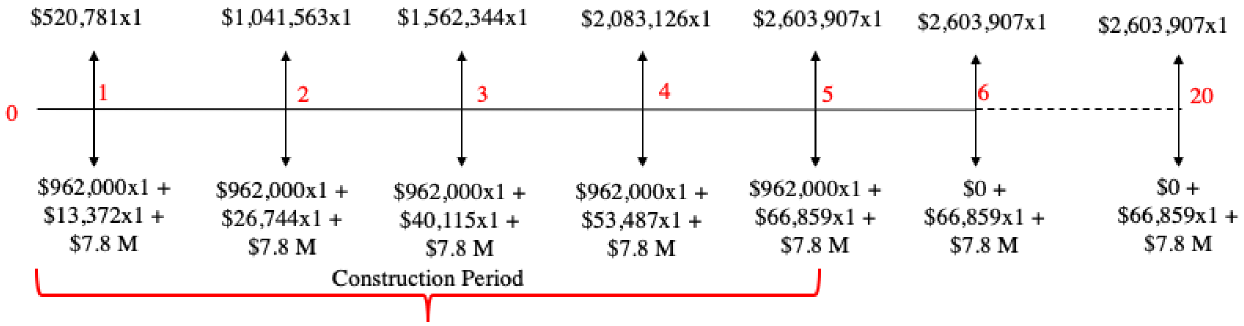


Figure 4.8 Cash Flow Diagram of Undergrounding Project

Table 4.6 Minimum Scope of Strategies

Risk Level	**Undergrounding in Miles**	**Rerouting in Miles**	**Elevating Substations in Nos**	**Strengthening of Poles in Nos**
50%	4.3	3.8	0.5	404.1
60%	5.4	4.7	0.7	509.4
70%	6.6	5.8	0.8	625.0
80%	7.9	7.0	1.0	755.3
90%	9.6	8.5	1.2	913.7

The minimum budget requirement for the different risk levels in table 4.7 is shown is figure 4.9.

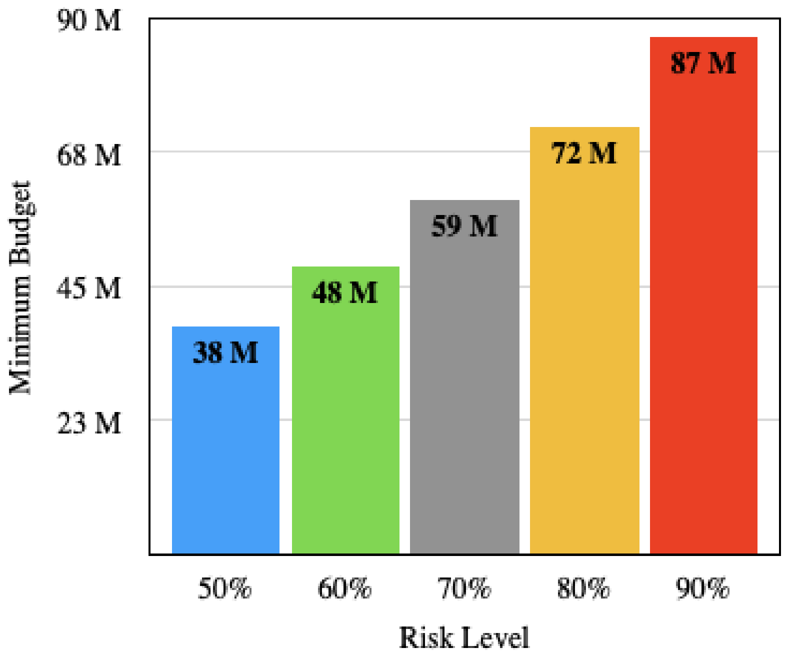


Figure 4.9 Minimum Budget Requirement for Different Risk Levels

If UCo allocates a budget of $45 Million to be used equally in 5 years for the resilience building projects, then the optimal scope of different strategies can be found using a simple linear optimization which maximizes the sum of the NPV of benefits from all strategies. Therefore, the objective function:

$$Max\ (27{,}721{,}226x1\ +\ 27{,}721{,}226x2\ +\ 100{,}601{,}224x3\ +\ 55{,}890x4) \qquad 76$$

Subject To,

$x1 \geq 4.3$ – BCR Constraint 77

$x2 \geq 3.8$ – BCR Constraint 78

$x3 \geq 0.5$ – BCR Constraint 79

$x4 \geq 404.1$ – BCR Constraint 80

$5(x1 + x2) \leq 60$ – Feasibility Constraint 81

$5x3 \leq 4$ – Feasibility Constraint 82

$$5x4 \leq 2{,}400 \text{ – Feasibility Constraint} \quad (83)$$

$$5(962{,}000x1 + 274{,}857x2 + 2{,}865{,}000x3 + 2{,}500x4) \leq 45{,}000{,}000 \quad (84)$$
– Budget Constraint

The optimization problem was solved using a linear programming. The optimal values of the four variables are shown in table 4.8

Table 4.7 Optimal Scope of Strategies

Strategy	Unit	Scope
Undergrounding	Miles	4.8
Rerouting	Miles	7.0
Elevating Substations	Nos	0.5
Strengthening Poles	Nos	404.1

At this stage, the decision maker can increase the level of risk, and repeat the same procedure or can stop the process here. It can be seen from figure 4.8 that without increasing the budget, the maximum level of risk that can be achieved will be between 50% and 60%. If the process is stopped here, the maximum value of the objective function will be approximately $400 million. This is the NPV of benefit from 20 years of design period.

4.10 Conclusion

Due to climate changes and aging of grid, severe weather induced power outages are getting more frequent. The last two decades have seen major weather-related events devastating the electricity grid and this trend is likely to continue. To overcome this challenge, utilities need to invest in resilience building projects to make their system robust, reliable and resilient to ensure long term reliability and economic benefit. The highly regulated environment of utility sector poses another challenge in terms of getting approval for resilience building projects. Under this situation, utilities face three key questions (1) where to invest, (2) how much to invest and (3) how to justify. This research has established a framework that can answer the three questions. It has been found that the distribution system of the grid is the most vulnerable. Therefore, investment need to be planned to make distribution system robust, reliable and resilient. There are numerous strategies that can be implemented to minimize the economic loss from weather induced power outages. This research has developed a benefit cost analysis-based framework that can identify the optimal scope of different strategies which will cumulatively minimize the economic loss from severe weather induced power outages. The economic loss has been derived in terms of loss of GDP for a state and the benefit is the reduction of loss of GDP for that state due to implementing the strategies. Therefore, it can be used by utilities to get approval for the projects from the state utility regulatory commissions. The framework can incorporate the risk appetite of the decision maker. Five levels of risk appetite have been defined and it has been shown that a scope of work will be lesser for a risk seeking decision maker than that of a risk averse decision maker.

There are some limitations of this study. The economic impact estimated in this research does not consider the cost of physical damage, restoration etc. It only estimates the loss of GDP due to loss of production output. The Make and Use tables of BEA with 71 industries and 71 commodities does not enlist electricity as a separate industry. It enlists electricity as a part of utility sector. However, the utility sector is comprised of two other industries: natural gas distribution industry and water, sewage and other industries. It is worth mentioning that Electricity is the single highest contributor of the three, contributing nearly 70% of the utility sectors production output. Therefore, for practical applications of the outcome of this research, this information should be kept in mind. The framework will not be able to find the minimum scope of a strategy using the BCA if the NPV of unit benefit derived is lower than the NPV of unit cost. Therefore, the planned risk reduction strategies need to have a higher NPV of unit benefit than NPV of unit cost. Again, the minimum scope of some strategies may not fulfill the feasibility constraint. For example, at 90% risk level, the minimum scope of pole strengthening is 913.7 nos each year. This clearly violates the feasibility constraint for this strategy. Therefore, it is suggested to make the feasibility constraints soft constraints and introduce a penalty in the objective function if the constraint is not fulfilled. The linearity assumption between vulnerable grid component and economic loss may not hold true in an actual case. In the distribution system, there may be some components which will contribute higher to the economic loss. This is another limitation.

The said limitations provide the setting for future recommendations. In future, the whole framework can be tried using real power outage data from utilities. In that case, the cost of physical damage and cost of restoration can be incorporated in the risk quantification. The increase in the risk value will definitely increase the scope of work. The nonlinear behavior between vulnerable grid component and economic loss can be investigated in future. Quantifying inoperability by leveraging historical power outage data can be another future research.

4.11 Acknowledgement

Funding for this research was provided by the NSF Grant — #1728209 entitled Towards a Resilient Electric Power Grid: An Investment Prioritization Decision Framework Integrating Risks of Severe Weather- Induced Outages.

5. SUMMARY AND CONCLUSION

In the previous two chapters the research has been thoroughly explained. This chapter concludes the research by summarizing it and mentioning its contributions, limitations and future recommendations.

5.1 Overall Summary and Conclusion

Critical infrastructures are the backbone of a nation. The loss of serviceability of critical infrastructure in the aftermath of a natural disaster can have colossal impact on a nation's economy. Electricity infrastructure is one of the critical infrastructures whose continuous service is essential for a nation. Every year power outages affect millions of people and causes billions of dollars of economic losses. The major power outages data collected by DoE shows that between 2000 and 2016, severe weather-related incidents have caused the most power outages. During the said timeline, out of the total numbers of customers, 86% were affected by severe weather induced power outages. The aging of the electricity grid and climate change are making the severe weather induced power outages more frequent. To overcome this situation, utilities need to invest to make their system robust, reliable and resilient thus ensuring long term economic benefit.

Utility being a regulated sector, poses another challenge in this regard. Any investment project planned by the utilities need to be approved by the state utility regulatory commission because the cost of the projects will be recovered from the customers. Under this situation, utilities face three key questions (1) where to invest, (2) how much to invest and (3) how to justify the investment. This research has developed a framework to answer the three questions. The proposed framework justifies the investment by showing its importance on a state's economy. Therefore, the first stage of the research focuses on finding the economic impact of severe weather induced power outages in terms of loss of GDP.

The economic loss has been assessed at both state level and national level. For state level loss assessment has been performed for the state of Indiana. For assessing the economic loss, this research has developed a disaster impact assessment mechanism. The mechanism considers the cascading economic impact of the loss of electricity production on other industries. The relationships between the industries have been mapped by adopting Leontief's I-O model. Historical I-O tables (Make and Use Tables) between 1997 and 2016 were collected from the BEA. The data were used to develop the interindustry relationships for 20 years. This has been used further to determine the economic loss due to severe weather induced power outages. An equation has been derived which can estimate the impacts of loss of production in terms of loss of GDP. The loss of GDP was estimated for 20 years for 1% production loss and a Monte Carlo Simulation has been performed using the historical loss to derive the expected GDP loss if there is an inoperability of 1%. The results show that the expected GDP loss due to 1% inoperability at national level is $16.4 billion in 2017 values. The GDP loss estimation equation is linear. Hence, the expected GDP loss for 2% inoperability will be twice that of 1% or $32.8 billion in 2017 values and so on so forth.

For state level assessment it has been assumed that the interindustry relationships derived at the national level holds true across all the states. The same BEA data has been used for the state level calculation. To convert the national level output of an industry into state level, a multiplier has been proposed which considers that the production output of an industry in a state is proportional to the employment created by the industry in that state. The derived multipliers were used to calculate the state level production of each industry which was subsequently used in the derived equation to find the historical GDP loss for 1% inoperability. The historical losses were used in a Monte Carlo simulation to calculate the expected GDP loss for the state of Indiana. The expected GDP loss for Indiana due to 1% inoperability in utility sector is $274.5 million in 2017 values. As the equation is linear, the expected loss for 2% inoperability is twice and so on so forth. The second part of the research focuses on developing a benefit cost analysis-based optimization framework that can identify the optimal risk reduction strategies to minimize the economic impacts of severe weather induced power outages. For the effective application of the framework, the power outage data has to be collected following a particular format which has been explained. The framework is flexible to the risk appetite of the decision makers. Five levels of risk appetite have been defined and the quantified risk will be different for each level. The risk of economic loss has been used as a cost component in the framework. The benefit cost analysis is performed to determine the minimum scope of a strategy that will keep the benefit to cost ratio greater than 1. The outcomes of the benefit cost analysis are used in the optimization process to determine the optimal scope of different strategies that will minimize the economic loss of severe weather induced power outages. The procedure has been explained with a simple example.

5.2 Research Contributions

The research has conceptualized a disaster impact assessment mechanism that considers the relationships between industries and infrastructures. The mechanism is followed in the assessment of economic loss in terms of loss of GDP at national level and state level. To the best knowledge of the author, the economic loss assessment in terms of loss of GDP has not been performed previously and the previous research in this domain has not considered the cascading impacts of weather-related power outages on economy. This research has considered the existing interindustry relationships in estimating the economic loss in terms of loss of GDP. Another key contribution is the identification of the vulnerable industries which are at risk of economic loss due to severe weather induced power outages. The research has also conceptualized the state level multipliers which can be used for the estimation of GDP loss for different states.

The second stage has developed a benefit cost analysis-based optimization framework. The framework determines the optimal scope of different strategies to minimize the economic loss of weather-related power outages under different budget situations. The framework uses the outcomes of the economic loss assessment to quantify risk and uses that in the benefit cost analysis. The research has also suggested a database format which is necessary to perform the benefit cost analysis. The framework helps the utilities to identify optimal scope of risk reduction strategies. They can be justified by showing their positive impact on the state's economy. Hence, the framework answers the three key questions. The answers to the first two questions are found from the optimal scope of the strategies. The answer of the third question is the optimal value of the objective function which is the outcome of the strategy implementation on a state's GDP. It is either minimizing the GDP loss or maximizing the benefit from the planned strategies.

5.3 Research Limitations

There are certain limitations of the research. They are listed below

- The research has considered that the economic equilibrium between production and consumption of commodities exists in a post disaster situation which may not be true. There might be imbalance between production and consumption of commodities in a post disaster situation.

- The research has also assumed that if there is an inoperability in the utility sector, the impact is equally suffered by the industries and the end users. This may not be true. In a natural disaster situation, the power supply to essential services are often prioritized over the end users. Therefore, this assumption may not hold true in a post disaster situation.
- Another limitation is related to the quantification of actual inoperability. The dataset which has been used for this research does not enlist electricity as a separate industry. It enlists electricity as a part of utility sector. However, the utility sector is comprised of two other industries: natural gas distribution industry and water, sewage and other industries. It is worth mentioning that Electricity is the single highest contributor of the three, contributing nearly 70% of the utility sectors production output. Therefore, for practical applications of the outcome of this research, this information should be kept in mind.
- The GDP loss estimation is based on the derived on the interindustry relationships. In estimating the expected GDP loss due to 1% inoperability, the research has considered that the interindustry relationships will not differ much from what has been observed between 1997 and 2016. But the interindustry relationships might change in future based on the advancement of technologies in different sectors.
- The economic loss estimated in this research does not consist the cost of physical damage to the facilities or the cost of restoration. This research has only estimated the loss of GDP due to loss of production of utility sector.
- The linearity of the GDP loss equation is another limitation. In actual scenario, the relationship between the inoperability and GDP loss due to inoperability may not be linear.
- The risk factors have been assumed to be independent of each other. This might be another limitation. In a real situation, the risk factors may not be independent of each other. Hence, the net impact due to all risk factors may not be cumulative.
- The framework will not be able to find the minimum scope of a strategy using the BCA if the NPV of unit benefit derived is lower than the NPV of unit cost. Therefore, the planned risk reduction strategies need to have a higher NPV of unit benefit than NPV of unit cost.
- Again, the minimum scope of some strategies may not fulfill the feasibility constraint of the optimization process. To keep the benefit to cost ratio higher than 1, the minimum

scope of some strategy might exceed the vulnerability. Therefore, it is suggested to make the feasibility constraints soft constraints and introduce a penalty in the objective function if the constraint is not fulfilled. In that way, the violation of the constraint can be kept at minimum.

- The linearity assumption between vulnerable grid component and economic loss may not hold true in an actual case. In the distribution system, there may be some components which will contribute higher to the economic loss than other. For an example a mile of distribution lines might fail more than others, thus contributing more to the economic loss. This is another limitation.

5.4 Recommendations for Future Research

The said limitations provide the setting for the future research. In future:

- The whole framework can be tested with real power outage data from a utility. In that case the cost of physical damage and restoration can be added to the economic loss assessment. The increase in the expected economic loss will increase the risk values and subsequently the scope of strategies.
- The economic loss assessment can be performed using different prioritization schemes. It has been assumed that the industries and end user are affected equally, which might not be true in a post disaster situation. Therefore, different prioritization schemes may be tried in the economic loss assessment to find the best scheme. The best scheme should keep the economic loss at minimum.
- In contrary to the linearity assumptions of vulnerable components, they can be relatively weighted to reflect the actual situation. The outcome of this might be classification of vulnerable components as high, medium, low. This might help to prioritize which part of the distribution system needs to be fixed first.
- Future research can be conducted to develop or quantify the inoperability based on historical data. This might lead to planning for smart initiatives to facilitate the data collection for effective inoperability quantification.

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APPENDIX A

Table A.1 I-O Codes of Industries

I-O Code	**Industry Name**
111CA	Farms
113FF	Forestry, fishing, and related activities
211	Oil and gas extraction
212	Mining, except oil and gas
213	Support activities for mining
22	Utilities
23	Construction
321	Wood products
327	Nonmetallic mineral products
331	Primary metals
332	Fabricated metal products
333	Machinery
334	Computer and electronic products
335	Electrical equipment, appliances, and components
3361MV	Motor vehicles, bodies and trailers, and parts
3364OT	Other transportation equipment
337	Furniture and related products
339	Miscellaneous manufacturing
311FT	Food and beverage and tobacco products
313TT	Textile mills and textile product mills
315AL	Apparel and leather and allied products
322	Paper products
323	Printing and related support activities
324	Petroleum and coal products
325	Chemical products
326	Plastics and rubber products
42	Wholesale trade
441	Motor vehicle and parts dealers
445	Food and beverage stores
452	General merchandise stores
4A0	Other retail
481	Air transportation
482	Rail transportation

483	Water transportation
484	Truck transportation
485	Transit and ground passenger transportation
486	Pipeline transportation
487OS	Other transportation and support activities
493	Warehousing and storage
511	Publishing industries, except internet (includes software)
512	Motion picture and sound recording industries
513	Broadcasting and telecommunications
514	Data processing, internet publishing, and other information services
521CI	Federal Reserve banks, credit intermediation, and related activities
523	Securities, commodity contracts, and investments
524	Insurance carriers and related activities
525	Funds, trusts, and other financial vehicles
HS	Housing
ORE	Other real estate
532RL	Rental and leasing services and lessors of intangible assets
5411	Legal services
5415	Computer systems design and related services
5412OP	Miscellaneous professional, scientific, and technical services
55	Management of companies and enterprises
561	Administrative and support services
562	Waste management and remediation services
61	Educational services
621	Ambulatory health care services
622	Hospitals
623	Nursing and residential care facilities
624	Social assistance
711AS	Performing arts, spectator sports, museums, and related activities
713	Amusements, gambling, and recreation industries
721	Accommodation
722	Food services and drinking places
81	Other services, except government
GFGD	Federal general government (defense)
GFGN	Federal general government (nondefense)
GFE	Federal government enterprises
GSLG	State and local general government
GSLE	State and local government enterprises

APPENDIX B

Inoperability Input Output Model Example

Table B.1 Sample Make Table (Source: Planting 2006)

Industry/Commodity	A	B	C	Scrap	Total Industry Output
A	300	25	0	3	328
B	30	360	20	2	412
C	0	15	250	0	265
Total Commodity Output	330	400	270	5	

Table B.2 Sample Use Table (Source: Planting 2006)

Commodity/Industry	A	B	C	Final Demand	Total Commodity Output
A	50	120	120	40	330
B	180	30	60	130	400
C	50	150	50	20	270
Scrap	1	3	1	0	5
Value Added	47	109	34		190
Total Industry Output	328	412	265	190	

$$\text{Total Industry Output} = X = \begin{bmatrix} 328 \\ 412 \\ 265 \end{bmatrix}$$

$$\text{Total Commodity Output} = Y = \begin{bmatrix} 330 \\ 400 \\ 270 \end{bmatrix}$$

Step 1: Column wise Normalization of Use Matrix (U)

$$\widehat{U} = U[Diag(X)]^{-1}$$

$$\widehat{U} = \begin{bmatrix} 50 & 120 & 120 \\ 180 & 30 & 60 \\ 50 & 150 & 50 \end{bmatrix} \begin{bmatrix} 328 & 0 & 0 \\ 0 & 412 & 0 \\ 0 & 0 & 265 \end{bmatrix}^{-1}$$

$$\widehat{U} = \begin{bmatrix} 0.15 & 0.29 & 0.45 \\ 0.55 & 0.07 & 0.23 \\ 0.15 & 0.36 & 0.19 \end{bmatrix}$$

Step 2: Column wise Normalization of Make Matrix (V)

$$\check{V} = V[Diag(Y)]^{-1}$$

$$\check{V} = \begin{bmatrix} 300 & 25 & 0 \\ 20 & 360 & 20 \\ 0 & 15 & 250 \end{bmatrix} \begin{bmatrix} 330 & 0 & 0 \\ 0 & 400 & 0 \\ 0 & 0 & 270 \end{bmatrix}^{-1}$$

$$\check{V} = \begin{bmatrix} 0.91 & 0.06 & 0 \\ 0.09 & 0.9 & 0.07 \\ 0 & 0.04 & 0.93 \end{bmatrix}$$

Step 3: Scrap Adjustment

$$\text{Scrap Production} = S = \begin{bmatrix} 3 \\ 2 \\ 0 \end{bmatrix}$$

The Non-Scrap Ratio (ρ)

$$\rho = \begin{bmatrix} \rho_1 = \dfrac{X_1 - S_1}{X_1} \\ \vdots \\ \rho_i = \dfrac{X_i - S_i}{X_i} \\ \vdots \\ \rho_n = \dfrac{X_n - S_n}{X_n} \end{bmatrix}$$

$$\rho = \begin{bmatrix} \rho_1 = \dfrac{328 - 3}{328} \\ \rho_2 = \dfrac{412 - 2}{412} \\ \rho_3 = \dfrac{265 - 0}{265} \end{bmatrix} = \begin{bmatrix} 0.990 \\ 0.995 \\ 1 \end{bmatrix}$$

Normalized Make Matrix After Scrap Adjustment ($\hat{V}$)

$$\hat{V} = [Diag(\rho)]^{-1}\, \check{V}$$

$$\hat{V} = \begin{bmatrix} 0.990 & 0 & 0 \\ 0 & 0.995 & 0 \\ 0 & 0 & 1 \end{bmatrix}^{-1} \begin{bmatrix} 0.91 & 0.06 & 0 \\ 0.09 & 0.9 & 0.07 \\ 0 & 0.04 & 0.93 \end{bmatrix}$$

$$\hat{V} = \begin{bmatrix} 0.92 & 0.06 & 0 \\ 0.09 & 0.9 & 0.07 \\ 0 & 0.04 & 0.93 \end{bmatrix}$$

Step 4: Technical Coefficient Matrix (A)

$$A = \hat{V}\hat{U}$$

$$A = \begin{bmatrix} 0.92 & 0.06 & 0 \\ 0.09 & 0.9 & 0.07 \\ 0 & 0.04 & 0.93 \end{bmatrix} \begin{bmatrix} 0.15 & 0.29 & 0.45 \\ 0.55 & 0.07 & 0.23 \\ 0.15 & 0.36 & 0.19 \end{bmatrix} = \begin{bmatrix} 0.17 & 0.27 & 0.43 \\ 0.52 & 0.12 & 0.26 \\ 0.16 & 0.34 & 0.18 \end{bmatrix}$$

Cross Validation:

End User Demand Vector (e)

$$e = \begin{bmatrix} 40 \\ 130 \\ 20 \end{bmatrix}$$

Final Demand Vector (C)

$$C = \begin{bmatrix} 0.92 & 0.06 & 0 \\ 0.09 & 0.9 & 0.07 \\ 0 & 0.04 & 0.93 \end{bmatrix} \begin{bmatrix} 40 \\ 130 \\ 20 \end{bmatrix} = \begin{bmatrix} 44.9 \\ 122.7 \\ 23.4 \end{bmatrix}$$

$$AX + C = \begin{bmatrix} 0.17 & 0.27 & 0.43 \\ 0.52 & 0.12 & 0.26 \\ 0.16 & 0.34 & 0.18 \end{bmatrix} \begin{bmatrix} 328 \\ 412 \\ 265 \end{bmatrix} + \begin{bmatrix} 44.9 \\ 122.7 \\ 23.4 \end{bmatrix} = \begin{bmatrix} 328 \\ 412 \\ 265 \end{bmatrix} = X$$

A* Matrix Derivation

$$[A^*] = \left[diag\left(\hat{X}\right)\right]^{-1} [A] \left[diag\left(\hat{X}\right)\right]$$

$$[A^*] = \begin{bmatrix} 328 & 0 & 0 \\ 0 & 412 & 0 \\ 0 & 0 & 265 \end{bmatrix}^{-1} \begin{bmatrix} 0.17 & 0.27 & 0.43 \\ 0.52 & 0.12 & 0.26 \\ 0.16 & 0.34 & 0.18 \end{bmatrix} \begin{bmatrix} 328 & 0 & 0 \\ 0 & 412 & 0 \\ 0 & 0 & 265 \end{bmatrix} = \begin{bmatrix} 0.17 & 0.34 & 0.35 \\ 0.42 & 0.12 & 0.17 \\ 0.20 & 0.53 & 0.18 \end{bmatrix}$$

Inoperability Vector Derivation: an initial inoperability of 1% in B

Cycle 1:

$$q = \begin{bmatrix} 0\% \\ 1\% \\ 0\% \end{bmatrix}$$

$$Modified\ A = \begin{bmatrix} 0.17 & 0.27 & 0.43 \\ 0.52 \times 99\% & 0.12 \times 99\% & 0.26 \times 99\% \\ 0.16 & 0.34 & 0.18 \end{bmatrix} = \begin{bmatrix} 0.17 & 0.27 & 0.43 \\ 0.52 & 0.12 & 0.26 \\ 0.16 & 0.34 & 0.18 \end{bmatrix}$$

$$Modified\ C = \begin{bmatrix} 44.9 \\ 122.7 \times 99\% \\ 23.4 \end{bmatrix} = \begin{bmatrix} 44.9 \\ 121.5 \\ 23.4 \end{bmatrix}$$

$$Reduced\ Production\ \left(\tilde{X}\right) = [I - Modified\ A]^{-1}\ [Modified\ C]$$

$$I = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$\tilde{X} = \begin{bmatrix} 322.16 \\ 402.40 \\ 259.85 \end{bmatrix}$$

$$[q] = \left[diag\left(\hat{X}\right)\right]^{-1} * \left[\left(\hat{X}\right) - \left(\tilde{X}\right)\right]$$

$$\mathrm{q} = \begin{bmatrix} \mathrm{q}_1 = & \dfrac{328 - 322.16}{328} \\ \mathrm{q}_2 = & \dfrac{412 - 402.40}{412} \\ \mathrm{q}_3 = & \dfrac{265 - 259.85}{265} \end{bmatrix} = \begin{bmatrix} 1.78\% \\ 2.33\% \\ 1.94\% \end{bmatrix}$$

Cycle 2:

$$q = \begin{bmatrix} 1.78\% \\ 2.33\% \\ 1.94\% \end{bmatrix}$$

$$Modified\ A = \begin{bmatrix} 0.17 \times (100\% - 1.78\%) & 0.27 \times (100\% - 1.78\%) & 0.43 \times (100\% - 1.78\%) \\ 0.52 \times (100\% - 2.33\%) & 0.12 \times (100\% - 2.33\%) & 0.26 \times (100\% - 2.33\%) \\ 0.16 \times (100\% - 1.94\%) & 0.34 \times (100\% - 1.94\%) & 0.18 \times (100\% - 1.94\%) \end{bmatrix}$$

$$= \begin{bmatrix} 0.17 & 0.27 & 0.42 \\ 0.51 & 0.12 & 0.25 \\ 0.16 & 0.33 & 0.18 \end{bmatrix}$$

$$Modified\ C = \begin{bmatrix} 44.9 \times (100\% - 1.78\%) \\ 122.7 \times (100\% - 2.33\%) \\ 23.4 \times (100\% - 1.94\%) \end{bmatrix} = \begin{bmatrix} 44.1 \\ 119.6 \\ 22.9 \end{bmatrix}$$

$$Reduced\ Production\ (\tilde{X}) = [I - Modified\ A]^{-1}\ [Modified\ C]$$

$$I = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$\tilde{X} = \begin{bmatrix} 293.9 \\ 373.2 \\ 236.4 \end{bmatrix}$$

$$[q] = \left[diag(\hat{X})\right]^{-1} * \left[(\hat{X}) - (\tilde{X})\right]$$

$$\mathrm{q} = \begin{bmatrix} \mathrm{q}_1 = & \dfrac{328 - 293.9}{328} \\ \mathrm{q}_2 = & \dfrac{412 - 373.2}{412} \\ \mathrm{q}_3 = & \dfrac{265 - 236.4}{265} \end{bmatrix} = \begin{bmatrix} 10.41\% \\ 9.42\% \\ 10.81\% \end{bmatrix}$$

Cycle 3:

$$q = \begin{bmatrix} 10.41\% \\ 9.42\% \\ 10.81\% \end{bmatrix}$$

$$Modified\ A = \begin{bmatrix} 0.17 \times (100\% - 10.41\%) & 0.27 \times (100\% - 10.41\%) & 0.43 \times (100\% - 10.41\%) \\ 0.52 \times (100\% - 9.42\%) & 0.12 \times (100\% - 9.42\%) & 0.26 \times (100\% - 9.42\%) \\ 0.16 \times (100\% - 10.81\%) & 0.34 \times (100\% - 10.81\%) & 0.18 \times (100\% - 10.81\%) \end{bmatrix}$$

$$= \begin{bmatrix} 0.16 & 0.24 & 0.39 \\ 0.47 & 0.11 & 0.24 \\ 0.14 & 0.30 & 0.16 \end{bmatrix}$$

$$Modified\ C = \begin{bmatrix} 44.9 \times (100\% - 10.41\%) \\ 122.7 \times (100\% - 9.42\%) \\ 23.4 \times (100\% - 10.81\%) \end{bmatrix} = \begin{bmatrix} 40.2 \\ 111.2 \\ 20.9 \end{bmatrix}$$

$$Reduced\ Production\ (\tilde{X}) = [I - Modified\ A]^{-1}\ [Modified\ C]$$

$$I = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$\tilde{X} = \begin{bmatrix} 197.6 \\ 270.9 \\ 157.2 \end{bmatrix}$$

$$[q] = \left[diag(\hat{X})\right]^{-1} * \left[(\hat{X}) - (\tilde{X})\right]$$

$$\mathrm{q} = \begin{bmatrix} \mathrm{q}_1 = & \dfrac{328 - 197.6}{328} \\ \mathrm{q}_2 = & \dfrac{412 - 270.9}{412} \\ \mathrm{q}_3 = & \dfrac{265 - 157.2}{265} \end{bmatrix} = \begin{bmatrix} 39.76\% \\ 34.25\% \\ 40.70\% \end{bmatrix}$$

$$\text{Final q vector } = \begin{bmatrix} 39.76\% \\ 34.25\% \\ 40.70\% \end{bmatrix}$$

GDP Loss Calculation

$$[e^{Loss}] = \left[\hat{V}\right]^{-1} * \left[diag(\hat{X})\right] * [I - A^{*}] * [q]$$

$$[e^{Loss}] = \begin{bmatrix} 0.92 & 0.06 & 0 \\ 0.09 & 0.9 & 0.07 \\ 0 & 0.04 & 0.93 \end{bmatrix}^{-1} \begin{bmatrix} 328 & 0 & 0 \\ 0 & 412 & 0 \\ 0 & 0 & 265 \end{bmatrix} \begin{bmatrix} 1 - 0.17 & 0 - 0.34 & 0 - 0.35 \\ 0 - 0.42 & 1 - 0.12 & 0 - 0.17 \\ 0 - 0.20 & 0 - 0.53 & 1 - 0.18 \end{bmatrix} \begin{bmatrix} 39.76\% \\ 34.25\% \\ 40.70\% \end{bmatrix}$$

$$= \begin{bmatrix} 23.2 \\ 27.2 \\ 19.5 \end{bmatrix}$$

$$Net\ GDP\ Loss = \sum_{i=1}^{n} e_i^{Loss} = 23.2 + 27.2 + 19.5 = 69.9$$

APPENDIX C

Table C.1 Historic Inoperability and GDP Loss Vector - 1997

Industries	**Inoperability**	**GDP Loss In Millions**
Farms	0.02%	13.78174
Forestry, fishing, and related activities	0.06%	8.793727
Oil and gas extraction	1.47%	1178.067
Mining, except oil and gas	0.30%	129.6312
Support activities for mining	0.14%	23.30462
Utilities	1.11%	5080.313
Construction	0.02%	118.8146
Wood products	0.07%	36.18854
Nonmetallic mineral products	0.06%	21.80241
Primary metals	0.11%	94.1506
Fabricated metal products	0.07%	90.61228
Machinery	0.05%	83.75366
Computer and electronic products	0.04%	72.73883
Electrical equipment, appliances, and components	0.04%	15.27255
Motor vehicles, bodies and trailers, and parts	0.03%	48.45598
Other transportation equipment	0.02%	15.43046
Furniture and related products	0.01%	-0.27992
Miscellaneous manufacturing	0.01%	-6.24689
Food and beverage and tobacco products	0.02%	53.06167
Textile mills and textile product mills	0.02%	-5.85469
Apparel and leather and allied products	0.01%	3.925343
Paper products	0.08%	63.92461
Printing and related support activities	0.09%	45.38934
Petroleum and coal products	0.19%	275.5942
Chemical products	0.06%	135.4007
Plastics and rubber products	0.05%	28.88829
Wholesale trade	0.06%	260.9943
Motor vehicle and parts dealers	0.02%	16.70522
Food and beverage stores	0.01%	5.06523
General merchandise stores	0.01%	10.3086
Other retail	0.02%	38.40629
Air transportation	0.05%	45.28118
Rail transportation	0.17%	46.86031

Water transportation	0.01%	-8.60651
Truck transportation	0.05%	36.65051
Transit and ground passenger transportation	0.09%	24.09563
Pipeline transportation	1.45%	304.3139
Other transportation and support activities	0.14%	89.21386
Warehousing and storage	0.07%	9.407202
Publishing industries, except internet (includes software)	0.04%	18.25071
Motion picture and sound recording industries	0.04%	22.49437
Broadcasting and telecommunications	0.06%	105.8866
Data processing, internet publishing, and other information services	0.10%	31.95685
Federal Reserve banks, credit intermediation, and related activities	0.15%	410.5727
Securities, commodity contracts, and investments	0.08%	109.6869
Insurance carriers and related activities	0.05%	90.28374
Funds, trusts, and other financial vehicles	0.00%	-4.37193
Housing	0.00%	0.000435
Other real estate	0.10%	253.7969
Rental and leasing services and lessors of intangible assets	0.19%	275.9877
Legal services	0.13%	160.5432
Computer systems design and related services	0.05%	50.02475
Miscellaneous professional, scientific, and technical services	0.10%	541.5564
Management of companies and enterprises	0.13%	140.5049
Administrative and support services	0.13%	252.4323
Waste management and remediation services	0.15%	48.26441
Educational services	0.02%	14.34562
Ambulatory health care services	0.00%	1.022604
Hospitals	0.00%	0.014041
Nursing and residential care facilities	0.00%	0.085732
Social assistance	0.01%	4.705435
Performing arts, spectator sports, museums, and related activities	0.07%	21.5964
Amusements, gambling, and recreation industries	0.02%	14.82904
Accommodation	0.05%	35.11072
Food services and drinking places	0.04%	124.638
Other services, except government	0.04%	115.48
Federal general government (defense)	0.00%	0.004089
Federal general government (nondefense)	0.01%	0.121858
Federal government enterprises	0.11%	-75.7208
State and local general government	0.01%	-8.7695
State and local government enterprises	0.06%	-844.504

Table C.2 Historic Inoperability and GDP Loss Vector – 1998

Industries	**Inoperability**	**GDP Loss In Millions**
Farms	0.03%	23.75763
Forestry, fishing, and related activities	0.06%	13.40449
Oil and gas extraction	1.69%	1039.043
Mining, except oil and gas	0.44%	205.4711
Support activities for mining	0.10%	13.44201
Utilities	1.10%	5001.044
Construction	0.02%	144.4512
Wood products	0.06%	22.39304
Nonmetallic mineral products	0.09%	50.44667
Primary metals	0.12%	94.03111
Fabricated metal products	0.08%	106.6821
Machinery	0.06%	101.1845
Computer and electronic products	0.05%	90.04851
Electrical equipment, appliances, and components	0.04%	8.907421
Motor vehicles, bodies and trailers, and parts	0.02%	49.74416
Other transportation equipment	0.01%	3.20655
Furniture and related products	0.02%	8.825452
Miscellaneous manufacturing	0.03%	13.46009
Food and beverage and tobacco products	0.02%	51.17695
Textile mills and textile product mills	0.05%	23.7893
Apparel and leather and allied products	0.01%	-0.5865
Paper products	0.07%	42.43634
Printing and related support activities	0.09%	38.19667
Petroleum and coal products	0.17%	194.7319
Chemical products	0.07%	133.3448
Plastics and rubber products	0.06%	44.48101
Wholesale trade	0.06%	273.9677
Motor vehicle and parts dealers	0.03%	21.18666
Food and beverage stores	0.01%	5.025341
General merchandise stores	0.01%	5.839372
Other retail	0.02%	35.19447
Air transportation	0.05%	32.32471
Rail transportation	0.25%	76.93466
Water transportation	0.02%	-4.45267
Truck transportation	0.06%	57.85609
Transit and ground passenger transportation	0.05%	8.655797
Pipeline transportation	1.60%	350.1631

Other transportation and support activities	0.15%	105.7611
Warehousing and storage	0.11%	26.61167
Publishing industries, except internet (includes software)	0.05%	23.63589
Motion picture and sound recording industries	0.03%	13.71069
Broadcasting and telecommunications	0.07%	141.345
Data processing, internet publishing, and other information services	0.11%	38.51312
Federal Reserve banks, credit intermediation, and related activities	0.16%	474.0276
Securities, commodity contracts, and investments	0.09%	146.91
Insurance carriers and related activities	0.05%	91.43674
Funds, trusts, and other financial vehicles	0.00%	0.458659
Housing	0.00%	0.000523
Other real estate	0.11%	282.5592
Rental and leasing services and lessors of intangible assets	0.21%	339.9691
Legal services	0.14%	196.7485
Computer systems design and related services	0.06%	65.56169
Miscellaneous professional, scientific, and technical services	0.10%	573.0354
Management of companies and enterprises	0.13%	155.9754
Administrative and support services	0.15%	344.6115
Waste management and remediation services	0.11%	22.55829
Educational services	0.02%	14.30836
Ambulatory health care services	0.00%	5.308797
Hospitals	0.00%	0.029941
Nursing and residential care facilities	0.00%	0.101664
Social assistance	0.00%	0.133551
Performing arts, spectator sports, museums, and related activities	0.08%	28.6599
Amusements, gambling, and recreation industries	0.01%	1.606799
Accommodation	0.05%	42.7009
Food services and drinking places	0.04%	98.8341
Other services, except government	0.04%	97.06763
Federal general government (defense)	0.00%	0.004101
Federal general government (nondefense)	0.01%	0.222127
Federal government enterprises	0.11%	-88.6756
State and local general government	0.01%	-8.95544
State and local government enterprises	0.06%	-855.229

Table C.3 Historic Inoperability and GDP Loss Vector – 1999

Industries	**Inoperability**	**GDP Loss In Millions**
Farms	0.03%	38.58486
Forestry, fishing, and related activities	0.09%	20.40148
Oil and gas extraction	1.94%	1314.8
Mining, except oil and gas	0.57%	250.7235
Support activities for mining	0.18%	24.63158
Utilities	1.13%	5698.48
Construction	0.03%	153.647
Wood products	0.08%	36.3359
Nonmetallic mineral products	0.11%	59.97549
Primary metals	0.17%	139.3109
Fabricated metal products	0.10%	136.2621
Machinery	0.08%	114.4314
Computer and electronic products	0.06%	111.6187
Electrical equipment, appliances, and components	0.07%	35.35464
Motor vehicles, bodies and trailers, and parts	0.03%	38.42022
Other transportation equipment	0.02%	1.633142
Furniture and related products	0.02%	5.441891
Miscellaneous manufacturing	0.03%	2.493943
Food and beverage and tobacco products	0.02%	42.17663
Textile mills and textile product mills	0.06%	32.74559
Apparel and leather and allied products	0.02%	8.798906
Paper products	0.10%	76.41648
Printing and related support activities	0.11%	34.9879
Petroleum and coal products	0.27%	364.4729
Chemical products	0.09%	180.5484
Plastics and rubber products	0.06%	33.6049
Wholesale trade	0.07%	385.4687
Motor vehicle and parts dealers	0.03%	21.95218
Food and beverage stores	0.01%	9.444919
General merchandise stores	0.01%	1.688591
Other retail	0.02%	35.06492
Air transportation	0.07%	45.50071
Rail transportation	0.28%	73.46874
Water transportation	0.05%	5.953103
Truck transportation	0.07%	71.86517
Transit and ground passenger transportation	0.06%	7.676603
Pipeline transportation	1.81%	395.911

Other transportation and support activities	0.18%	124.3507
Warehousing and storage	0.10%	19.25453
Publishing industries, except internet (includes software)	0.06%	36.47865
Motion picture and sound recording industries	0.05%	29.35724
Broadcasting and telecommunications	0.09%	191.7838
Data processing, internet publishing, and other information services	0.15%	70.7813
Federal Reserve banks, credit intermediation, and related activities	0.20%	623.5392
Securities, commodity contracts, and investments	0.12%	234.665
Insurance carriers and related activities	0.06%	131.9918
Funds, trusts, and other financial vehicles	0.00%	0.994329
Housing	0.00%	0.000685
Other real estate	0.12%	322.0868
Rental and leasing services and lessors of intangible assets	0.25%	440.7426
Legal services	0.18%	258.5759
Computer systems design and related services	0.09%	132.6345
Miscellaneous professional, scientific, and technical services	0.13%	793.9402
Management of companies and enterprises	0.18%	242.3504
Administrative and support services	0.18%	436.593
Waste management and remediation services	0.14%	35.027
Educational services	0.02%	-2.25473
Ambulatory health care services	0.00%	9.790209
Hospitals	0.00%	4.456761
Nursing and residential care facilities	0.00%	4.492864
Social assistance	0.00%	4.517544
Performing arts, spectator sports, museums, and related activities	0.08%	20.0903
Amusements, gambling, and recreation industries	0.02%	11.7359
Accommodation	0.06%	31.41518
Food services and drinking places	0.05%	140.1551
Other services, except government	0.05%	142.0585
Federal general government (defense)	0.00%	0.007019
Federal general government (nondefense)	0.01%	0.11595
Federal government enterprises	0.16%	-48.6816
State and local general government	0.01%	-9.18426
State and local government enterprises	0.07%	-868.568

Table C.4 Historic Inoperability and GDP Loss Vector – 2000

Industries	**Inoperability**	**GDP Loss In Millions**
Farms	0.05%	45.9401
Forestry, fishing, and related activities	0.14%	29.72305
Oil and gas extraction	2.28%	2380.23
Mining, except oil and gas	0.61%	254.1911
Support activities for mining	0.24%	38.78792
Utilities	1.21%	6662.547
Construction	0.04%	232.7631
Wood products	0.12%	52.69918
Nonmetallic mineral products	0.15%	59.22839
Primary metals	0.29%	225.6427
Fabricated metal products	0.17%	211.029
Machinery	0.13%	212.7428
Computer and electronic products	0.09%	169.4384
Electrical equipment, appliances, and components	0.12%	78.6675
Motor vehicles, bodies and trailers, and parts	0.05%	99.34463
Other transportation equipment	0.04%	17.2985
Furniture and related products	0.03%	12.08325
Miscellaneous manufacturing	0.04%	5.253565
Food and beverage and tobacco products	0.03%	71.84378
Textile mills and textile product mills	0.09%	35.4236
Apparel and leather and allied products	0.05%	25.60461
Paper products	0.15%	109.4408
Printing and related support activities	0.17%	67.44715
Petroleum and coal products	0.39%	740.4173
Chemical products	0.15%	318.6783
Plastics and rubber products	0.12%	105.2307
Wholesale trade	0.10%	534.6129
Motor vehicle and parts dealers	0.04%	19.10808
Food and beverage stores	0.03%	35.12803
General merchandise stores	0.01%	11.05481
Other retail	0.03%	60.46652
Air transportation	0.11%	93.50907
Rail transportation	0.41%	122.5251
Water transportation	0.05%	3.243373
Truck transportation	0.10%	110.0947
Transit and ground passenger transportation	0.09%	13.59848
Pipeline transportation	1.99%	379.7231

Other transportation and support activities	0.26%	210.0353
Warehousing and storage	0.16%	32.47774
Publishing industries, except internet (includes software)	0.09%	42.89826
Motion picture and sound recording industries	0.05%	27.21454
Broadcasting and telecommunications	0.12%	261.1304
Data processing, internet publishing, and other information services	0.21%	97.45067
Federal Reserve banks, credit intermediation, and related activities	0.30%	1044.849
Securities, commodity contracts, and investments	0.17%	372.9391
Insurance carriers and related activities	0.10%	223.8826
Funds, trusts, and other financial vehicles	0.00%	2.303713
Housing	0.00%	0.001337
Other real estate	0.19%	556.0009
Rental and leasing services and lessors of intangible assets	0.32%	578.6349
Legal services	0.24%	335.2464
Computer systems design and related services	0.12%	195.7555
Miscellaneous professional, scientific, and technical services	0.19%	1217.088
Management of companies and enterprises	0.31%	434.9858
Administrative and support services	0.25%	635.4452
Waste management and remediation services	0.23%	74.43476
Educational services	0.03%	7.812728
Ambulatory health care services	0.00%	1.211762
Hospitals	0.00%	0.010489
Nursing and residential care facilities	0.00%	0.199152
Social assistance	0.00%	-4.04535
Performing arts, spectator sports, museums, and related activities	0.10%	17.93193
Amusements, gambling, and recreation industries	0.03%	18.10841
Accommodation	0.10%	91.46572
Food services and drinking places	0.07%	219.931
Other services, except government	0.07%	236.0936
Federal general government (defense)	0.01%	0.015724
Federal general government (nondefense)	0.01%	0.322905
Federal government enterprises	0.23%	-30.4418
State and local general government	0.01%	-9.6537
State and local government enterprises	0.12%	-858.677

Table C.5 Historic Inoperability and GDP Loss Vector – 2001

Industries	**Inoperability**	**GDP Loss In Millions**
Farms	0.04%	33.80909
Forestry, fishing, and related activities	0.16%	31.6471
Oil and gas extraction	2.46%	2557.342
Mining, except oil and gas	0.78%	329.7647
Support activities for mining	0.23%	53.62708
Utilities	1.22%	7680.667
Construction	0.05%	322.0629
Wood products	0.18%	87.40385
Nonmetallic mineral products	0.17%	71.89444
Primary metals	0.33%	220.3263
Fabricated metal products	0.19%	227.8596
Machinery	0.17%	269.4778
Computer and electronic products	0.11%	187.9678
Electrical equipment, appliances, and components	0.13%	73.94407
Motor vehicles, bodies and trailers, and parts	0.06%	122.9917
Other transportation equipment	0.05%	31.94048
Furniture and related products	0.02%	-3.18655
Miscellaneous manufacturing	0.05%	17.24472
Food and beverage and tobacco products	0.03%	79.4854
Textile mills and textile product mills	0.06%	2.396332
Apparel and leather and allied products	0.03%	2.54746
Paper products	0.16%	100.5313
Printing and related support activities	0.19%	60.912
Petroleum and coal products	0.43%	777.53
Chemical products	0.16%	331.8718
Plastics and rubber products	0.13%	109.6595
Wholesale trade	0.12%	655.6824
Motor vehicle and parts dealers	0.05%	2.255513
Food and beverage stores	0.01%	9.704917
General merchandise stores	0.02%	15.73999
Other retail	0.03%	69.86417
Air transportation	0.14%	99.90505
Rail transportation	0.48%	146.5013
Water transportation	0.12%	25.99651
Truck transportation	0.12%	146.5052
Transit and ground passenger transportation	0.10%	14.0626
Pipeline transportation	2.07%	398.6726

Other transportation and support activities	0.29%	227.9712
Warehousing and storage	0.20%	48.52642
Publishing industries, except internet (includes software)	0.11%	40.09415
Motion picture and sound recording industries	0.06%	18.03585
Broadcasting and telecommunications	0.14%	343.6118
Data processing, internet publishing, and other information services	0.26%	142.6592
Federal Reserve banks, credit intermediation, and related activities	0.38%	1418.693
Securities, commodity contracts, and investments	0.22%	440.4632
Insurance carriers and related activities	0.13%	304.3661
Funds, trusts, and other financial vehicles	0.01%	2.305937
Housing	0.00%	0.002203
Other real estate	0.22%	683.6654
Rental and leasing services and lessors of intangible assets	0.40%	735.4952
Legal services	0.31%	476.965
Computer systems design and related services	0.15%	238.5904
Miscellaneous professional, scientific, and technical services	0.24%	1609.262
Management of companies and enterprises	0.31%	428.8844
Administrative and support services	0.30%	792.4326
Waste management and remediation services	0.24%	79.40734
Educational services	0.04%	11.82094
Ambulatory health care services	0.00%	10.02881
Hospitals	0.00%	0.025468
Nursing and residential care facilities	0.00%	4.476018
Social assistance	0.00%	0.286035
Performing arts, spectator sports, museums, and related activities	0.13%	41.63
Amusements, gambling, and recreation industries	0.04%	23.32903
Accommodation	0.13%	116.0019
Food services and drinking places	0.10%	300.5395
Other services, except government	0.09%	288.1918
Federal general government (defense)	0.01%	0.027839
Federal general government (nondefense)	0.01%	0.28878
Federal government enterprises	0.27%	-24.4171
State and local general government	0.01%	-10.1573
State and local government enterprises	0.14%	-837.212

Table C.6 Historic Inoperability and GDP Loss Vector – 2002

Industries	**Inoperability**	**GDP Loss In Millions**
Farms	0.03%	25.10375
Forestry, fishing, and related activities	0.11%	29.74669
Oil and gas extraction	1.63%	1415.37
Mining, except oil and gas	0.40%	160.8283
Support activities for mining	0.14%	32.21061
Utilities	1.09%	5567.18
Construction	0.03%	162.4971
Wood products	0.07%	28.01791
Nonmetallic mineral products	0.08%	31.53924
Primary metals	0.18%	124.3341
Fabricated metal products	0.11%	125.0247
Machinery	0.11%	185.3016
Computer and electronic products	0.06%	79.2015
Electrical equipment, appliances, and components	0.08%	41.27136
Motor vehicles, bodies and trailers, and parts	0.03%	73.67872
Other transportation equipment	0.02%	2.082794
Furniture and related products	0.02%	4.837543
Miscellaneous manufacturing	0.03%	7.525958
Food and beverage and tobacco products	0.02%	42.10999
Textile mills and textile product mills	0.06%	20.77047
Apparel and leather and allied products	0.03%	11.85932
Paper products	0.09%	54.29518
Printing and related support activities	0.12%	54.81908
Petroleum and coal products	0.21%	348.8273
Chemical products	0.07%	147.4112
Plastics and rubber products	0.07%	64.62629
Wholesale trade	0.06%	304.8181
Motor vehicle and parts dealers	0.03%	11.84059
Food and beverage stores	0.01%	17.01033
General merchandise stores	0.00%	-6.60124
Other retail	0.02%	39.80573
Air transportation	0.07%	47.14318
Rail transportation	0.30%	98.28372
Water transportation	0.05%	10.59432
Truck transportation	0.06%	58.41006
Transit and ground passenger transportation	0.11%	37.95144
Pipeline transportation	1.61%	310.6235

Other transportation and support activities	0.15%	130.1517
Warehousing and storage	0.11%	26.81036
Publishing industries, except internet (includes software)	0.05%	13.56677
Motion picture and sound recording industries	0.03%	14.52703
Broadcasting and telecommunications	0.07%	143.2577
Data processing, internet publishing, and other information services	0.12%	57.86972
Federal Reserve banks, credit intermediation, and related activities	0.21%	842.8268
Securities, commodity contracts, and investments	0.12%	229.0692
Insurance carriers and related activities	0.07%	172.0761
Funds, trusts, and other financial vehicles	0.00%	-2.82279
Housing	0.00%	0.000661
Other real estate	0.12%	397.8118
Rental and leasing services and lessors of intangible assets	0.22%	387.4529
Legal services	0.17%	275.2156
Computer systems design and related services	0.08%	122.3093
Miscellaneous professional, scientific, and technical services	0.13%	854.5509
Management of companies and enterprises	0.14%	183.7683
Administrative and support services	0.16%	413.1858
Waste management and remediation services	0.14%	48.15515
Educational services	0.02%	8.7773
Ambulatory health care services	0.00%	0.715056
Hospitals	0.00%	0.006394
Nursing and residential care facilities	0.00%	0.159838
Social assistance	0.00%	0.137828
Performing arts, spectator sports, museums, and related activities	0.08%	36.35248
Amusements, gambling, and recreation industries	0.02%	7.01764
Accommodation	0.06%	50.87513
Food services and drinking places	0.05%	178.1582
Other services, except government	0.04%	146.944
Federal general government (defense)	0.00%	0.008552
Federal general government (nondefense)	0.01%	0.144834
Federal government enterprises	0.16%	-44.6331
State and local general government	0.01%	-10.5127
State and local government enterprises	0.07%	-857.469

Table C.7 Historic Inoperability and GDP Loss Vector – 2003

Industries	**Inoperability**	**GDP Loss In Millions**
Farms	0.02%	10.49969
Forestry, fishing, and related activities	0.09%	23.74031
Oil and gas extraction	1.97%	2332.753
Mining, except oil and gas	0.30%	112.9171
Support activities for mining	0.17%	41.01974
Utilities	1.10%	5741.567
Construction	0.03%	180.0429
Wood products	0.08%	34.35401
Nonmetallic mineral products	0.11%	61.02097
Primary metals	0.20%	135.6402
Fabricated metal products	0.12%	140.0089
Machinery	0.12%	191.0371
Computer and electronic products	0.05%	64.63326
Electrical equipment, appliances, and components	0.07%	23.24969
Motor vehicles, bodies and trailers, and parts	0.03%	49.20751
Other transportation equipment	0.03%	6.839402
Furniture and related products	0.03%	13.19066
Miscellaneous manufacturing	0.03%	10.94005
Food and beverage and tobacco products	0.01%	38.13467
Textile mills and textile product mills	0.06%	20.77174
Apparel and leather and allied products	0.04%	16.14687
Paper products	0.09%	64.9244
Printing and related support activities	0.10%	38.04132
Petroleum and coal products	0.19%	344.2108
Chemical products	0.08%	190.9978
Plastics and rubber products	0.07%	51.41555
Wholesale trade	0.06%	294.3939
Motor vehicle and parts dealers	0.03%	15.7337
Food and beverage stores	0.01%	8.614221
General merchandise stores	0.00%	-6.37541
Other retail	0.01%	24.88943
Air transportation	0.06%	30.75792
Rail transportation	0.20%	51.34207
Water transportation	0.07%	16.24125
Truck transportation	0.05%	47.80682
Transit and ground passenger transportation	0.06%	13.59166
Pipeline transportation	1.77%	312.532

Other transportation and support activities	0.16%	145.7925
Warehousing and storage	0.10%	26.88169
Publishing industries, except internet (includes software)	0.06%	27.48394
Motion picture and sound recording industries	0.04%	26.3204
Broadcasting and telecommunications	0.07%	166.8607
Data processing, internet publishing, and other information services	0.11%	50.77294
Federal Reserve banks, credit intermediation, and related activities	0.19%	753.8582
Securities, commodity contracts, and investments	0.12%	233.9095
Insurance carriers and related activities	0.07%	191.9307
Funds, trusts, and other financial vehicles	0.00%	1.657492
Housing	0.00%	0.000765
Other real estate	0.11%	431.0322
Rental and leasing services and lessors of intangible assets	0.20%	339.4572
Legal services	0.16%	263.5388
Computer systems design and related services	0.08%	122.1743
Miscellaneous professional, scientific, and technical services	0.12%	791.7545
Management of companies and enterprises	0.17%	241.4842
Administrative and support services	0.16%	404.0337
Waste management and remediation services	0.17%	71.12661
Educational services	0.02%	8.215661
Ambulatory health care services	0.00%	-3.40436
Hospitals	0.00%	4.04816
Nursing and residential care facilities	0.00%	0.145959
Social assistance	0.00%	4.131896
Performing arts, spectator sports, museums, and related activities	0.06%	18.37889
Amusements, gambling, and recreation industries	0.01%	-1.82979
Accommodation	0.05%	43.83422
Food services and drinking places	0.05%	155.742
Other services, except government	0.04%	137.2671
Federal general government (defense)	0.00%	0.007973
Federal general government (nondefense)	0.01%	0.182312
Federal government enterprises	0.12%	-86.3609
State and local general government	0.01%	-10.8175
State and local government enterprises	0.07%	-868.838

Table C.8 Historic Inoperability and GDP Loss Vector – 2004

Industries	**Inoperability**	**GDP Loss In Millions**
Farms	0.02%	11.76335
Forestry, fishing, and related activities	0.07%	8.992341
Oil and gas extraction	1.91%	2707.331
Mining, except oil and gas	0.26%	110.1761
Support activities for mining	0.16%	44.77607
Utilities	1.09%	5992.562
Construction	0.03%	212.071
Wood products	0.10%	59.44354
Nonmetallic mineral products	0.09%	42.72051
Primary metals	0.19%	174.7651
Fabricated metal products	0.10%	133.6517
Machinery	0.09%	132.435
Computer and electronic products	0.05%	78.80039
Electrical equipment, appliances, and components	0.06%	32.50218
Motor vehicles, bodies and trailers, and parts	0.02%	28.42833
Other transportation equipment	0.03%	15.56093
Furniture and related products	0.03%	18.12354
Miscellaneous manufacturing	0.03%	22.36116
Food and beverage and tobacco products	0.01%	44.7042
Textile mills and textile product mills	0.06%	25.12734
Apparel and leather and allied products	0.05%	16.67783
Paper products	0.08%	58.59014
Printing and related support activities	0.07%	15.15316
Petroleum and coal products	0.17%	426.4512
Chemical products	0.08%	225.1273
Plastics and rubber products	0.07%	59.31397
Wholesale trade	0.05%	319.9065
Motor vehicle and parts dealers	0.02%	-0.6233
Food and beverage stores	0.01%	0.56735
General merchandise stores	0.00%	-10.6325
Other retail	0.01%	48.4794
Air transportation	0.06%	41.60491
Rail transportation	0.17%	51.287
Water transportation	0.08%	23.64969
Truck transportation	0.05%	42.39175
Transit and ground passenger transportation	0.08%	28.81884
Pipeline transportation	1.73%	310.5688

Other transportation and support activities	0.16%	163.456
Warehousing and storage	0.07%	19.75506
Publishing industries, except internet (includes software)	0.04%	2.070383
Motion picture and sound recording industries	0.02%	7.5886
Broadcasting and telecommunications	0.06%	133.2351
Data processing, internet publishing, and other information services	0.10%	54.16672
Federal Reserve banks, credit intermediation, and related activities	0.15%	609.1213
Securities, commodity contracts, and investments	0.09%	186.4018
Insurance carriers and related activities	0.06%	176.5953
Funds, trusts, and other financial vehicles	0.00%	1.82707
Housing	0.00%	0.000941
Other real estate	0.09%	386.2653
Rental and leasing services and lessors of intangible assets	0.17%	305.4164
Legal services	0.13%	232.1614
Computer systems design and related services	0.06%	103.1593
Miscellaneous professional, scientific, and technical services	0.10%	720.2355
Management of companies and enterprises	0.15%	238.0285
Administrative and support services	0.13%	361.8325
Waste management and remediation services	0.12%	45.98181
Educational services	0.02%	3.35684
Ambulatory health care services	0.00%	-3.43685
Hospitals	0.00%	0.006022
Nursing and residential care facilities	0.00%	0.123312
Social assistance	0.00%	-3.99169
Performing arts, spectator sports, museums, and related activities	0.05%	18.45081
Amusements, gambling, and recreation industries	0.01%	5.964308
Accommodation	0.05%	60.44585
Food services and drinking places	0.03%	107.5835
Other services, except government	0.03%	109.3011
Federal general government (defense)	0.00%	0.005857
Federal general government (nondefense)	0.01%	0.22594
Federal government enterprises	0.11%	-89.3477
State and local general government	0.01%	-11.6177
State and local government enterprises	0.06%	-935.003

Table C.9 Historic Inoperability and GDP Loss Vector – 2005

Industries	**Inoperability**	**GDP Loss In Millions**
Farms	0.02%	8.497012
Forestry, fishing, and related activities	0.10%	28.60822
Oil and gas extraction	2.08%	4599.561
Mining, except oil and gas	0.38%	253.1614
Support activities for mining	0.19%	86.79174
Utilities	1.12%	8550.415
Construction	0.04%	401.0384
Wood products	0.10%	58.13677
Nonmetallic mineral products	0.13%	98.02687
Primary metals	0.26%	303.4246
Fabricated metal products	0.14%	221.416
Machinery	0.13%	244.5458
Computer and electronic products	0.07%	119.1841
Electrical equipment, appliances, and components	0.09%	61.84408
Motor vehicles, bodies and trailers, and parts	0.04%	127.4504
Other transportation equipment	0.03%	12.9983
Furniture and related products	0.02%	9.565198
Miscellaneous manufacturing	0.03%	27.39658
Food and beverage and tobacco products	0.01%	43.24514
Textile mills and textile product mills	0.06%	14.95911
Apparel and leather and allied products	0.05%	16.763
Paper products	0.11%	94.52732
Printing and related support activities	0.12%	52.15812
Petroleum and coal products	0.25%	1025.759
Chemical products	0.12%	409.5798
Plastics and rubber products	0.09%	85.16638
Wholesale trade	0.07%	545.9529
Motor vehicle and parts dealers	0.03%	11.26709
Food and beverage stores	0.01%	10.8659
General merchandise stores	0.00%	-2.07571
Other retail	0.02%	53.20248
Air transportation	0.08%	77.86243
Rail transportation	0.26%	116.469
Water transportation	0.08%	25.09216
Truck transportation	0.07%	116.794
Transit and ground passenger transportation	0.09%	41.50077
Pipeline transportation	1.76%	369.8873

Other transportation and support activities	0.21%	269.2537
Warehousing and storage	0.14%	67.89446
Publishing industries, except internet (includes software)	0.06%	5.267783
Motion picture and sound recording industries	0.04%	33.72529
Broadcasting and telecommunications	0.08%	227.9815
Data processing, internet publishing, and other information services	0.13%	91.50261
Federal Reserve banks, credit intermediation, and related activities	0.19%	994.3686
Securities, commodity contracts, and investments	0.12%	354.525
Insurance carriers and related activities	0.08%	308.9071
Funds, trusts, and other financial vehicles	0.01%	4.050315
Housing	0.00%	0.002291
Other real estate	0.12%	755.7215
Rental and leasing services and lessors of intangible assets	0.19%	410.1903
Legal services	0.17%	376.5381
Computer systems design and related services	0.08%	165.6622
Miscellaneous professional, scientific, and technical services	0.14%	1302.515
Management of companies and enterprises	0.22%	489.7845
Administrative and support services	0.18%	662.4107
Waste management and remediation services	0.20%	123.1727
Educational services	0.02%	7.578519
Ambulatory health care services	0.00%	1.234277
Hospitals	0.00%	5.045793
Nursing and residential care facilities	0.00%	0.211433
Social assistance	0.00%	0.143283
Performing arts, spectator sports, museums, and related activities	0.06%	26.35427
Amusements, gambling, and recreation industries	0.01%	-5.53948
Accommodation	0.05%	49.87882
Food services and drinking places	0.05%	199.3919
Other services, except government	0.04%	190.6121
Federal general government (defense)	0.00%	0.014584
Federal general government (nondefense)	0.01%	0.620137
Federal government enterprises	0.15%	-98.2376
State and local general government	0.01%	-14.6509
State and local government enterprises	0.08%	-1202.96

Table C.10 Historic Inoperability and GDP Loss Vector – 2006

Industries	**Inoperability**	**GDP Loss In Millions**
Farms	0.03%	50.21721
Forestry, fishing, and related activities	0.10%	38.21301
Oil and gas extraction	1.59%	4291.085
Mining, except oil and gas	0.33%	310.3988
Support activities for mining	0.15%	124.0944
Utilities	1.10%	10020.41
Construction	0.03%	444.7503
Wood products	0.10%	87.12791
Nonmetallic mineral products	0.09%	78.67257
Primary metals	0.20%	279.3811
Fabricated metal products	0.11%	234.0569
Machinery	0.08%	192.7938
Computer and electronic products	0.06%	118.5172
Electrical equipment, appliances, and components	0.08%	70.90029
Motor vehicles, bodies and trailers, and parts	0.03%	85.69954
Other transportation equipment	0.03%	26.52581
Furniture and related products	0.02%	4.461998
Miscellaneous manufacturing	0.01%	-14.7221
Food and beverage and tobacco products	0.01%	51.46765
Textile mills and textile product mills	0.06%	30.10155
Apparel and leather and allied products	0.02%	4.490576
Paper products	0.09%	99.0207
Printing and related support activities	0.10%	65.65487
Petroleum and coal products	0.19%	1035.994
Chemical products	0.11%	494.8741
Plastics and rubber products	0.08%	108.8101
Wholesale trade	0.06%	552.9204
Motor vehicle and parts dealers	0.02%	17.68668
Food and beverage stores	0.00%	-4.63256
General merchandise stores	0.00%	2.987119
Other retail	0.02%	80.67776
Air transportation	0.06%	68.52952
Rail transportation	0.23%	135.069
Water transportation	0.06%	25.66967
Truck transportation	0.05%	98.60565
Transit and ground passenger transportation	0.07%	39.47343
Pipeline transportation	1.52%	399.0759

Other transportation and support activities	0.20%	348.3125
Warehousing and storage	0.10%	56.40008
Publishing industries, except internet (includes software)	0.04%	25.59967
Motion picture and sound recording industries	0.03%	24.22032
Broadcasting and telecommunications	0.06%	202.9201
Data processing, internet publishing, and other information services	0.11%	102.8926
Federal Reserve banks, credit intermediation, and related activities	0.14%	898.1188
Securities, commodity contracts, and investments	0.09%	337.0384
Insurance carriers and related activities	0.06%	258.2208
Funds, trusts, and other financial vehicles	0.00%	-0.9882
Housing	0.00%	0.002302
Other real estate	0.09%	651.6959
Rental and leasing services and lessors of intangible assets	0.14%	382.0785
Legal services	0.14%	377.9856
Computer systems design and related services	0.06%	131.4894
Miscellaneous professional, scientific, and technical services	0.10%	1229.29
Management of companies and enterprises	0.16%	433.9713
Administrative and support services	0.14%	619.8785
Waste management and remediation services	0.11%	62.86184
Educational services	0.02%	5.217416
Ambulatory health care services	0.00%	6.594167
Hospitals	0.00%	0.026554
Nursing and residential care facilities	0.00%	-5.5555
Social assistance	0.00%	0.103181
Performing arts, spectator sports, museums, and related activities	0.05%	29.56737
Amusements, gambling, and recreation industries	0.01%	-1.96196
Accommodation	0.04%	71.53532
Food services and drinking places	0.03%	185.3821
Other services, except government	0.03%	164.788
Federal general government (defense)	0.00%	0.010636
Federal general government (nondefense)	0.01%	0.593564
Federal government enterprises	0.12%	-147.854
State and local general government	0.01%	-18.1725
State and local government enterprises	0.06%	-1545.14

Table C.11 Historic Inoperability and GDP Loss Vector – 2007

Industries	**Inoperability**	**GDP Loss In Millions**
Farms	0.03%	56.2078
Forestry, fishing, and related activities	0.09%	29.78959
Oil and gas extraction	1.69%	4489.133
Mining, except oil and gas	0.36%	318.6211
Support activities for mining	0.17%	131.8876
Utilities	1.11%	9889.195
Construction	0.04%	498.893
Wood products	0.10%	59.70624
Nonmetallic mineral products	0.10%	78.78445
Primary metals	0.21%	308.1763
Fabricated metal products	0.13%	280.2244
Machinery	0.08%	196.0564
Computer and electronic products	0.06%	139.9798
Electrical equipment, appliances, and components	0.08%	66.46489
Motor vehicles, bodies and trailers, and parts	0.04%	113.7293
Other transportation equipment	0.02%	10.55758
Furniture and related products	0.01%	-9.96923
Miscellaneous manufacturing	0.03%	28.30751
Food and beverage and tobacco products	0.01%	47.64976
Textile mills and textile product mills	0.03%	-1.01633
Apparel and leather and allied products	-0.02%	-18.9166
Paper products	0.09%	91.75211
Printing and related support activities	0.10%	52.25712
Petroleum and coal products	0.22%	1278.894
Chemical products	0.13%	624.087
Plastics and rubber products	0.08%	96.03421
Wholesale trade	0.06%	552.8309
Motor vehicle and parts dealers	0.02%	6.480434
Food and beverage stores	0.00%	-9.55343
General merchandise stores	0.01%	8.231023
Other retail	0.02%	74.91251
Air transportation	0.06%	77.06961
Rail transportation	0.25%	139.8165
Water transportation	0.07%	28.49871
Truck transportation	0.06%	111.681
Transit and ground passenger transportation	0.04%	6.841352
Pipeline transportation	1.68%	439.2388

Other transportation and support activities	0.26%	475.0452
Warehousing and storage	0.10%	54.57881
Publishing industries, except internet (includes software)	0.05%	34.56704
Motion picture and sound recording industries	0.01%	-6.12536
Broadcasting and telecommunications	0.05%	148.0657
Data processing, internet publishing, and other information services	0.12%	118.4375
Federal Reserve banks, credit intermediation, and related activities	0.13%	772.2181
Securities, commodity contracts, and investments	0.08%	277.4872
Insurance carriers and related activities	0.06%	297.8423
Funds, trusts, and other financial vehicles	0.01%	6.757245
Housing	0.00%	0.002758
Other real estate	0.09%	576.5463
Rental and leasing services and lessors of intangible assets	0.12%	310.0517
Legal services	0.15%	390.052
Computer systems design and related services	0.06%	154.3248
Miscellaneous professional, scientific, and technical services	0.10%	1195.044
Management of companies and enterprises	0.15%	420.4601
Administrative and support services	0.14%	623.561
Waste management and remediation services	0.12%	74.07028
Educational services	0.01%	2.573904
Ambulatory health care services	0.00%	0.673904
Hospitals	0.00%	0.008223
Nursing and residential care facilities	0.00%	-5.17306
Social assistance	0.00%	5.349315
Performing arts, spectator sports, museums, and related activities	0.05%	49.11115
Amusements, gambling, and recreation industries	0.02%	17.54286
Accommodation	0.03%	25.84174
Food services and drinking places	0.03%	179.848
Other services, except government	0.03%	147.2743
Federal general government (defense)	0.00%	0.010241
Federal general government (nondefense)	0.01%	0.450612
Federal government enterprises	0.14%	-120.762
State and local general government	0.01%	-17.7764
State and local government enterprises	0.07%	-1507.01

Table C.12 Historic Inoperability and GDP Loss Vector – 2008

Industries	**Inoperability**	**GDP Loss In Millions**
Farms	0.02%	31.02793
Forestry, fishing, and related activities	0.07%	10.63027
Oil and gas extraction	1.77%	4409.924
Mining, except oil and gas	0.39%	269.9501
Support activities for mining	0.15%	77.9817
Utilities	1.12%	7586.057
Construction	0.05%	394.9421
Wood products	0.10%	30.8321
Nonmetallic mineral products	0.12%	51.73541
Primary metals	0.24%	250.5749
Fabricated metal products	0.14%	223.7722
Machinery	0.09%	156.086
Computer and electronic products	0.07%	94.52833
Electrical equipment, appliances, and components	0.09%	43.58532
Motor vehicles, bodies and trailers, and parts	0.04%	41.51289
Other transportation equipment	0.03%	20.38887
Furniture and related products	0.03%	7.93061
Miscellaneous manufacturing	0.02%	4.510923
Food and beverage and tobacco products	0.01%	40.88022
Textile mills and textile product mills	0.04%	-0.89312
Apparel and leather and allied products	0.05%	6.541887
Paper products	0.10%	67.9272
Printing and related support activities	0.11%	38.392
Petroleum and coal products	0.22%	1040.801
Chemical products	0.14%	494.1963
Plastics and rubber products	0.09%	72.46414
Wholesale trade	0.07%	457.7589
Motor vehicle and parts dealers	0.02%	1.113272
Food and beverage stores	0.00%	-10.0948
General merchandise stores	0.01%	13.27959
Other retail	0.02%	62.46533
Air transportation	0.07%	64.68249
Rail transportation	0.25%	103.299
Water transportation	0.07%	17.04179
Truck transportation	0.07%	73.60367
Transit and ground passenger transportation	0.06%	20.26524
Pipeline transportation	1.88%	393.2351

Other transportation and support activities	0.24%	300.4333
Warehousing and storage	0.11%	44.83158
Publishing industries, except internet (includes software)	0.05%	29.36078
Motion picture and sound recording industries	0.03%	20.89407
Broadcasting and telecommunications	0.06%	121.6443
Data processing, internet publishing, and other information services	0.12%	77.19723
Federal Reserve banks, credit intermediation, and related activities	0.15%	615.14
Securities, commodity contracts, and investments	0.07%	164.4126
Insurance carriers and related activities	0.07%	210.5176
Funds, trusts, and other financial vehicles	0.01%	4.155415
Housing	0.00%	0.00214
Other real estate	0.10%	384.4114
Rental and leasing services and lessors of intangible assets	0.13%	248.1016
Legal services	0.18%	326.2661
Computer systems design and related services	0.07%	138.7662
Miscellaneous professional, scientific, and technical services	0.12%	999.8455
Management of companies and enterprises	0.19%	377.9785
Administrative and support services	0.15%	508.145
Waste management and remediation services	0.15%	73.10805
Educational services	0.02%	4.746325
Ambulatory health care services	0.00%	0.583335
Hospitals	0.00%	0.009072
Nursing and residential care facilities	0.00%	0.064159
Social assistance	0.00%	-3.56504
Performing arts, spectator sports, museums, and related activities	0.05%	27.79341
Amusements, gambling, and recreation industries	0.01%	0.731582
Accommodation	0.05%	47.52413
Food services and drinking places	0.04%	139.9623
Other services, except government	0.03%	98.13041
Federal general government (defense)	0.00%	0.009875
Federal general government (nondefense)	0.01%	0.556476
Federal government enterprises	0.13%	-105.452
State and local general government	0.01%	-12.6858
State and local government enterprises	0.08%	-1090.35

Table C.13 Historic Inoperability and GDP Loss Vector – 2009

Industries	**Inoperability**	**GDP Loss In Millions**
Farms	0.01%	20.20519
Forestry, fishing, and related activities	0.05%	8.722667
Oil and gas extraction	1.13%	1462.128
Mining, except oil and gas	0.34%	206.5173
Support activities for mining	0.08%	25.92756
Utilities	1.06%	5330.599
Construction	0.03%	177.6379
Wood products	0.08%	21.59848
Nonmetallic mineral products	0.07%	27.98393
Primary metals	0.13%	65.24089
Fabricated metal products	0.08%	101.5705
Machinery	0.06%	71.4979
Computer and electronic products	0.04%	51.99366
Electrical equipment, appliances, and components	0.05%	23.06041
Motor vehicles, bodies and trailers, and parts	0.02%	20.66921
Other transportation equipment	0.02%	23.08302
Furniture and related products	0.03%	12.45424
Miscellaneous manufacturing	0.00%	-10.9499
Food and beverage and tobacco products	0.01%	9.019062
Textile mills and textile product mills	0.05%	10.00286
Apparel and leather and allied products	0.03%	4.195739
Paper products	0.06%	40.1967
Printing and related support activities	0.07%	28.47081
Petroleum and coal products	0.13%	367.7705
Chemical products	0.06%	167.5659
Plastics and rubber products	0.05%	26.35033
Wholesale trade	0.04%	203.3426
Motor vehicle and parts dealers	0.02%	8.49111
Food and beverage stores	0.00%	-8.93509
General merchandise stores	0.00%	4.466391
Other retail	0.01%	19.34576
Air transportation	0.04%	21.99422
Rail transportation	0.21%	68.70541
Water transportation	0.04%	8.147196
Truck transportation	0.04%	26.06644
Transit and ground passenger transportation	0.05%	17.47051
Pipeline transportation	1.33%	206.4932

Other transportation and support activities	0.17%	171.723
Warehousing and storage	0.07%	27.22639
Publishing industries, except internet (includes software)	0.02%	6.418581
Motion picture and sound recording industries	0.02%	8.49854
Broadcasting and telecommunications	0.03%	73.81714
Data processing, internet publishing, and other information services	0.07%	48.44787
Federal Reserve banks, credit intermediation, and related activities	0.08%	258.9733
Securities, commodity contracts, and investments	0.04%	80.33001
Insurance carriers and related activities	0.04%	97.4733
Funds, trusts, and other financial vehicles	0.00%	1.467949
Housing	0.00%	0.000351
Other real estate	0.06%	193.1001
Rental and leasing services and lessors of intangible assets	0.07%	96.52276
Legal services	0.10%	148.0205
Computer systems design and related services	0.04%	60.58903
Miscellaneous professional, scientific, and technical services	0.06%	459.0512
Management of companies and enterprises	0.08%	125.1729
Administrative and support services	0.09%	227.4121
Waste management and remediation services	0.09%	35.67311
Educational services	0.01%	4.904644
Ambulatory health care services	0.00%	6.687606
Hospitals	0.00%	-3.12044
Nursing and residential care facilities	0.00%	0.038471
Social assistance	0.00%	0.049169
Performing arts, spectator sports, museums, and related activities	0.04%	25.21433
Amusements, gambling, and recreation industries	0.00%	-2.21413
Accommodation	0.03%	23.04297
Food services and drinking places	0.02%	64.05739
Other services, except government	0.02%	65.37691
Federal general government (defense)	0.00%	0.002535
Federal general government (nondefense)	0.00%	0.535134
Federal government enterprises	0.08%	-101.681
State and local general government	0.00%	-11.3711
State and local government enterprises	0.04%	-980.924

Table C.14 Historic Inoperability and GDP Loss Vector – 2010

Industries	**Inoperability**	**GDP Loss In Millions**
Farms	0.02%	18.12969
Forestry, fishing, and related activities	0.06%	10.40038
Oil and gas extraction	1.08%	1782.378
Mining, except oil and gas	0.35%	223.5994
Support activities for mining	0.09%	34.65151
Utilities	1.07%	5807.364
Construction	0.04%	211.2194
Wood products	0.09%	25.68669
Nonmetallic mineral products	0.08%	26.83371
Primary metals	0.18%	157.7986
Fabricated metal products	0.10%	112.4219
Machinery	0.07%	87.95294
Computer and electronic products	0.05%	53.4702
Electrical equipment, appliances, and components	0.07%	33.60472
Motor vehicles, bodies and trailers, and parts	0.03%	57.72253
Other transportation equipment	0.02%	11.61098
Furniture and related products	0.03%	10.4678
Miscellaneous manufacturing	0.02%	6.789587
Food and beverage and tobacco products	0.01%	26.29058
Textile mills and textile product mills	0.05%	7.12284
Apparel and leather and allied products	0.02%	1.627822
Paper products	0.06%	36.07617
Printing and related support activities	0.07%	18.58058
Petroleum and coal products	0.13%	455.2879
Chemical products	0.09%	282.5442
Plastics and rubber products	0.05%	30.37697
Wholesale trade	0.05%	256.6179
Motor vehicle and parts dealers	0.02%	15.90754
Food and beverage stores	0.00%	-2.62742
General merchandise stores	0.00%	-4.60804
Other retail	0.01%	30.10231
Air transportation	0.05%	39.70668
Rail transportation	0.21%	76.99713
Water transportation	0.04%	8.108469
Truck transportation	0.05%	53.23075
Transit and ground passenger transportation	0.04%	10.43762
Pipeline transportation	1.25%	203.8899

Other transportation and support activities	0.12%	114.6798
Warehousing and storage	0.06%	17.24446
Publishing industries, except internet (includes software)	0.03%	7.45349
Motion picture and sound recording industries	0.02%	7.535743
Broadcasting and telecommunications	0.04%	84.19771
Data processing, internet publishing, and other information services	0.08%	57.94663
Federal Reserve banks, credit intermediation, and related activities	0.10%	321.9603
Securities, commodity contracts, and investments	0.06%	112.7721
Insurance carriers and related activities	0.04%	104.1708
Funds, trusts, and other financial vehicles	0.00%	-0.88133
Housing	0.00%	0.000438
Other real estate	0.06%	206.4962
Rental and leasing services and lessors of intangible assets	0.09%	136.7931
Legal services	0.12%	177.7849
Computer systems design and related services	0.05%	92.18257
Miscellaneous professional, scientific, and technical services	0.08%	573.046
Management of companies and enterprises	0.13%	244.721
Administrative and support services	0.11%	321.013
Waste management and remediation services	0.12%	65.50817
Educational services	0.01%	0.634747
Ambulatory health care services	0.00%	3.759024
Hospitals	0.00%	0.005363
Nursing and residential care facilities	0.00%	-3.11077
Social assistance	0.00%	-3.0901
Performing arts, spectator sports, museums, and related activities	0.03%	7.923837
Amusements, gambling, and recreation industries	0.01%	8.468632
Accommodation	0.03%	19.7606
Food services and drinking places	0.03%	81.76191
Other services, except government	0.03%	84.25216
Federal general government (defense)	0.00%	0.003964
Federal general government (nondefense)	0.00%	0.742442
Federal government enterprises	0.10%	-105.825
State and local general government	0.00%	-12.0539
State and local government enterprises	0.05%	-1006.75

Table C.15 Historic Inoperability and GDP Loss Vector – 2011

Industries	**Inoperability**	**GDP Loss In Millions**
Farms	0.01%	9.47647
Forestry, fishing, and related activities	0.07%	20.62939
Oil and gas extraction	0.75%	1412.228
Mining, except oil and gas	0.25%	178.5637
Support activities for mining	0.07%	33.98515
Utilities	1.05%	5498.319
Construction	0.03%	190.9271
Wood products	0.08%	29.00593
Nonmetallic mineral products	0.10%	44.63085
Primary metals	0.15%	137.7954
Fabricated metal products	0.08%	102.643
Machinery	0.06%	89.8699
Computer and electronic products	0.04%	29.87117
Electrical equipment, appliances, and components	0.05%	21.85739
Motor vehicles, bodies and trailers, and parts	0.02%	30.50342
Other transportation equipment	0.01%	8.21196
Furniture and related products	0.02%	3.316141
Miscellaneous manufacturing	0.02%	8.969644
Food and beverage and tobacco products	0.01%	17.34815
Textile mills and textile product mills	0.05%	9.997457
Apparel and leather and allied products	0.02%	1.527791
Paper products	0.05%	23.6142
Printing and related support activities	0.06%	21.80117
Petroleum and coal products	0.10%	454.2713
Chemical products	0.08%	292.5251
Plastics and rubber products	0.05%	43.45077
Wholesale trade	0.04%	230.7905
Motor vehicle and parts dealers	0.01%	-6.60182
Food and beverage stores	0.00%	3.598527
General merchandise stores	0.00%	-1.67905
Other retail	0.01%	29.56371
Air transportation	0.04%	32.17818
Rail transportation	0.16%	62.04248
Water transportation	0.01%	-6.73249
Truck transportation	0.04%	43.1953
Transit and ground passenger transportation	0.05%	20.80326
Pipeline transportation	1.04%	177.7728

Other transportation and support activities	0.09%	96.55387
Warehousing and storage	0.06%	22.15932
Publishing industries, except internet (includes software)	0.03%	18.81353
Motion picture and sound recording industries	0.02%	12.28734
Broadcasting and telecommunications	0.03%	68.98655
Data processing, internet publishing, and other information services	0.06%	36.57712
Federal Reserve banks, credit intermediation, and related activities	0.07%	213.0052
Securities, commodity contracts, and investments	0.04%	73.85591
Insurance carriers and related activities	0.03%	86.92174
Funds, trusts, and other financial vehicles	0.00%	1.320868
Housing	0.00%	0.000373
Other real estate	0.05%	150.5438
Rental and leasing services and lessors of intangible assets	0.08%	131.2335
Legal services	0.09%	134.6999
Computer systems design and related services	0.04%	73.28567
Miscellaneous professional, scientific, and technical services	0.06%	471.319
Management of companies and enterprises	0.10%	195.1728
Administrative and support services	0.09%	271.6931
Waste management and remediation services	0.07%	26.86232
Educational services	0.01%	9.234608
Ambulatory health care services	0.00%	3.619489
Hospitals	0.00%	0.003789
Nursing and residential care facilities	0.00%	0.039553
Social assistance	0.00%	-3.10517
Performing arts, spectator sports, museums, and related activities	0.03%	8.89708
Amusements, gambling, and recreation industries	0.01%	-2.01392
Accommodation	0.02%	22.91939
Food services and drinking places	0.02%	74.30843
Other services, except government	0.02%	52.62288
Federal general government (defense)	0.00%	0.002753
Federal general government (nondefense)	0.00%	1.135044
Federal government enterprises	0.07%	-123.738
State and local general government	0.00%	-12.4035
State and local government enterprises	0.03%	-1027.45

Table C.16 Historic Inoperability and GDP Loss Vector – 2012

Industries	**Inoperability**	**GDP Loss In Millions**
Farms	0.01%	16.8848
Forestry, fishing, and related activities	0.04%	5.101727
Oil and gas extraction	0.57%	1035.549
Mining, except oil and gas	0.20%	144.4613
Support activities for mining	0.05%	27.32774
Utilities	1.04%	5107.044
Construction	0.03%	178.7958
Wood products	0.08%	35.34111
Nonmetallic mineral products	0.08%	41.3246
Primary metals	0.12%	128.0733
Fabricated metal products	0.07%	99.6261
Machinery	0.05%	110.7252
Computer and electronic products	0.04%	42.13143
Electrical equipment, appliances, and components	0.05%	22.52371
Motor vehicles, bodies and trailers, and parts	0.02%	21.1563
Other transportation equipment	0.01%	3.670406
Furniture and related products	0.01%	2.926313
Miscellaneous manufacturing	0.02%	14.6293
Food and beverage and tobacco products	0.01%	3.467872
Textile mills and textile product mills	0.03%	5.747353
Apparel and leather and allied products	0.02%	5.598305
Paper products	0.04%	21.14653
Printing and related support activities	0.04%	9.308704
Petroleum and coal products	0.10%	480.4984
Chemical products	0.06%	200.788
Plastics and rubber products	0.04%	22.95365
Wholesale trade	0.03%	212.5454
Motor vehicle and parts dealers	0.01%	11.89462
Food and beverage stores	0.00%	0.319934
General merchandise stores	0.01%	13.52874
Other retail	0.01%	15.80683
Air transportation	0.03%	22.95521
Rail transportation	0.13%	56.07983
Water transportation	0.04%	11.58085
Truck transportation	0.03%	43.58886
Transit and ground passenger transportation	0.01%	0.235242
Pipeline transportation	0.88%	147.3611

Other transportation and support activities	0.13%	155.2731
Warehousing and storage	0.05%	19.47824
Publishing industries, except internet (includes software)	0.02%	15.80024
Motion picture and sound recording industries	0.02%	9.799039
Broadcasting and telecommunications	0.02%	43.13873
Data processing, internet publishing, and other information services	0.05%	40.55745
Federal Reserve banks, credit intermediation, and related activities	0.05%	134.0886
Securities, commodity contracts, and investments	0.03%	54.80207
Insurance carriers and related activities	0.02%	48.37821
Funds, trusts, and other financial vehicles	0.00%	3.956301
Housing	0.00%	0.000285
Other real estate	0.04%	141.5452
Rental and leasing services and lessors of intangible assets	0.05%	79.01441
Legal services	0.06%	95.11227
Computer systems design and related services	0.03%	61.25573
Miscellaneous professional, scientific, and technical services	0.05%	345.8048
Management of companies and enterprises	0.07%	137.1779
Administrative and support services	0.07%	248.517
Waste management and remediation services	0.06%	21.45728
Educational services	0.01%	10.13566
Ambulatory health care services	0.00%	0.389065
Hospitals	0.00%	0.00622
Nursing and residential care facilities	0.00%	0.041439
Social assistance	0.00%	3.139234
Performing arts, spectator sports, museums, and related activities	0.03%	12.70142
Amusements, gambling, and recreation industries	0.01%	6.022776
Accommodation	0.02%	19.11144
Food services and drinking places	0.01%	37.48592
Other services, except government	0.02%	50.46182
Federal general government (defense)	0.00%	0.001419
Federal general government (nondefense)	0.00%	0.344424
Federal government enterprises	0.05%	-131.926
State and local general government	0.00%	-12.6378
State and local government enterprises	0.04%	-1023.41

Table C.17 Historic Inoperability and GDP Loss Vector – 2013

Industries	**Inoperability**	**GDP Loss In Millions**
Farms	0.02%	28.14594
Forestry, fishing, and related activities	0.04%	4.686959
Oil and gas extraction	0.63%	1331.917
Mining, except oil and gas	0.23%	157.6574
Support activities for mining	0.05%	31.8835
Utilities	1.05%	5371.973
Construction	0.02%	153.4702
Wood products	0.06%	21.95107
Nonmetallic mineral products	0.06%	27.10811
Primary metals	0.11%	105.2533
Fabricated metal products	0.07%	99.03384
Machinery	0.05%	103.115
Computer and electronic products	0.04%	45.02007
Electrical equipment, appliances, and components	0.04%	14.89436
Motor vehicles, bodies and trailers, and parts	0.02%	36.75807
Other transportation equipment	0.01%	-2.69812
Furniture and related products	0.02%	6.597327
Miscellaneous manufacturing	0.01%	-1.70805
Food and beverage and tobacco products	0.01%	32.42842
Textile mills and textile product mills	0.02%	3.383734
Apparel and leather and allied products	-0.01%	-7.53266
Paper products	0.04%	21.9278
Printing and related support activities	0.04%	6.154139
Petroleum and coal products	0.12%	594.2353
Chemical products	0.06%	211.479
Plastics and rubber products	0.04%	31.67343
Wholesale trade	0.03%	239.1028
Motor vehicle and parts dealers	0.01%	2.537806
Food and beverage stores	0.01%	6.517445
General merchandise stores	0.00%	4.133007
Other retail	0.01%	19.51549
Air transportation	0.03%	30.1999
Rail transportation	0.15%	66.04508
Water transportation	0.02%	-2.79852
Truck transportation	0.03%	41.04999
Transit and ground passenger transportation	0.02%	4.461666
Pipeline transportation	0.97%	173.9865

Other transportation and support activities	0.15%	186.1968
Warehousing and storage	0.06%	32.11434
Publishing industries, except internet (includes software)	0.02%	20.05113
Motion picture and sound recording industries	0.02%	10.79977
Broadcasting and telecommunications	0.02%	50.03081
Data processing, internet publishing, and other information services	0.06%	53.96375
Federal Reserve banks, credit intermediation, and related activities	0.05%	157.6768
Securities, commodity contracts, and investments	0.03%	58.35302
Insurance carriers and related activities	0.02%	59.30823
Funds, trusts, and other financial vehicles	0.00%	1.050433
Housing	0.00%	0.000192
Other real estate	0.04%	169.0952
Rental and leasing services and lessors of intangible assets	0.06%	100.8762
Legal services	0.08%	116.1747
Computer systems design and related services	0.04%	66.60333
Miscellaneous professional, scientific, and technical services	0.05%	381.9184
Management of companies and enterprises	0.07%	144.9887
Administrative and support services	0.08%	262.7838
Waste management and remediation services	0.06%	25.10071
Educational services	0.01%	1.419866
Ambulatory health care services	0.00%	-5.77618
Hospitals	0.00%	0.011575
Nursing and residential care facilities	0.00%	0.067288
Social assistance	0.00%	3.118736
Performing arts, spectator sports, museums, and related activities	0.03%	17.32545
Amusements, gambling, and recreation industries	0.01%	15.75355
Accommodation	0.02%	12.64094
Food services and drinking places	0.02%	58.50781
Other services, except government	0.02%	48.58814
Federal general government (defense)	0.00%	0.001716
Federal general government (nondefense)	0.00%	0.273993
Federal government enterprises	0.05%	-135.06
State and local general government	0.00%	-12.9293
State and local government enterprises	0.03%	-1056.38

Table C.18 Historic Inoperability and GDP Loss Vector – 2014

Industries	**Inoperability**	**GDP Loss In Millions**
Farms	0.02%	28.45689
Forestry, fishing, and related activities	0.03%	0.701215
Oil and gas extraction	0.67%	1624.845
Mining, except oil and gas	0.28%	190.1707
Support activities for mining	0.05%	38.66383
Utilities	1.05%	5776.396
Construction	0.03%	200.8202
Wood products	0.05%	6.929985
Nonmetallic mineral products	0.05%	10.9796
Primary metals	0.13%	125.1559
Fabricated metal products	0.07%	99.62642
Machinery	0.06%	106.6452
Computer and electronic products	0.05%	57.4647
Electrical equipment, appliances, and components	0.05%	19.48164
Motor vehicles, bodies and trailers, and parts	0.02%	43.48895
Other transportation equipment	0.02%	15.16167
Furniture and related products	0.01%	0.86161
Miscellaneous manufacturing	0.01%	-1.00596
Food and beverage and tobacco products	0.01%	19.6316
Textile mills and textile product mills	0.05%	16.10097
Apparel and leather and allied products	0.01%	0.42288
Paper products	0.06%	46.00971
Printing and related support activities	0.06%	22.36407
Petroleum and coal products	0.12%	543.2698
Chemical products	0.06%	210.1477
Plastics and rubber products	0.05%	48.16887
Wholesale trade	0.04%	271.0116
Motor vehicle and parts dealers	0.01%	6.165058
Food and beverage stores	0.00%	0.622717
General merchandise stores	0.00%	-1.24478
Other retail	0.01%	33.50781
Air transportation	0.04%	27.57209
Rail transportation	0.18%	92.25647
Water transportation	0.05%	19.61981
Truck transportation	0.04%	61.29722
Transit and ground passenger transportation	0.03%	6.804392
Pipeline transportation	1.09%	216.4329

Other transportation and support activities	0.16%	194.3488
Warehousing and storage	0.07%	35.84979
Publishing industries, except internet (includes software)	0.02%	9.494467
Motion picture and sound recording industries	0.02%	10.03595
Broadcasting and telecommunications	0.03%	83.75238
Data processing, internet publishing, and other information services	0.06%	45.07138
Federal Reserve banks, credit intermediation, and related activities	0.06%	213.2121
Securities, commodity contracts, and investments	0.03%	73.13179
Insurance carriers and related activities	0.03%	89.88718
Funds, trusts, and other financial vehicles	0.00%	4.536802
Housing	0.00%	0.000322
Other real estate	0.05%	224.4263
Rental and leasing services and lessors of intangible assets	0.07%	124.8654
Legal services	0.09%	136.4388
Computer systems design and related services	0.05%	90.59202
Miscellaneous professional, scientific, and technical services	0.06%	456.7336
Management of companies and enterprises	0.08%	180.8765
Administrative and support services	0.09%	311.9158
Waste management and remediation services	0.09%	49.76877
Educational services	0.01%	2.647421
Ambulatory health care services	0.00%	0.579203
Hospitals	0.00%	-3.06111
Nursing and residential care facilities	0.00%	0.092024
Social assistance	0.00%	3.109639
Performing arts, spectator sports, museums, and related activities	0.03%	20.9897
Amusements, gambling, and recreation industries	0.01%	10.31522
Accommodation	0.03%	29.94074
Food services and drinking places	0.02%	78.81436
Other services, except government	0.02%	60.93824
Federal general government (defense)	0.00%	0.002342
Federal general government (nondefense)	0.00%	0.497899
Federal government enterprises	0.05%	-142.455
State and local general government	0.00%	-13.3251
State and local government enterprises	0.04%	-1068.34

Table C.19 Historic Inoperability and GDP Loss Vector – 2015

Industries	**Inoperability**	**GDP Loss In Millions**
Farms	0.01%	12.88722
Forestry, fishing, and related activities	0.02%	-1.04409
Oil and gas extraction	0.62%	939.8515
Mining, except oil and gas	0.25%	155.6306
Support activities for mining	0.04%	23.92546
Utilities	1.05%	5513.242
Construction	0.02%	185.4824
Wood products	0.04%	10.47461
Nonmetallic mineral products	0.06%	34.35605
Primary metals	0.10%	98.10688
Fabricated metal products	0.06%	77.83748
Machinery	0.04%	83.10715
Computer and electronic products	0.04%	54.92923
Electrical equipment, appliances, and components	0.05%	21.47401
Motor vehicles, bodies and trailers, and parts	0.01%	4.738815
Other transportation equipment	0.02%	20.20699
Furniture and related products	0.02%	3.694944
Miscellaneous manufacturing	0.02%	10.82502
Food and beverage and tobacco products	0.01%	23.03068
Textile mills and textile product mills	0.03%	4.872534
Apparel and leather and allied products	0.02%	5.568828
Paper products	0.04%	13.99945
Printing and related support activities	0.03%	5.394529
Petroleum and coal products	0.10%	294.8456
Chemical products	0.05%	152.5361
Plastics and rubber products	0.05%	46.65424
Wholesale trade	0.03%	218.3557
Motor vehicle and parts dealers	0.01%	8.11844
Food and beverage stores	0.00%	3.591376
General merchandise stores	0.00%	4.601075
Other retail	0.01%	36.87796
Air transportation	0.04%	33.09927
Rail transportation	0.12%	46.86905
Water transportation	0.04%	12.23762
Truck transportation	0.03%	40.75727
Transit and ground passenger transportation	0.03%	11.4221
Pipeline transportation	1.04%	217.8677

Other transportation and support activities	0.15%	207.1496
Warehousing and storage	0.06%	27.77462
Publishing industries, except internet (includes software)	0.02%	7.710781
Motion picture and sound recording industries	0.02%	11.63946
Broadcasting and telecommunications	0.02%	60.71874
Data processing, internet publishing, and other information services	0.05%	43.83688
Federal Reserve banks, credit intermediation, and related activities	0.05%	196.0655
Securities, commodity contracts, and investments	0.03%	63.53595
Insurance carriers and related activities	0.03%	86.03084
Funds, trusts, and other financial vehicles	0.00%	1.364197
Housing	0.00%	0.000267
Other real estate	0.04%	188.5959
Rental and leasing services and lessors of intangible assets	0.05%	96.23767
Legal services	0.08%	128.6427
Computer systems design and related services	0.03%	68.74621
Miscellaneous professional, scientific, and technical services	0.05%	412.393
Management of companies and enterprises	0.06%	148.2805
Administrative and support services	0.08%	302.326
Waste management and remediation services	0.04%	12.69509
Educational services	0.01%	7.531222
Ambulatory health care services	0.00%	-2.54208
Hospitals	0.00%	0.009245
Nursing and residential care facilities	0.00%	3.131359
Social assistance	0.00%	3.081569
Performing arts, spectator sports, museums, and related activities	0.02%	2.21767
Amusements, gambling, and recreation industries	0.00%	0.257431
Accommodation	0.02%	12.6314
Food services and drinking places	0.02%	65.42707
Other services, except government	0.01%	46.55187
Federal general government (defense)	0.00%	0.001629
Federal general government (nondefense)	0.00%	0.355703
Federal government enterprises	0.05%	-129.251
State and local general government	0.00%	-13.7932
State and local government enterprises	0.04%	-1088.73

Table C.20 Historic Inoperability and GDP Loss Vector – 2016

Industries	**Inoperability**	**GDP Loss In Millions**
Farms	0.01%	21.64735
Forestry, fishing, and related activities	0.04%	9.627184
Oil and gas extraction	0.62%	753.3781
Mining, except oil and gas	0.24%	140.5527
Support activities for mining	0.04%	12.96681
Utilities	1.04%	5338.285
Construction	0.02%	165.0949
Wood products	0.04%	10.26082
Nonmetallic mineral products	0.05%	22.4458
Primary metals	0.09%	73.77649
Fabricated metal products	0.06%	85.01354
Machinery	0.05%	90.4005
Computer and electronic products	0.04%	46.36839
Electrical equipment, appliances, and components	0.05%	26.37694
Motor vehicles, bodies and trailers, and parts	0.01%	39.12902
Other transportation equipment	0.01%	12.60517
Furniture and related products	0.02%	9.921678
Miscellaneous manufacturing	0.02%	13.51472
Food and beverage and tobacco products	0.01%	19.00344
Textile mills and textile product mills	0.04%	15.2767
Apparel and leather and allied products	0.02%	5.949927
Paper products	0.04%	16.35103
Printing and related support activities	0.05%	19.79721
Petroleum and coal products	0.09%	219.6061
Chemical products	0.04%	139.8516
Plastics and rubber products	0.04%	29.4132
Wholesale trade	0.03%	190.483
Motor vehicle and parts dealers	0.01%	17.00684
Food and beverage stores	0.01%	9.58462
General merchandise stores	0.00%	-1.5902
Other retail	0.01%	29.45154
Air transportation	0.03%	26.46607
Rail transportation	0.12%	51.59614
Water transportation	0.02%	4.723748
Truck transportation	0.03%	27.21036
Transit and ground passenger transportation	0.02%	7.289787
Pipeline transportation	1.01%	208.8158

Other transportation and support activities	0.12%	165.1472
Warehousing and storage	0.05%	20.52863
Publishing industries, except internet (includes software)	0.02%	7.177099
Motion picture and sound recording industries	0.02%	11.0636
Broadcasting and telecommunications	0.02%	56.20812
Data processing, internet publishing, and other information services	0.04%	40.09702
Federal Reserve banks, credit intermediation, and related activities	0.05%	173.1129
Securities, commodity contracts, and investments	0.03%	60.76748
Insurance carriers and related activities	0.03%	92.90007
Funds, trusts, and other financial vehicles	0.00%	4.119499
Housing	0.00%	0.000189
Other real estate	0.04%	175.5929
Rental and leasing services and lessors of intangible assets	0.04%	88.58471
Legal services	0.06%	103.7206
Computer systems design and related services	0.03%	63.01362
Miscellaneous professional, scientific, and technical services	0.04%	375.7239
Management of companies and enterprises	0.06%	141.5523
Administrative and support services	0.06%	254.2001
Waste management and remediation services	0.04%	17.34936
Educational services	0.01%	-1.88162
Ambulatory health care services	0.00%	6.512473
Hospitals	0.00%	0.008101
Nursing and residential care facilities	0.00%	0.079373
Social assistance	0.00%	3.066857
Performing arts, spectator sports, museums, and related activities	0.03%	23.31467
Amusements, gambling, and recreation industries	0.00%	-0.25764
Accommodation	0.02%	22.40789
Food services and drinking places	0.01%	61.90955
Other services, except government	0.01%	50.22643
Federal general government (defense)	0.00%	0.001303
Federal general government (nondefense)	0.00%	0.492305
Federal government enterprises	0.05%	-119.935
State and local general government	0.00%	-14.2057
State and local government enterprises	0.03%	-1118.89

Table C.21 Summary of Historic GDP Loss (in Millions)

Industries	**Min**	**Median**	**Max**
Farms	8.5	22.7	56.2
Forestry, fishing, and related activities	-1.0	12.0	38.2
Oil and gas extraction	753.4	1543.5	4599.6
Mining, except oil and gas	110.2	197.8	329.8
Support activities for mining	13.0	34.3	131.9
Utilities	5001.0	5720.0	10020.4
Construction	118.8	188.2	498.9
Wood products	6.9	32.6	87.4
Nonmetallic mineral products	11.0	43.7	98.0
Primary metals	65.2	136.7	308.2
Fabricated metal products	77.8	118.7	280.2
Machinery	71.5	112.6	269.5
Computer and electronic products	29.9	75.8	188.0
Electrical equipment, appliances, and components	8.9	29.4	78.7
Motor vehicles, bodies and trailers, and parts	4.7	46.0	127.5
Other transportation equipment	-2.7	12.8	31.9
Furniture and related products	-10.0	6.0	18.1
Miscellaneous manufacturing	-14.7	8.2	28.3
Food and beverage and tobacco products	3.5	41.5	79.5
Textile mills and textile product mills	-5.9	12.5	35.4
Apparel and leather and allied products	-18.9	5.0	25.6
Paper products	14.0	56.4	109.4
Printing and related support activities	5.4	36.5	67.4
Petroleum and coal products	194.7	454.8	1278.9
Chemical products	133.3	210.8	624.1
Plastics and rubber products	23.0	47.4	109.7
Wholesale trade	190.5	284.2	655.7
Motor vehicle and parts dealers	-6.6	11.6	22.0
Food and beverage stores	-10.1	4.3	35.1
General merchandise stores	-10.6	3.6	15.7
Other retail	15.8	36.0	80.7
Air transportation	22.0	40.7	99.9
Rail transportation	46.9	75.2	146.5
Water transportation	-8.6	11.1	28.5
Truck transportation	26.1	55.5	146.5
Transit and ground passenger transportation	0.2	13.6	41.5
Pipeline transportation	147.4	310.6	439.2
Other transportation and support activities	89.2	168.4	475.0

Warehousing and storage	9.4	27.1	67.9
Publishing industries, except internet (includes software)	2.1	18.5	42.9
Motion picture and sound recording industries	-6.1	13.0	33.7
Broadcasting and telecommunications	43.1	127.4	343.6
Data processing, internet publishing, and other information services	32.0	54.1	142.7
Federal Reserve banks, credit intermediation, and related activities	134.1	541.6	1418.7
Securities, commodity contracts, and investments	54.8	155.7	440.5
Insurance carriers and related activities	48.4	118.1	308.9
Funds, trusts, and other financial vehicles	-4.4	1.6	6.8
Housing	0.0	0.0	0.0
Other real estate	141.5	302.3	755.7
Rental and leasing services and lessors of intangible assets	79.0	290.7	735.5
Legal services	95.1	214.5	477.0
Computer systems design and related services	50.0	97.7	238.6
Miscellaneous professional, scientific, and technical services	345.8	646.6	1609.3
Management of companies and enterprises	125.2	216.6	489.8
Administrative and support services	227.4	353.2	792.4
Waste management and remediation services	12.7	48.2	123.2
Educational services	-2.3	6.4	14.3
Ambulatory health care services	-5.8	1.1	10.0
Hospitals	-3.1	0.0	5.0
Nursing and residential care facilities	-5.6	0.1	4.5
Social assistance	-4.0	0.2	5.3
Performing arts, spectator sports, museums, and related activities	2.2	21.3	49.1
Amusements, gambling, and recreation industries	-5.5	6.0	23.3
Accommodation	12.6	33.3	116.0
Food services and drinking places	37.5	116.1	300.5
Other services, except government	46.6	103.7	288.2
Federal general government (defense)	0.0	0.0	0.0
Federal general government (nondefense)	0.1	0.4	1.1
Federal government enterprises	-147.9	-103.6	-24.4
State and local general government	-18.2	-12.2	-8.8
State and local government enterprises	-1545.1	-1015.1	-837.2

Table C.22 Vulnerable Industries (in Descending Order)

Rank	**Industry**	**Mean GDP Loss in Millions**
1	Utilities	6360.7
2	Oil and gas extraction	2152.8
3	Miscellaneous professional, scientific, and technical services	765.2
4	Petroleum and coal products	563.2
5	Federal Reserve banks, credit intermediation, and related activities	556.3
6	Administrative and support services	412.7
7	Other real estate	356.5
8	Wholesale trade	348.1
9	Pipeline transportation	295.8
10	Rental and leasing services and lessors of intangible assets	280.4
11	Chemical products	267.2
12	Management of companies and enterprises	255.3
13	Construction	236.5
14	Legal services	235.5
15	Mining, except oil and gas	205.1
16	Other transportation and support activities	194.0
17	Securities, commodity contracts, and investments	183.3
18	Primary metals	162.0
19	Insurance carriers and related activities	156.2
20	Fabricated metal products	145.4
21	Machinery	141.2
22	Broadcasting and telecommunications	135.4
23	Food services and drinking places	127.6
24	Other services, except government	116.6
25	Computer systems design and related services	109.8
26	Computer and electronic products	85.4
27	Rail transportation	84.1
28	Truck transportation	65.4
29	Data processing, internet publishing, and other information services	65.0
30	Paper products	57.2
31	Plastics and rubber products	56.9
32	Motor vehicles, bodies and trailers, and parts	56.6
33	Waste management and remediation services	50.6
34	Air transportation	47.9
35	Nonmetallic mineral products	47.1
36	Support activities for mining	46.1

37	Other retail	41.9
38	Accommodation	41.5
39	Food and beverage and tobacco products	37.8
40	Wood products	37.7
41	Electrical equipment, appliances, and components	36.8
42	Printing and related support activities	34.8
43	Warehousing and storage	31.8
44	Farms	25.3
45	Performing arts, spectator sports, museums, and related activities	22.7
46	Publishing industries, except internet (includes software)	19.6
47	Transit and ground passenger transportation	16.8
48	Forestry, fishing, and related activities	16.6
49	Motion picture and sound recording industries	15.7
50	Textile mills and textile product mills	13.5
51	Other transportation equipment	12.8
52	Water transportation	11.2
53	Motor vehicle and parts dealers	10.4
54	Miscellaneous manufacturing	8.0
55	Amusements, gambling, and recreation industries	6.4
56	Furniture and related products	6.1
57	Educational services	6.1
58	Apparel and leather and allied products	5.6
59	Food and beverage stores	4.5
60	General merchandise stores	3.1
61	Ambulatory health care services	2.2
62	Funds, trusts, and other financial vehicles	1.7
63	Social assistance	0.9
64	Federal general government (nondefense)	0.4
65	Hospitals	0.4
66	Federal general government (defense)	0.0
67	Housing	0.0
68	Nursing and residential care facilities	0.0
69	State and local general government	-12.3
70	Federal government enterprises	-97.5
71	State and local government enterprises	-1032.1

APPENDIX D

State Level Multipliers – Indiana

The state level employment data were collected for all 71 industries for the year 2017 from the Bureau of Labor Statistics (BLS). The multipliers are created based on following formula

$$Multiplier\ of\ Industry\ i\ for\ a\ State$$
$$= \frac{Employment\ Created\ by\ Industry\ i\ in\ that\ State}{Employment\ Created\ by\ Industry\ i\ in\ at\ national\ level}$$

Some industries recorded zero employment for Indiana. They are Rail Transportation and Water Transportation. For them the multipliers are zero. Again, some industries recorded zero employment at state as well as at national level. They are Federal General Government (Defense), Federal Government Enterprises, State and Local General Government and State and Local Government Enterprises. For these industries, it has been assumed that the total industry production is equally distributed over all 50 states. Therefore, the multipliers for these states are 100 divided by 50 or 2%.

Table D.1 State Level Multipliers – Indiana

Industry	Employment Indiana	Employment National	Multipliers
Farms	11007	776911	0.0142
Forestry, fishing, and related activities	1577	448690	0.0035
Oil and gas extraction	147	143925	0.0010
Mining, except oil and gas	1590	184369	0.0086
Support activities for mining	162	57316	0.0028
Utilities	15182	813996	0.0187
Construction	138040	7098128	0.0194
Wood products	14263	396996	0.0359
Nonmetallic mineral products	12877	409814	0.0314
Primary metals	36425	325474	0.1119
Fabricated metal products	50382	1154625	0.0436
Machinery	23025	743677	0.0310
Computer and electronic products	8459	928478	0.0091
Electrical equipment, appliances, and components	4443	334042	0.0133
Motor vehicles, bodies and trailers, and parts	99802	905006	0.1103

Other transportation equipment	6826	714830	0.0095
Furniture and related products	25157	393079	0.0640
Miscellaneous manufacturing	29347	592826	0.0495
Food and beverage and tobacco products	31364	1435976	0.0218
Textile mills and textile product mills	3769	227836	0.0165
Apparel and leather and allied products	1394	148115	0.0094
Paper products	8209	367015	0.0224
Printing and related support activities	15349	441828	0.0347
Petroleum and coal products	954	112848	0.0085
Chemical products	30269	820840	0.0369
Plastics and rubber products	40140	714192	0.0562
Wholesale trade	119289	5899022	0.0202
Motor vehicle and parts dealers	43967	1998719	0.0220
Food and beverage stores	46935	3111345	0.0151
General merchandise stores	76590	3154616	0.0243
Other retail	11223	598001	0.0188
Air transportation	2792	493425	0.0057
Rail transportation	0	521	0.0000
Water transportation	0	66364	0.0000
Truck transportation	54656	1452682	0.0376
Transit and ground passenger transportation	9687	737306	0.0131
Pipeline transportation	519	50354	0.0103
Other transportation and support activities	27105	1461997	0.0185
Warehousing and storage	31679	1026985	0.0308
Publishing industries, except internet (includes software)	8486	724651	0.0117
Motion picture and sound recording industries	3618	424576	0.0085
Broadcasting and telecommunications	4056	358320	0.0113
Data processing, internet publishing, and other information services	4709	561892	0.0084
Federal Reserve banks, credit intermediation, and related activities	29267	1730029	0.0169
Securities, commodity contracts, and investments	4236	749813	0.0056
Insurance carriers and related activities	44858	2333201	0.0192

Funds, trusts, and other financial vehicles	132	12710	0.0104
Housing	12148	821323.5	0.0148
Other real estate	12148	821323.5	0.0148
Rental and leasing services and lessors of intangible assets	5695	389807	0.0146
Legal services	14099	1133510	0.0124
Computer systems design and related services	25627	2055239	0.0125
Miscellaneous professional, scientific, and technical services	75373	5912956	0.0127
Management of companies and enterprises	34483	2278042	0.0151
Administrative and support services	179173	8700705	0.0206
Waste management and remediation services	9179	449714	0.0204
Educational services	157978	8054333	0.0196
Ambulatory health care services	143865	7405473	0.0194
Hospitals	149296	6399690	0.0233
Nursing and residential care facilities	78953	3516757	0.0225
Social assistance	45273	3471788	0.0130
Performing arts, spectator sports, museums, and related activities	8547	565942	0.0151
Amusements, gambling, and recreation industries	32388	1936100	0.0167
Accommodation	23169	2063991	0.0112
Food services and drinking places	244655	11637653	0.0210
Other services, except government	87118	4473194	0.0195
Federal general government (defense)	0	0	0.0200
Federal general government (nondefense)	12353	622308	0.0199
Federal government enterprises	0	0	0.0200
State and local general government	0	0	0.0200
State and local government enterprises	0	0	0.0200

APPENDIX E

Table E.1 Historic Inoperability and GDP Loss Vector of Indiana - 1997

Industries	**Inoperability**	**GDP Loss In Millions**
Farms	0.02%	0.21
Forestry, fishing, and related activities	0.06%	0.03
Oil and gas extraction	1.47%	1.10
Mining, except oil and gas	0.30%	1.10
Support activities for mining	0.14%	0.06
Utilities	1.11%	95.33
Construction	0.02%	2.31
Wood products	0.07%	1.30
Nonmetallic mineral products	0.06%	0.74
Primary metals	0.11%	10.69
Fabricated metal products	0.07%	3.80
Machinery	0.05%	2.60
Computer and electronic products	0.04%	0.51
Electrical equipment, appliances, and components	0.04%	0.06
Motor vehicles, bodies and trailers, and parts	0.03%	6.19
Other transportation equipment	0.02%	0.08
Furniture and related products	0.01%	0.02
Miscellaneous manufacturing	0.01%	-0.13
Food and beverage and tobacco products	0.02%	1.16
Textile mills and textile product mills	0.02%	-0.15
Apparel and leather and allied products	0.01%	0.03
Paper products	0.08%	1.41
Printing and related support activities	0.09%	2.01
Petroleum and coal products	0.19%	2.19
Chemical products	0.06%	5.40
Plastics and rubber products	0.05%	1.72
Wholesale trade	0.06%	5.39
Motor vehicle and parts dealers	0.02%	0.42
Food and beverage stores	0.01%	0.06
General merchandise stores	0.01%	0.26
Other retail	0.02%	0.74
Air transportation	0.05%	0.26
Rail transportation	0.17%	-0.01

Water transportation	0.01%	-0.01
Truck transportation	0.05%	1.41
Transit and ground passenger transportation	0.09%	0.32
Pipeline transportation	1.45%	2.70
Other transportation and support activities	0.14%	1.65
Warehousing and storage	0.07%	0.30
Publishing industries, except internet (includes software)	0.04%	0.15
Motion picture and sound recording industries	0.04%	0.19
Broadcasting and telecommunications	0.06%	1.13
Data processing, internet publishing, and other information services	0.10%	0.24
Federal Reserve banks, credit intermediation, and related activities	0.15%	7.25
Securities, commodity contracts, and investments	0.08%	0.53
Insurance carriers and related activities	0.05%	1.75
Funds, trusts, and other financial vehicles	0.00%	-0.05
Housing	0.00%	-0.02
Other real estate	0.10%	3.75
Rental and leasing services and lessors of intangible assets	0.19%	4.03
Legal services	0.13%	2.00
Computer systems design and related services	0.05%	0.61
Miscellaneous professional, scientific, and technical services	0.10%	6.89
Management of companies and enterprises	0.13%	2.14
Administrative and support services	0.13%	5.20
Waste management and remediation services	0.15%	1.06
Educational services	0.02%	0.39
Ambulatory health care services	0.00%	0.02
Hospitals	0.00%	0.02
Nursing and residential care facilities	0.00%	0.00
Social assistance	0.01%	0.06
Performing arts, spectator sports, museums, and related activities	0.07%	0.33
Amusements, gambling, and recreation industries	0.02%	0.22
Accommodation	0.05%	0.30
Food services and drinking places	0.04%	2.62
Other services, except government	0.04%	2.26
Federal general government (defense)	0.00%	0.05
Federal general government (nondefense)	0.01%	0.05
Federal government enterprises	0.11%	-1.35
State and local general government	0.01%	-0.07
State and local government enterprises	0.06%	-15.71

Table E.2 Historic Inoperability and GDP Loss Vector of Indiana – 1998

Industries	**Inoperability**	**GDP Loss In Millions**
Farms	0.03%	0.35
Forestry, fishing, and related activities	0.06%	0.05
Oil and gas extraction	1.69%	0.98
Mining, except oil and gas	0.44%	1.75
Support activities for mining	0.10%	0.03
Utilities	1.10%	93.74
Construction	0.02%	2.81
Wood products	0.06%	0.81
Nonmetallic mineral products	0.09%	1.66
Primary metals	0.12%	10.66
Fabricated metal products	0.08%	4.46
Machinery	0.06%	3.14
Computer and electronic products	0.05%	0.64
Electrical equipment, appliances, and components	0.04%	-0.08
Motor vehicles, bodies and trailers, and parts	0.02%	6.29
Other transportation equipment	0.01%	-0.04
Furniture and related products	0.02%	0.61
Miscellaneous manufacturing	0.03%	0.85
Food and beverage and tobacco products	0.02%	1.12
Textile mills and textile product mills	0.05%	0.34
Apparel and leather and allied products	0.01%	-0.02
Paper products	0.07%	0.92
Printing and related support activities	0.09%	1.78
Petroleum and coal products	0.17%	1.52
Chemical products	0.07%	5.30
Plastics and rubber products	0.06%	2.54
Wholesale trade	0.06%	5.66
Motor vehicle and parts dealers	0.03%	0.52
Food and beverage stores	0.01%	0.06
General merchandise stores	0.01%	0.15
Other retail	0.02%	0.68
Air transportation	0.05%	0.18
Rail transportation	0.25%	-0.01
Water transportation	0.02%	-0.01
Truck transportation	0.06%	2.22
Transit and ground passenger transportation	0.05%	0.11
Pipeline transportation	1.60%	3.32

Other transportation and support activities	0.15%	1.94
Warehousing and storage	0.11%	0.83
Publishing industries, except internet (includes software)	0.05%	0.21
Motion picture and sound recording industries	0.03%	0.12
Broadcasting and telecommunications	0.07%	1.53
Data processing, internet publishing, and other information services	0.11%	0.29
Federal Reserve banks, credit intermediation, and related activities	0.16%	8.39
Securities, commodity contracts, and investments	0.09%	0.72
Insurance carriers and related activities	0.05%	1.77
Funds, trusts, and other financial vehicles	0.00%	0.00
Housing	0.00%	-0.02
Other real estate	0.11%	4.18
Rental and leasing services and lessors of intangible assets	0.21%	4.96
Legal services	0.14%	2.45
Computer systems design and related services	0.06%	0.80
Miscellaneous professional, scientific, and technical services	0.10%	7.29
Management of companies and enterprises	0.13%	2.37
Administrative and support services	0.15%	7.10
Waste management and remediation services	0.11%	0.55
Educational services	0.02%	0.39
Ambulatory health care services	0.00%	0.11
Hospitals	0.00%	0.03
Nursing and residential care facilities	0.00%	0.01
Social assistance	0.00%	0.00
Performing arts, spectator sports, museums, and related activities	0.08%	0.44
Amusements, gambling, and recreation industries	0.01%	0.01
Accommodation	0.05%	0.42
Food services and drinking places	0.04%	2.08
Other services, except government	0.04%	1.90
Federal general government (defense)	0.00%	0.05
Federal general government (nondefense)	0.01%	0.05
Federal government enterprises	0.11%	-1.60
State and local general government	0.01%	-0.06
State and local government enterprises	0.06%	-15.93

Table E.3 Historic Inoperability and GDP Loss Vector of Indiana – 1999

Industries	**Inoperability**	**GDP Loss In Millions**
Farms	0.03%	0.57
Forestry, fishing, and related activities	0.09%	0.07
Oil and gas extraction	1.94%	1.18
Mining, except oil and gas	0.57%	2.13
Support activities for mining	0.18%	0.06
Utilities	1.13%	106.69
Construction	0.03%	2.99
Wood products	0.08%	1.31
Nonmetallic mineral products	0.11%	1.99
Primary metals	0.17%	15.78
Fabricated metal products	0.10%	5.61
Machinery	0.08%	3.56
Computer and electronic products	0.06%	0.82
Electrical equipment, appliances, and components	0.07%	0.24
Motor vehicles, bodies and trailers, and parts	0.03%	5.33
Other transportation equipment	0.02%	-0.07
Furniture and related products	0.02%	0.40
Miscellaneous manufacturing	0.03%	0.36
Food and beverage and tobacco products	0.02%	0.92
Textile mills and textile product mills	0.06%	0.48
Apparel and leather and allied products	0.02%	0.06
Paper products	0.10%	1.69
Printing and related support activities	0.11%	1.81
Petroleum and coal products	0.27%	2.92
Chemical products	0.09%	7.27
Plastics and rubber products	0.06%	2.00
Wholesale trade	0.07%	7.98
Motor vehicle and parts dealers	0.03%	0.56
Food and beverage stores	0.01%	0.13
General merchandise stores	0.01%	0.06
Other retail	0.02%	0.69
Air transportation	0.07%	0.26
Rail transportation	0.28%	-0.01
Water transportation	0.05%	-0.01
Truck transportation	0.07%	2.74
Transit and ground passenger transportation	0.06%	0.10
Pipeline transportation	1.81%	3.86

Other transportation and support activities	0.18%	2.29
Warehousing and storage	0.10%	0.61
Publishing industries, except internet (includes software)	0.06%	0.35
Motion picture and sound recording industries	0.05%	0.25
Broadcasting and telecommunications	0.09%	2.07
Data processing, internet publishing, and other information services	0.15%	0.53
Federal Reserve banks, credit intermediation, and related activities	0.20%	11.08
Securities, commodity contracts, and investments	0.12%	1.17
Insurance carriers and related activities	0.06%	2.56
Funds, trusts, and other financial vehicles	0.00%	0.01
Housing	0.00%	-0.02
Other real estate	0.12%	4.76
Rental and leasing services and lessors of intangible assets	0.25%	6.43
Legal services	0.18%	3.22
Computer systems design and related services	0.09%	1.65
Miscellaneous professional, scientific, and technical services	0.13%	10.11
Management of companies and enterprises	0.18%	3.68
Administrative and support services	0.18%	9.01
Waste management and remediation services	0.14%	0.80
Educational services	0.02%	0.09
Ambulatory health care services	0.00%	0.20
Hospitals	0.00%	0.14
Nursing and residential care facilities	0.00%	0.10
Social assistance	0.00%	0.06
Performing arts, spectator sports, museums, and related activities	0.08%	0.31
Amusements, gambling, and recreation industries	0.02%	0.17
Accommodation	0.06%	0.26
Food services and drinking places	0.05%	2.95
Other services, except government	0.05%	2.78
Federal general government (defense)	0.00%	0.06
Federal general government (nondefense)	0.01%	0.07
Federal government enterprises	0.16%	-0.80
State and local general government	0.01%	-0.02
State and local government enterprises	0.07%	-16.15

Table E.4 Historic Inoperability and GDP Loss Vector of Indiana – 2000

Industries	**Inoperability**	**GDP Loss In Millions**
Farms	0.05%	0.68
Forestry, fishing, and related activities	0.14%	0.10
Oil and gas extraction	2.28%	2.05
Mining, except oil and gas	0.61%	2.14
Support activities for mining	0.24%	0.09
Utilities	1.21%	124.65
Construction	0.04%	4.53
Wood products	0.12%	1.89
Nonmetallic mineral products	0.15%	1.98
Primary metals	0.29%	25.55
Fabricated metal products	0.17%	8.54
Machinery	0.13%	6.59
Computer and electronic products	0.09%	1.19
Electrical equipment, appliances, and components	0.12%	0.55
Motor vehicles, bodies and trailers, and parts	0.05%	12.48
Other transportation equipment	0.04%	0.02
Furniture and related products	0.03%	0.86
Miscellaneous manufacturing	0.04%	0.61
Food and beverage and tobacco products	0.03%	1.53
Textile mills and textile product mills	0.09%	0.44
Apparel and leather and allied products	0.05%	0.22
Paper products	0.15%	2.38
Printing and related support activities	0.17%	3.22
Petroleum and coal products	0.39%	5.88
Chemical products	0.15%	13.36
Plastics and rubber products	0.12%	6.03
Wholesale trade	0.10%	11.05
Motor vehicle and parts dealers	0.04%	0.54
Food and beverage stores	0.03%	0.50
General merchandise stores	0.01%	0.29
Other retail	0.03%	1.18
Air transportation	0.11%	0.53
Rail transportation	0.41%	-0.01
Water transportation	0.05%	-0.02
Truck transportation	0.10%	4.21
Transit and ground passenger transportation	0.09%	0.18
Pipeline transportation	1.99%	3.70

Other transportation and support activities	0.26%	3.87
Warehousing and storage	0.16%	1.02
Publishing industries, except internet (includes software)	0.09%	0.37
Motion picture and sound recording industries	0.05%	0.23
Broadcasting and telecommunications	0.12%	2.80
Data processing, internet publishing, and other information services	0.21%	0.71
Federal Reserve banks, credit intermediation, and related activities	0.30%	18.40
Securities, commodity contracts, and investments	0.17%	1.84
Insurance carriers and related activities	0.10%	4.34
Funds, trusts, and other financial vehicles	0.00%	0.02
Housing	0.00%	-0.03
Other real estate	0.19%	8.22
Rental and leasing services and lessors of intangible assets	0.32%	8.44
Legal services	0.24%	4.17
Computer systems design and related services	0.12%	2.43
Miscellaneous professional, scientific, and technical services	0.19%	15.49
Management of companies and enterprises	0.31%	6.61
Administrative and support services	0.25%	13.11
Waste management and remediation services	0.23%	1.59
Educational services	0.03%	0.37
Ambulatory health care services	0.00%	0.04
Hospitals	0.00%	0.06
Nursing and residential care facilities	0.00%	0.01
Social assistance	0.00%	-0.05
Performing arts, spectator sports, museums, and related activities	0.10%	0.28
Amusements, gambling, and recreation industries	0.03%	0.26
Accommodation	0.10%	0.87
Food services and drinking places	0.07%	4.63
Other services, except government	0.07%	4.62
Federal general government (defense)	0.01%	0.10
Federal general government (nondefense)	0.01%	0.10
Federal government enterprises	0.23%	-0.41
State and local general government	0.01%	0.08
State and local government enterprises	0.12%	-15.86

Table E.5 Historic Inoperability and GDP Loss Vector of Indiana – 2001

Industries	**Inoperability**	**GDP Loss In Millions**
Farms	0.04%	0.50
Forestry, fishing, and related activities	0.16%	0.11
Oil and gas extraction	2.46%	2.17
Mining, except oil and gas	0.78%	2.79
Support activities for mining	0.23%	0.13
Utilities	1.22%	143.52
Construction	0.05%	6.27
Wood products	0.18%	3.14
Nonmetallic mineral products	0.17%	2.40
Primary metals	0.33%	24.96
Fabricated metal products	0.19%	9.44
Machinery	0.17%	8.37
Computer and electronic products	0.11%	1.34
Electrical equipment, appliances, and components	0.13%	0.60
Motor vehicles, bodies and trailers, and parts	0.06%	15.48
Other transportation equipment	0.05%	0.13
Furniture and related products	0.02%	-0.11
Miscellaneous manufacturing	0.05%	1.29
Food and beverage and tobacco products	0.03%	1.67
Textile mills and textile product mills	0.06%	-0.09
Apparel and leather and allied products	0.03%	-0.01
Paper products	0.16%	2.17
Printing and related support activities	0.19%	3.20
Petroleum and coal products	0.43%	6.15
Chemical products	0.16%	13.80
Plastics and rubber products	0.13%	6.32
Wholesale trade	0.12%	13.53
Motor vehicle and parts dealers	0.05%	0.20
Food and beverage stores	0.01%	0.11
General merchandise stores	0.02%	0.40
Other retail	0.03%	1.36
Air transportation	0.14%	0.56
Rail transportation	0.48%	-0.01
Water transportation	0.12%	-0.02
Truck transportation	0.12%	5.58
Transit and ground passenger transportation	0.10%	0.18
Pipeline transportation	2.07%	3.98

Other transportation and support activities	0.29%	4.19
Warehousing and storage	0.20%	1.52
Publishing industries, except internet (includes software)	0.11%	0.32
Motion picture and sound recording industries	0.06%	0.15
Broadcasting and telecommunications	0.14%	3.70
Data processing, internet publishing, and other information services	0.26%	1.07
Federal Reserve banks, credit intermediation, and related activities	0.38%	24.99
Securities, commodity contracts, and investments	0.22%	2.19
Insurance carriers and related activities	0.13%	5.90
Funds, trusts, and other financial vehicles	0.01%	0.02
Housing	0.00%	-0.03
Other real estate	0.22%	10.11
Rental and leasing services and lessors of intangible assets	0.40%	10.73
Legal services	0.31%	5.93
Computer systems design and related services	0.15%	3.00
Miscellaneous professional, scientific, and technical services	0.24%	20.48
Management of companies and enterprises	0.31%	6.52
Administrative and support services	0.30%	16.36
Waste management and remediation services	0.24%	1.67
Educational services	0.04%	0.53
Ambulatory health care services	0.00%	0.21
Hospitals	0.00%	0.09
Nursing and residential care facilities	0.00%	0.11
Social assistance	0.00%	0.00
Performing arts, spectator sports, museums, and related activities	0.13%	0.64
Amusements, gambling, and recreation industries	0.04%	0.33
Accommodation	0.13%	1.11
Food services and drinking places	0.10%	6.33
Other services, except government	0.09%	5.64
Federal general government (defense)	0.01%	0.14
Federal general government (nondefense)	0.01%	0.13
Federal government enterprises	0.27%	-0.27
State and local general government	0.01%	0.18
State and local government enterprises	0.14%	-15.37

Table E.6 Historic Inoperability and GDP Loss Vector of Indiana – 2002

Industries	**Inoperability**	**GDP Loss In Millions**
Farms	0.03%	0.38
Forestry, fishing, and related activities	0.11%	0.10
Oil and gas extraction	1.63%	1.27
Mining, except oil and gas	0.40%	1.38
Support activities for mining	0.14%	0.07
Utilities	1.09%	103.88
Construction	0.03%	3.16
Wood products	0.07%	1.01
Nonmetallic mineral products	0.08%	1.06
Primary metals	0.18%	14.12
Fabricated metal products	0.11%	5.23
Machinery	0.11%	5.77
Computer and electronic products	0.06%	0.52
Electrical equipment, appliances, and components	0.08%	0.41
Motor vehicles, bodies and trailers, and parts	0.03%	9.12
Other transportation equipment	0.02%	-0.08
Furniture and related products	0.02%	0.36
Miscellaneous manufacturing	0.03%	0.59
Food and beverage and tobacco products	0.02%	0.92
Textile mills and textile product mills	0.06%	0.28
Apparel and leather and allied products	0.03%	0.10
Paper products	0.09%	1.17
Printing and related support activities	0.12%	2.38
Petroleum and coal products	0.21%	2.77
Chemical products	0.07%	5.95
Plastics and rubber products	0.07%	3.77
Wholesale trade	0.06%	6.29
Motor vehicle and parts dealers	0.03%	0.34
Food and beverage stores	0.01%	0.23
General merchandise stores	0.00%	-0.15
Other retail	0.02%	0.78
Air transportation	0.07%	0.27
Rail transportation	0.30%	0.00
Water transportation	0.05%	-0.01
Truck transportation	0.06%	2.24
Transit and ground passenger transportation	0.11%	0.50
Pipeline transportation	1.61%	3.18

Other transportation and support activities	0.15%	2.39
Warehousing and storage	0.11%	0.84
Publishing industries, except internet (includes software)	0.05%	0.07
Motion picture and sound recording industries	0.03%	0.12
Broadcasting and telecommunications	0.07%	1.52
Data processing, internet publishing, and other information services	0.12%	0.42
Federal Reserve banks, credit intermediation, and related activities	0.21%	14.82
Securities, commodity contracts, and investments	0.12%	1.16
Insurance carriers and related activities	0.07%	3.33
Funds, trusts, and other financial vehicles	0.00%	-0.03
Housing	0.00%	-0.02
Other real estate	0.12%	5.88
Rental and leasing services and lessors of intangible assets	0.22%	5.66
Legal services	0.17%	3.42
Computer systems design and related services	0.08%	1.53
Miscellaneous professional, scientific, and technical services	0.13%	10.88
Management of companies and enterprises	0.14%	2.79
Administrative and support services	0.16%	8.53
Waste management and remediation services	0.14%	1.00
Educational services	0.02%	0.34
Ambulatory health care services	0.00%	0.02
Hospitals	0.00%	0.05
Nursing and residential care facilities	0.00%	0.01
Social assistance	0.00%	0.00
Performing arts, spectator sports, museums, and related activities	0.08%	0.56
Amusements, gambling, and recreation industries	0.02%	0.08
Accommodation	0.06%	0.47
Food services and drinking places	0.05%	3.75
Other services, except government	0.04%	2.87
Federal general government (defense)	0.00%	0.08
Federal general government (nondefense)	0.01%	0.07
Federal government enterprises	0.16%	-0.70
State and local general government	0.01%	0.00
State and local government enterprises	0.07%	-15.82

Table E.7 Historic Inoperability and GDP Loss Vector of Indiana – 2003

Industries	**Inoperability**	**GDP Loss In Millions**
Farms	0.02%	0.17
Forestry, fishing, and related activities	0.09%	0.08
Oil and gas extraction	1.97%	2.21
Mining, except oil and gas	0.30%	0.96
Support activities for mining	0.17%	0.10
Utilities	1.10%	107.16
Construction	0.03%	3.50
Wood products	0.08%	1.23
Nonmetallic mineral products	0.11%	1.96
Primary metals	0.20%	15.39
Fabricated metal products	0.12%	5.89
Machinery	0.12%	5.92
Computer and electronic products	0.05%	0.38
Electrical equipment, appliances, and components	0.07%	0.18
Motor vehicles, bodies and trailers, and parts	0.03%	6.38
Other transportation equipment	0.03%	-0.06
Furniture and related products	0.03%	0.90
Miscellaneous manufacturing	0.03%	0.74
Food and beverage and tobacco products	0.01%	0.82
Textile mills and textile product mills	0.06%	0.26
Apparel and leather and allied products	0.04%	0.14
Paper products	0.09%	1.42
Printing and related support activities	0.10%	1.75
Petroleum and coal products	0.19%	2.67
Chemical products	0.08%	7.67
Plastics and rubber products	0.07%	3.02
Wholesale trade	0.06%	6.07
Motor vehicle and parts dealers	0.03%	0.41
Food and beverage stores	0.01%	0.11
General merchandise stores	0.00%	-0.15
Other retail	0.01%	0.49
Air transportation	0.06%	0.17
Rail transportation	0.20%	0.00
Water transportation	0.07%	-0.01
Truck transportation	0.05%	1.84
Transit and ground passenger transportation	0.06%	0.18
Pipeline transportation	1.77%	3.19

Other transportation and support activities	0.16%	2.68
Warehousing and storage	0.10%	0.84
Publishing industries, except internet (includes software)	0.06%	0.24
Motion picture and sound recording industries	0.04%	0.22
Broadcasting and telecommunications	0.07%	1.80
Data processing, internet publishing, and other information services	0.11%	0.35
Federal Reserve banks, credit intermediation, and related activities	0.19%	13.28
Securities, commodity contracts, and investments	0.12%	1.18
Insurance carriers and related activities	0.07%	3.71
Funds, trusts, and other financial vehicles	0.00%	0.02
Housing	0.00%	-0.02
Other real estate	0.11%	6.38
Rental and leasing services and lessors of intangible assets	0.20%	4.95
Legal services	0.16%	3.28
Computer systems design and related services	0.08%	1.53
Miscellaneous professional, scientific, and technical services	0.12%	10.07
Management of companies and enterprises	0.17%	3.67
Administrative and support services	0.16%	8.34
Waste management and remediation services	0.17%	1.48
Educational services	0.02%	0.32
Ambulatory health care services	0.00%	-0.05
Hospitals	0.00%	0.14
Nursing and residential care facilities	0.00%	0.01
Social assistance	0.00%	0.05
Performing arts, spectator sports, museums, and related activities	0.06%	0.28
Amusements, gambling, and recreation industries	0.01%	-0.06
Accommodation	0.05%	0.42
Food services and drinking places	0.05%	3.28
Other services, except government	0.04%	2.69
Federal general government (defense)	0.00%	0.08
Federal general government (nondefense)	0.01%	0.07
Federal government enterprises	0.12%	-1.54
State and local general government	0.01%	-0.02
State and local government enterprises	0.07%	-16.07

Table E.8 Historic Inoperability and GDP Loss Vector of Indiana – 2004

Industries	**Inoperability**	**GDP Loss In Millions**
Farms	0.02%	0.17
Forestry, fishing, and related activities	0.07%	0.03
Oil and gas extraction	1.91%	2.57
Mining, except oil and gas	0.26%	0.94
Support activities for mining	0.16%	0.12
Utilities	1.09%	111.85
Construction	0.03%	4.13
Wood products	0.10%	2.13
Nonmetallic mineral products	0.09%	1.38
Primary metals	0.19%	19.75
Fabricated metal products	0.10%	5.60
Machinery	0.09%	4.10
Computer and electronic products	0.05%	0.52
Electrical equipment, appliances, and components	0.06%	0.32
Motor vehicles, bodies and trailers, and parts	0.02%	3.94
Other transportation equipment	0.03%	0.05
Furniture and related products	0.03%	1.21
Miscellaneous manufacturing	0.03%	1.27
Food and beverage and tobacco products	0.01%	0.96
Textile mills and textile product mills	0.06%	0.34
Apparel and leather and allied products	0.05%	0.15
Paper products	0.08%	1.28
Printing and related support activities	0.07%	0.91
Petroleum and coal products	0.17%	3.26
Chemical products	0.08%	8.98
Plastics and rubber products	0.07%	3.46
Wholesale trade	0.05%	6.56
Motor vehicle and parts dealers	0.02%	0.04
Food and beverage stores	0.01%	-0.01
General merchandise stores	0.00%	-0.25
Other retail	0.01%	0.92
Air transportation	0.06%	0.24
Rail transportation	0.17%	0.00
Water transportation	0.08%	-0.02
Truck transportation	0.05%	1.65
Transit and ground passenger transportation	0.08%	0.38
Pipeline transportation	1.73%	3.16

Other transportation and support activities	0.16%	3.02
Warehousing and storage	0.07%	0.62
Publishing industries, except internet (includes software)	0.04%	-0.03
Motion picture and sound recording industries	0.02%	0.06
Broadcasting and telecommunications	0.06%	1.42
Data processing, internet publishing, and other information services	0.10%	0.39
Federal Reserve banks, credit intermediation, and related activities	0.15%	10.70
Securities, commodity contracts, and investments	0.09%	0.91
Insurance carriers and related activities	0.06%	3.42
Funds, trusts, and other financial vehicles	0.00%	0.02
Housing	0.00%	-0.03
Other real estate	0.09%	5.71
Rental and leasing services and lessors of intangible assets	0.17%	4.46
Legal services	0.13%	2.89
Computer systems design and related services	0.06%	1.31
Miscellaneous professional, scientific, and technical services	0.10%	9.16
Management of companies and enterprises	0.15%	3.61
Administrative and support services	0.13%	7.48
Waste management and remediation services	0.12%	0.98
Educational services	0.02%	0.22
Ambulatory health care services	0.00%	-0.05
Hospitals	0.00%	0.04
Nursing and residential care facilities	0.00%	0.00
Social assistance	0.00%	-0.05
Performing arts, spectator sports, museums, and related activities	0.05%	0.28
Amusements, gambling, and recreation industries	0.01%	0.08
Accommodation	0.05%	0.61
Food services and drinking places	0.03%	2.27
Other services, except government	0.03%	2.14
Federal general government (defense)	0.00%	0.07
Federal general government (nondefense)	0.01%	0.06
Federal government enterprises	0.11%	-1.59
State and local general government	0.01%	-0.05
State and local government enterprises	0.06%	-17.29

Table E.9 Historic Inoperability and GDP Loss Vector of Indiana – 2005

Industries	**Inoperability**	**GDP Loss In Millions**
Farms	0.02%	0.14
Forestry, fishing, and related activities	0.10%	0.10
Oil and gas extraction	2.08%	4.31
Mining, except oil and gas	0.38%	2.16
Support activities for mining	0.19%	0.24
Utilities	1.12%	159.60
Construction	0.04%	7.80
Wood products	0.10%	2.09
Nonmetallic mineral products	0.13%	3.16
Primary metals	0.26%	34.29
Fabricated metal products	0.14%	9.33
Machinery	0.13%	7.61
Computer and electronic products	0.07%	0.80
Electrical equipment, appliances, and components	0.09%	0.65
Motor vehicles, bodies and trailers, and parts	0.04%	15.48
Other transportation equipment	0.03%	-0.08
Furniture and related products	0.02%	0.69
Miscellaneous manufacturing	0.03%	1.66
Food and beverage and tobacco products	0.01%	0.93
Textile mills and textile product mills	0.06%	0.13
Apparel and leather and allied products	0.05%	0.15
Paper products	0.11%	2.07
Printing and related support activities	0.12%	2.49
Petroleum and coal products	0.25%	7.95
Chemical products	0.12%	16.58
Plastics and rubber products	0.09%	4.98
Wholesale trade	0.07%	11.19
Motor vehicle and parts dealers	0.03%	0.34
Food and beverage stores	0.01%	0.14
General merchandise stores	0.00%	-0.04
Other retail	0.02%	1.01
Air transportation	0.08%	0.44
Rail transportation	0.26%	-0.01
Water transportation	0.08%	-0.03
Truck transportation	0.07%	4.51
Transit and ground passenger transportation	0.09%	0.54
Pipeline transportation	1.76%	3.74

Other transportation and support activities	0.21%	4.94
Warehousing and storage	0.14%	2.10
Publishing industries, except internet (includes software)	0.06%	-0.04
Motion picture and sound recording industries	0.04%	0.28
Broadcasting and telecommunications	0.08%	2.44
Data processing, internet publishing, and other information services	0.13%	0.65
Federal Reserve banks, credit intermediation, and related activities	0.19%	17.49
Securities, commodity contracts, and investments	0.12%	1.70
Insurance carriers and related activities	0.08%	5.98
Funds, trusts, and other financial vehicles	0.01%	0.04
Housing	0.00%	-0.04
Other real estate	0.12%	11.18
Rental and leasing services and lessors of intangible assets	0.19%	5.98
Legal services	0.17%	4.68
Computer systems design and related services	0.08%	2.11
Miscellaneous professional, scientific, and technical services	0.14%	16.56
Management of companies and enterprises	0.22%	7.43
Administrative and support services	0.18%	13.67
Waste management and remediation services	0.20%	2.57
Educational services	0.02%	0.39
Ambulatory health care services	0.00%	0.04
Hospitals	0.00%	0.19
Nursing and residential care facilities	0.00%	0.01
Social assistance	0.00%	0.00
Performing arts, spectator sports, museums, and related activities	0.06%	0.41
Amusements, gambling, and recreation industries	0.01%	-0.13
Accommodation	0.05%	0.45
Food services and drinking places	0.05%	4.19
Other services, except government	0.04%	3.73
Federal general government (defense)	0.00%	0.13
Federal general government (nondefense)	0.01%	0.11
Federal government enterprises	0.15%	-1.70
State and local general government	0.01%	0.00
State and local government enterprises	0.08%	-22.18

Table E.10 Historic Inoperability and GDP Loss Vector of Indiana – 2006

Industries	**Inoperability**	**GDP Loss In Millions**
Farms	0.03%	0.74
Forestry, fishing, and related activities	0.10%	0.13
Oil and gas extraction	1.59%	4.00
Mining, except oil and gas	0.33%	2.66
Support activities for mining	0.15%	0.34
Utilities	1.10%	187.02
Construction	0.03%	8.65
Wood products	0.10%	3.13
Nonmetallic mineral products	0.09%	2.55
Primary metals	0.20%	31.58
Fabricated metal products	0.11%	10.00
Machinery	0.08%	6.03
Computer and electronic products	0.06%	0.83
Electrical equipment, appliances, and components	0.08%	0.81
Motor vehicles, bodies and trailers, and parts	0.03%	10.75
Other transportation equipment	0.03%	0.08
Furniture and related products	0.02%	0.36
Miscellaneous manufacturing	0.01%	-0.44
Food and beverage and tobacco products	0.01%	1.10
Textile mills and textile product mills	0.06%	0.39
Apparel and leather and allied products	0.02%	0.03
Paper products	0.09%	2.17
Printing and related support activities	0.10%	2.91
Petroleum and coal products	0.19%	7.90
Chemical products	0.11%	19.58
Plastics and rubber products	0.08%	6.32
Wholesale trade	0.06%	11.32
Motor vehicle and parts dealers	0.02%	0.46
Food and beverage stores	0.00%	-0.10
General merchandise stores	0.00%	0.09
Other retail	0.02%	1.53
Air transportation	0.06%	0.39
Rail transportation	0.23%	-0.01
Water transportation	0.06%	-0.04
Truck transportation	0.05%	3.83
Transit and ground passenger transportation	0.07%	0.51
Pipeline transportation	1.52%	4.01

Other transportation and support activities	0.20%	6.42
Warehousing and storage	0.10%	1.75
Publishing industries, except internet (includes software)	0.04%	0.20
Motion picture and sound recording industries	0.03%	0.20
Broadcasting and telecommunications	0.06%	2.16
Data processing, internet publishing, and other information services	0.11%	0.74
Federal Reserve banks, credit intermediation, and related activities	0.14%	15.78
Securities, commodity contracts, and investments	0.09%	1.54
Insurance carriers and related activities	0.06%	4.99
Funds, trusts, and other financial vehicles	0.00%	-0.01
Housing	0.00%	-0.05
Other real estate	0.09%	9.64
Rental and leasing services and lessors of intangible assets	0.14%	5.57
Legal services	0.14%	4.70
Computer systems design and related services	0.06%	1.71
Miscellaneous professional, scientific, and technical services	0.10%	15.61
Management of companies and enterprises	0.16%	6.58
Administrative and support services	0.14%	12.78
Waste management and remediation services	0.11%	1.34
Educational services	0.02%	0.34
Ambulatory health care services	0.00%	0.15
Hospitals	0.00%	0.06
Nursing and residential care facilities	0.00%	-0.12
Social assistance	0.00%	0.00
Performing arts, spectator sports, museums, and related activities	0.05%	0.46
Amusements, gambling, and recreation industries	0.01%	-0.06
Accommodation	0.04%	0.69
Food services and drinking places	0.03%	3.90
Other services, except government	0.03%	3.22
Federal general government (defense)	0.00%	0.12
Federal general government (nondefense)	0.01%	0.10
Federal government enterprises	0.12%	-2.63
State and local general government	0.01%	-0.06
State and local government enterprises	0.06%	-28.58

Table E.11 Historic Inoperability and GDP Loss Vector of Indiana – 2007

Industries	**Inoperability**	**GDP Loss In Millions**
Farms	0.03%	0.82
Forestry, fishing, and related activities	0.09%	0.10
Oil and gas extraction	1.69%	4.18
Mining, except oil and gas	0.36%	2.71
Support activities for mining	0.17%	0.36
Utilities	1.11%	184.59
Construction	0.04%	9.70
Wood products	0.10%	2.15
Nonmetallic mineral products	0.10%	2.54
Primary metals	0.21%	34.75
Fabricated metal products	0.13%	12.11
Machinery	0.08%	6.14
Computer and electronic products	0.06%	1.03
Electrical equipment, appliances, and components	0.08%	0.72
Motor vehicles, bodies and trailers, and parts	0.04%	13.68
Other transportation equipment	0.02%	-0.07
Furniture and related products	0.01%	-0.56
Miscellaneous manufacturing	0.03%	1.73
Food and beverage and tobacco products	0.01%	1.02
Textile mills and textile product mills	0.03%	-0.11
Apparel and leather and allied products	-0.02%	-0.19
Paper products	0.09%	2.02
Printing and related support activities	0.10%	2.43
Petroleum and coal products	0.22%	9.76
Chemical products	0.13%	23.91
Plastics and rubber products	0.08%	5.56
Wholesale trade	0.06%	11.30
Motor vehicle and parts dealers	0.02%	0.21
Food and beverage stores	0.00%	-0.17
General merchandise stores	0.01%	0.21
Other retail	0.02%	1.40
Air transportation	0.06%	0.44
Rail transportation	0.25%	-0.01
Water transportation	0.07%	-0.05
Truck transportation	0.06%	4.35
Transit and ground passenger transportation	0.04%	0.08
Pipeline transportation	1.68%	4.41

Other transportation and support activities	0.26%	8.78
Warehousing and storage	0.10%	1.68
Publishing industries, except internet (includes software)	0.05%	0.33
Motion picture and sound recording industries	0.01%	-0.05
Broadcasting and telecommunications	0.05%	1.55
Data processing, internet publishing, and other information services	0.12%	0.85
Federal Reserve banks, credit intermediation, and related activities	0.13%	13.50
Securities, commodity contracts, and investments	0.08%	1.21
Insurance carriers and related activities	0.06%	5.76
Funds, trusts, and other financial vehicles	0.01%	0.07
Housing	0.00%	-0.05
Other real estate	0.09%	8.53
Rental and leasing services and lessors of intangible assets	0.12%	4.52
Legal services	0.15%	4.85
Computer systems design and related services	0.06%	2.03
Miscellaneous professional, scientific, and technical services	0.10%	15.18
Management of companies and enterprises	0.15%	6.38
Administrative and support services	0.14%	12.86
Waste management and remediation services	0.12%	1.58
Educational services	0.01%	0.25
Ambulatory health care services	0.00%	0.03
Hospitals	0.00%	0.06
Nursing and residential care facilities	0.00%	-0.12
Social assistance	0.00%	0.07
Performing arts, spectator sports, museums, and related activities	0.05%	0.75
Amusements, gambling, and recreation industries	0.02%	0.26
Accommodation	0.03%	0.16
Food services and drinking places	0.03%	3.78
Other services, except government	0.03%	2.88
Federal general government (defense)	0.00%	0.12
Federal general government (nondefense)	0.01%	0.09
Federal government enterprises	0.14%	-2.11
State and local general government	0.01%	-0.09
State and local government enterprises	0.07%	-27.89

Table E.12 Historic Inoperability and GDP Loss Vector of Indiana – 2008

Industries	**Inoperability**	**GDP Loss In Millions**
Farms	0.02%	0.45
Forestry, fishing, and related activities	0.07%	0.03
Oil and gas extraction	1.77%	4.18
Mining, except oil and gas	0.39%	2.26
Support activities for mining	0.15%	0.20
Utilities	1.12%	141.62
Construction	0.05%	7.68
Wood products	0.10%	1.11
Nonmetallic mineral products	0.12%	1.67
Primary metals	0.24%	28.26
Fabricated metal products	0.14%	9.73
Machinery	0.09%	4.90
Computer and electronic products	0.07%	0.68
Electrical equipment, appliances, and components	0.09%	0.49
Motor vehicles, bodies and trailers, and parts	0.04%	5.27
Other transportation equipment	0.03%	0.06
Furniture and related products	0.03%	0.56
Miscellaneous manufacturing	0.02%	0.49
Food and beverage and tobacco products	0.01%	0.88
Textile mills and textile product mills	0.04%	-0.07
Apparel and leather and allied products	0.05%	0.05
Paper products	0.10%	1.48
Printing and related support activities	0.11%	1.79
Petroleum and coal products	0.22%	7.64
Chemical products	0.14%	18.97
Plastics and rubber products	0.09%	4.18
Wholesale trade	0.07%	9.37
Motor vehicle and parts dealers	0.02%	0.07
Food and beverage stores	0.00%	-0.17
General merchandise stores	0.01%	0.33
Other retail	0.02%	1.17
Air transportation	0.07%	0.37
Rail transportation	0.25%	-0.01
Water transportation	0.07%	-0.03
Truck transportation	0.07%	2.87
Transit and ground passenger transportation	0.06%	0.26
Pipeline transportation	1.88%	3.96

Other transportation and support activities	0.24%	5.54
Warehousing and storage	0.11%	1.38
Publishing industries, except internet (includes software)	0.05%	0.28
Motion picture and sound recording industries	0.03%	0.18
Broadcasting and telecommunications	0.06%	1.27
Data processing, internet publishing, and other information services	0.12%	0.51
Federal Reserve banks, credit intermediation, and related activities	0.15%	10.69
Securities, commodity contracts, and investments	0.07%	0.75
Insurance carriers and related activities	0.07%	4.07
Funds, trusts, and other financial vehicles	0.01%	0.04
Housing	0.00%	-0.03
Other real estate	0.10%	5.68
Rental and leasing services and lessors of intangible assets	0.13%	3.62
Legal services	0.18%	4.06
Computer systems design and related services	0.07%	1.80
Miscellaneous professional, scientific, and technical services	0.12%	12.71
Management of companies and enterprises	0.19%	5.73
Administrative and support services	0.15%	10.49
Waste management and remediation services	0.15%	1.55
Educational services	0.02%	0.27
Ambulatory health care services	0.00%	0.03
Hospitals	0.00%	0.05
Nursing and residential care facilities	0.00%	0.00
Social assistance	0.00%	-0.05
Performing arts, spectator sports, museums, and related activities	0.05%	0.43
Amusements, gambling, and recreation industries	0.01%	-0.01
Accommodation	0.05%	0.45
Food services and drinking places	0.04%	2.94
Other services, except government	0.03%	1.92
Federal general government (defense)	0.00%	0.10
Federal general government (nondefense)	0.01%	0.07
Federal government enterprises	0.13%	-1.87
State and local general government	0.01%	-0.04
State and local government enterprises	0.08%	-20.16

Table E.13 Historic Inoperability and GDP Loss Vector of Indiana – 2009

Industries	**Inoperability**	**GDP Loss In Millions**
Farms	0.01%	0.30
Forestry, fishing, and related activities	0.05%	0.03
Oil and gas extraction	1.13%	1.38
Mining, except oil and gas	0.34%	1.75
Support activities for mining	0.08%	0.06
Utilities	1.06%	99.48
Construction	0.03%	3.46
Wood products	0.08%	0.78
Nonmetallic mineral products	0.07%	0.91
Primary metals	0.13%	7.41
Fabricated metal products	0.08%	4.44
Machinery	0.06%	2.25
Computer and electronic products	0.04%	0.40
Electrical equipment, appliances, and components	0.05%	0.28
Motor vehicles, bodies and trailers, and parts	0.02%	2.68
Other transportation equipment	0.02%	0.16
Furniture and related products	0.03%	0.83
Miscellaneous manufacturing	0.00%	-0.40
Food and beverage and tobacco products	0.01%	0.19
Textile mills and textile product mills	0.05%	0.15
Apparel and leather and allied products	0.03%	0.04
Paper products	0.06%	0.88
Printing and related support activities	0.07%	1.18
Petroleum and coal products	0.13%	2.81
Chemical products	0.06%	6.51
Plastics and rubber products	0.05%	1.55
Wholesale trade	0.04%	4.16
Motor vehicle and parts dealers	0.02%	0.21
Food and beverage stores	0.00%	-0.14
General merchandise stores	0.00%	0.11
Other retail	0.01%	0.37
Air transportation	0.04%	0.12
Rail transportation	0.21%	0.00
Water transportation	0.04%	-0.02
Truck transportation	0.04%	1.03
Transit and ground passenger transportation	0.05%	0.23
Pipeline transportation	1.33%	2.07

Other transportation and support activities	0.17%	3.17
Warehousing and storage	0.07%	0.84
Publishing industries, except internet (includes software)	0.02%	0.05
Motion picture and sound recording industries	0.02%	0.07
Broadcasting and telecommunications	0.03%	0.79
Data processing, internet publishing, and other information services	0.07%	0.34
Federal Reserve banks, credit intermediation, and related activities	0.08%	4.53
Securities, commodity contracts, and investments	0.04%	0.36
Insurance carriers and related activities	0.04%	1.89
Funds, trusts, and other financial vehicles	0.00%	0.02
Housing	0.00%	-0.01
Other real estate	0.06%	2.86
Rental and leasing services and lessors of intangible assets	0.07%	1.41
Legal services	0.10%	1.84
Computer systems design and related services	0.04%	0.81
Miscellaneous professional, scientific, and technical services	0.06%	5.83
Management of companies and enterprises	0.08%	1.90
Administrative and support services	0.09%	4.69
Waste management and remediation services	0.09%	0.76
Educational services	0.01%	0.19
Ambulatory health care services	0.00%	0.14
Hospitals	0.00%	-0.05
Nursing and residential care facilities	0.00%	0.00
Social assistance	0.00%	0.00
Performing arts, spectator sports, museums, and related activities	0.04%	0.38
Amusements, gambling, and recreation industries	0.00%	-0.05
Accommodation	0.03%	0.22
Food services and drinking places	0.02%	1.35
Other services, except government	0.02%	1.28
Federal general government (defense)	0.00%	0.05
Federal general government (nondefense)	0.00%	0.04
Federal government enterprises	0.08%	-1.84
State and local general government	0.00%	-0.10
State and local government enterprises	0.04%	-18.19

Table E.14 Historic Inoperability and GDP Loss Vector of Indiana – 2010

Industries	**Inoperability**	**GDP Loss In Millions**
Farms	0.02%	0.27
Forestry, fishing, and related activities	0.06%	0.03
Oil and gas extraction	1.08%	1.68
Mining, except oil and gas	0.35%	1.89
Support activities for mining	0.09%	0.08
Utilities	1.07%	108.37
Construction	0.04%	4.11
Wood products	0.09%	0.92
Nonmetallic mineral products	0.08%	0.88
Primary metals	0.18%	17.80
Fabricated metal products	0.10%	4.86
Machinery	0.07%	2.75
Computer and electronic products	0.05%	0.39
Electrical equipment, appliances, and components	0.07%	0.39
Motor vehicles, bodies and trailers, and parts	0.03%	6.79
Other transportation equipment	0.02%	0.04
Furniture and related products	0.03%	0.70
Miscellaneous manufacturing	0.02%	0.49
Food and beverage and tobacco products	0.01%	0.56
Textile mills and textile product mills	0.05%	0.09
Apparel and leather and allied products	0.02%	0.01
Paper products	0.06%	0.79
Printing and related support activities	0.07%	0.86
Petroleum and coal products	0.13%	3.30
Chemical products	0.09%	10.82
Plastics and rubber products	0.05%	1.78
Wholesale trade	0.05%	5.25
Motor vehicle and parts dealers	0.02%	0.38
Food and beverage stores	0.00%	-0.05
General merchandise stores	0.00%	-0.11
Other retail	0.01%	0.56
Air transportation	0.05%	0.22
Rail transportation	0.21%	-0.01
Water transportation	0.04%	-0.01
Truck transportation	0.05%	2.05
Transit and ground passenger transportation	0.04%	0.14
Pipeline transportation	1.25%	2.04

Other transportation and support activities	0.12%	2.12
Warehousing and storage	0.06%	0.53
Publishing industries, except internet (includes software)	0.03%	0.06
Motion picture and sound recording industries	0.02%	0.06
Broadcasting and telecommunications	0.04%	0.89
Data processing, internet publishing, and other information services	0.08%	0.40
Federal Reserve banks, credit intermediation, and related activities	0.10%	5.63
Securities, commodity contracts, and investments	0.06%	0.52
Insurance carriers and related activities	0.04%	2.02
Funds, trusts, and other financial vehicles	0.00%	-0.01
Housing	0.00%	-0.01
Other real estate	0.06%	3.05
Rental and leasing services and lessors of intangible assets	0.09%	1.99
Legal services	0.12%	2.21
Computer systems design and related services	0.05%	1.21
Miscellaneous professional, scientific, and technical services	0.08%	7.28
Management of companies and enterprises	0.13%	3.71
Administrative and support services	0.11%	6.62
Waste management and remediation services	0.12%	1.37
Educational services	0.01%	0.13
Ambulatory health care services	0.00%	0.08
Hospitals	0.00%	0.03
Nursing and residential care facilities	0.00%	-0.07
Social assistance	0.00%	-0.04
Performing arts, spectator sports, museums, and related activities	0.03%	0.12
Amusements, gambling, and recreation industries	0.01%	0.13
Accommodation	0.03%	0.17
Food services and drinking places	0.03%	1.72
Other services, except government	0.03%	1.65
Federal general government (defense)	0.00%	0.06
Federal general government (nondefense)	0.00%	0.05
Federal government enterprises	0.10%	-1.91
State and local general government	0.00%	-0.10
State and local government enterprises	0.05%	-18.66

Table E.15 Historic Inoperability and GDP Loss Vector of Indiana – 2011

Industries	**Inoperability**	**GDP Loss In Millions**
Farms	0.01%	0.16
Forestry, fishing, and related activities	0.07%	0.07
Oil and gas extraction	0.75%	1.32
Mining, except oil and gas	0.25%	1.49
Support activities for mining	0.07%	0.07
Utilities	1.05%	102.59
Construction	0.03%	3.71
Wood products	0.08%	1.04
Nonmetallic mineral products	0.10%	1.42
Primary metals	0.15%	15.55
Fabricated metal products	0.08%	4.46
Machinery	0.06%	2.81
Computer and electronic products	0.04%	0.17
Electrical equipment, appliances, and components	0.05%	0.24
Motor vehicles, bodies and trailers, and parts	0.02%	3.69
Other transportation equipment	0.01%	0.02
Furniture and related products	0.02%	0.24
Miscellaneous manufacturing	0.02%	0.57
Food and beverage and tobacco products	0.01%	0.36
Textile mills and textile product mills	0.05%	0.14
Apparel and leather and allied products	0.02%	0.01
Paper products	0.05%	0.51
Printing and related support activities	0.06%	0.92
Petroleum and coal products	0.10%	3.28
Chemical products	0.08%	11.08
Plastics and rubber products	0.05%	2.50
Wholesale trade	0.04%	4.72
Motor vehicle and parts dealers	0.01%	-0.12
Food and beverage stores	0.00%	0.04
General merchandise stores	0.00%	-0.04
Other retail	0.01%	0.55
Air transportation	0.04%	0.18
Rail transportation	0.16%	0.00
Water transportation	0.01%	-0.01
Truck transportation	0.04%	1.66
Transit and ground passenger transportation	0.05%	0.27
Pipeline transportation	1.04%	1.77

Other transportation and support activities	0.09%	1.77
Warehousing and storage	0.06%	0.68
Publishing industries, except internet (includes software)	0.03%	0.20
Motion picture and sound recording industries	0.02%	0.10
Broadcasting and telecommunications	0.03%	0.73
Data processing, internet publishing, and other information services	0.06%	0.23
Federal Reserve banks, credit intermediation, and related activities	0.07%	3.73
Securities, commodity contracts, and investments	0.04%	0.34
Insurance carriers and related activities	0.03%	1.68
Funds, trusts, and other financial vehicles	0.00%	0.01
Housing	0.00%	-0.01
Other real estate	0.05%	2.23
Rental and leasing services and lessors of intangible assets	0.08%	1.91
Legal services	0.09%	1.68
Computer systems design and related services	0.04%	0.95
Miscellaneous professional, scientific, and technical services	0.06%	5.99
Management of companies and enterprises	0.10%	2.96
Administrative and support services	0.09%	5.60
Waste management and remediation services	0.07%	0.57
Educational services	0.01%	0.29
Ambulatory health care services	0.00%	0.08
Hospitals	0.00%	0.03
Nursing and residential care facilities	0.00%	0.00
Social assistance	0.00%	-0.04
Performing arts, spectator sports, museums, and related activities	0.03%	0.14
Amusements, gambling, and recreation industries	0.01%	-0.04
Accommodation	0.02%	0.22
Food services and drinking places	0.02%	1.56
Other services, except government	0.02%	1.03
Federal general government (defense)	0.00%	0.05
Federal general government (nondefense)	0.00%	0.05
Federal government enterprises	0.07%	-2.26
State and local general government	0.00%	-0.12
State and local government enterprises	0.03%	-19.07

Table E.16 Historic Inoperability and GDP Loss Vector of Indiana – 2012

Industries	**Inoperability**	**GDP Loss In Millions**
Farms	0.01%	0.24
Forestry, fishing, and related activities	0.04%	0.02
Oil and gas extraction	0.57%	0.97
Mining, except oil and gas	0.20%	1.21
Support activities for mining	0.05%	0.05
Utilities	1.04%	95.28
Construction	0.03%	3.48
Wood products	0.08%	1.27
Nonmetallic mineral products	0.08%	1.32
Primary metals	0.12%	14.40
Fabricated metal products	0.07%	4.09
Machinery	0.05%	3.31
Computer and electronic products	0.04%	0.15
Electrical equipment, appliances, and components	0.05%	0.17
Motor vehicles, bodies and trailers, and parts	0.02%	2.66
Other transportation equipment	0.01%	-0.06
Furniture and related products	0.01%	0.22
Miscellaneous manufacturing	0.02%	0.81
Food and beverage and tobacco products	0.01%	0.00
Textile mills and textile product mills	0.03%	0.10
Apparel and leather and allied products	0.02%	0.05
Paper products	0.04%	0.37
Printing and related support activities	0.04%	0.46
Petroleum and coal products	0.10%	3.62
Chemical products	0.06%	7.54
Plastics and rubber products	0.04%	1.32
Wholesale trade	0.03%	4.34
Motor vehicle and parts dealers	0.01%	0.28
Food and beverage stores	0.00%	0.00
General merchandise stores	0.01%	0.33
Other retail	0.01%	0.29
Air transportation	0.03%	0.13
Rail transportation	0.13%	0.00
Water transportation	0.04%	-0.02
Truck transportation	0.03%	1.69
Transit and ground passenger transportation	0.01%	0.00
Pipeline transportation	0.88%	1.46

Other transportation and support activities	0.13%	2.87
Warehousing and storage	0.05%	0.60
Publishing industries, except internet (includes software)	0.02%	0.17
Motion picture and sound recording industries	0.02%	0.08
Broadcasting and telecommunications	0.02%	0.45
Data processing, internet publishing, and other information services	0.05%	0.27
Federal Reserve banks, credit intermediation, and related activities	0.05%	2.36
Securities, commodity contracts, and investments	0.03%	0.26
Insurance carriers and related activities	0.02%	0.94
Funds, trusts, and other financial vehicles	0.00%	0.04
Housing	0.00%	-0.01
Other real estate	0.04%	2.09
Rental and leasing services and lessors of intangible assets	0.05%	1.15
Legal services	0.06%	1.18
Computer systems design and related services	0.03%	0.80
Miscellaneous professional, scientific, and technical services	0.05%	4.39
Management of companies and enterprises	0.07%	2.08
Administrative and support services	0.07%	5.13
Waste management and remediation services	0.06%	0.45
Educational services	0.01%	0.28
Ambulatory health care services	0.00%	0.01
Hospitals	0.00%	0.02
Nursing and residential care facilities	0.00%	0.00
Social assistance	0.00%	0.04
Performing arts, spectator sports, museums, and related activities	0.03%	0.19
Amusements, gambling, and recreation industries	0.01%	0.10
Accommodation	0.02%	0.19
Food services and drinking places	0.01%	0.79
Other services, except government	0.02%	0.99
Federal general government (defense)	0.00%	0.04
Federal general government (nondefense)	0.00%	0.03
Federal government enterprises	0.05%	-2.43
State and local general government	0.00%	-0.15
State and local government enterprises	0.04%	-19.00

Table E.17 Historic Inoperability and GDP Loss Vector of Indiana – 2013

Industries	**Inoperability**	**GDP Loss In Millions**
Farms	0.02%	0.40
Forestry, fishing, and related activities	0.04%	0.01
Oil and gas extraction	0.63%	1.25
Mining, except oil and gas	0.23%	1.34
Support activities for mining	0.05%	0.06
Utilities	1.05%	100.23
Construction	0.02%	2.98
Wood products	0.06%	0.78
Nonmetallic mineral products	0.06%	0.87
Primary metals	0.11%	11.84
Fabricated metal products	0.07%	4.09
Machinery	0.05%	2.97
Computer and electronic products	0.04%	0.19
Electrical equipment, appliances, and components	0.04%	0.08
Motor vehicles, bodies and trailers, and parts	0.02%	4.42
Other transportation equipment	0.01%	-0.19
Furniture and related products	0.02%	0.45
Miscellaneous manufacturing	0.01%	-0.02
Food and beverage and tobacco products	0.01%	0.61
Textile mills and textile product mills	0.02%	0.03
Apparel and leather and allied products	-0.01%	-0.07
Paper products	0.04%	0.31
Printing and related support activities	0.04%	0.32
Petroleum and coal products	0.12%	4.56
Chemical products	0.06%	7.96
Plastics and rubber products	0.04%	1.79
Wholesale trade	0.03%	4.88
Motor vehicle and parts dealers	0.01%	0.07
Food and beverage stores	0.01%	0.09
General merchandise stores	0.00%	0.10
Other retail	0.01%	0.37
Air transportation	0.03%	0.17
Rail transportation	0.15%	0.00
Water transportation	0.02%	-0.02
Truck transportation	0.03%	1.60
Transit and ground passenger transportation	0.02%	0.06
Pipeline transportation	0.97%	1.73

Other transportation and support activities	0.15%	3.43
Warehousing and storage	0.06%	0.99
Publishing industries, except internet (includes software)	0.02%	0.22
Motion picture and sound recording industries	0.02%	0.09
Broadcasting and telecommunications	0.02%	0.52
Data processing, internet publishing, and other information services	0.06%	0.37
Federal Reserve banks, credit intermediation, and related activities	0.05%	2.77
Securities, commodity contracts, and investments	0.03%	0.27
Insurance carriers and related activities	0.02%	1.15
Funds, trusts, and other financial vehicles	0.00%	0.01
Housing	0.00%	-0.01
Other real estate	0.04%	2.50
Rental and leasing services and lessors of intangible assets	0.06%	1.47
Legal services	0.08%	1.44
Computer systems design and related services	0.04%	0.88
Miscellaneous professional, scientific, and technical services	0.05%	4.85
Management of companies and enterprises	0.07%	2.20
Administrative and support services	0.08%	5.43
Waste management and remediation services	0.06%	0.53
Educational services	0.01%	0.10
Ambulatory health care services	0.00%	-0.11
Hospitals	0.00%	0.02
Nursing and residential care facilities	0.00%	0.00
Social assistance	0.00%	0.04
Performing arts, spectator sports, museums, and related activities	0.03%	0.26
Amusements, gambling, and recreation industries	0.01%	0.26
Accommodation	0.02%	0.09
Food services and drinking places	0.02%	1.23
Other services, except government	0.02%	0.95
Federal general government (defense)	0.00%	0.04
Federal general government (nondefense)	0.00%	0.03
Federal government enterprises	0.05%	-2.50
State and local general government	0.00%	-0.15
State and local government enterprises	0.03%	-19.62

Table E.18 Historic Inoperability and GDP Loss Vector of Indiana – 2014

Industries	**Inoperability**	**GDP Loss In Millions**
Farms	0.02%	0.40
Forestry, fishing, and related activities	0.03%	0.00
Oil and gas extraction	0.67%	1.55
Mining, except oil and gas	0.28%	1.62
Support activities for mining	0.05%	0.05
Utilities	1.05%	107.79
Construction	0.03%	3.91
Wood products	0.05%	0.25
Nonmetallic mineral products	0.05%	0.37
Primary metals	0.13%	14.08
Fabricated metal products	0.07%	4.09
Machinery	0.06%	3.01
Computer and electronic products	0.05%	0.08
Electrical equipment, appliances, and components	0.05%	0.10
Motor vehicles, bodies and trailers, and parts	0.02%	5.30
Other transportation equipment	0.02%	-0.05
Furniture and related products	0.01%	0.10
Miscellaneous manufacturing	0.01%	0.05
Food and beverage and tobacco products	0.01%	0.35
Textile mills and textile product mills	0.05%	0.26
Apparel and leather and allied products	0.01%	0.00
Paper products	0.06%	0.86
Printing and related support activities	0.06%	0.92
Petroleum and coal products	0.12%	4.06
Chemical products	0.06%	7.87
Plastics and rubber products	0.05%	2.71
Wholesale trade	0.04%	5.54
Motor vehicle and parts dealers	0.01%	0.16
Food and beverage stores	0.00%	0.00
General merchandise stores	0.00%	-0.03
Other retail	0.01%	0.63
Air transportation	0.04%	0.16
Rail transportation	0.18%	-0.01
Water transportation	0.05%	-0.02
Truck transportation	0.04%	2.38
Transit and ground passenger transportation	0.03%	0.09
Pipeline transportation	1.09%	2.16

Other transportation and support activities	0.16%	3.58
Warehousing and storage	0.07%	1.11
Publishing industries, except internet (includes software)	0.02%	0.09
Motion picture and sound recording industries	0.02%	0.08
Broadcasting and telecommunications	0.03%	0.89
Data processing, internet publishing, and other information services	0.06%	0.28
Federal Reserve banks, credit intermediation, and related activities	0.06%	3.73
Securities, commodity contracts, and investments	0.03%	0.33
Insurance carriers and related activities	0.03%	1.74
Funds, trusts, and other financial vehicles	0.00%	0.05
Housing	0.00%	-0.01
Other real estate	0.05%	3.32
Rental and leasing services and lessors of intangible assets	0.07%	1.82
Legal services	0.09%	1.70
Computer systems design and related services	0.05%	1.17
Miscellaneous professional, scientific, and technical services	0.06%	5.80
Management of companies and enterprises	0.08%	2.75
Administrative and support services	0.09%	6.44
Waste management and remediation services	0.09%	1.04
Educational services	0.01%	0.15
Ambulatory health care services	0.00%	0.02
Hospitals	0.00%	-0.04
Nursing and residential care facilities	0.00%	0.00
Social assistance	0.00%	0.04
Performing arts, spectator sports, museums, and related activities	0.03%	0.32
Amusements, gambling, and recreation industries	0.01%	0.16
Accommodation	0.03%	0.28
Food services and drinking places	0.02%	1.66
Other services, except government	0.02%	1.19
Federal general government (defense)	0.00%	0.05
Federal general government (nondefense)	0.00%	0.04
Federal government enterprises	0.05%	-2.64
State and local general government	0.00%	-0.15
State and local government enterprises	0.04%	-19.82

Table E.19 Historic Inoperability and GDP Loss Vector of Indiana – 2015

Industries	**Inoperability**	**GDP Loss In Millions**
Farms	0.01%	0.18
Forestry, fishing, and related activities	0.02%	-0.01
Oil and gas extraction	0.62%	0.91
Mining, except oil and gas	0.25%	1.33
Support activities for mining	0.04%	0.02
Utilities	1.05%	102.87
Construction	0.02%	3.61
Wood products	0.04%	0.37
Nonmetallic mineral products	0.06%	1.11
Primary metals	0.10%	11.05
Fabricated metal products	0.06%	3.06
Machinery	0.04%	2.50
Computer and electronic products	0.04%	0.34
Electrical equipment, appliances, and components	0.05%	0.17
Motor vehicles, bodies and trailers, and parts	0.01%	0.94
Other transportation equipment	0.02%	0.11
Furniture and related products	0.02%	0.30
Miscellaneous manufacturing	0.02%	0.57
Food and beverage and tobacco products	0.01%	0.43
Textile mills and textile product mills	0.03%	0.08
Apparel and leather and allied products	0.02%	0.05
Paper products	0.04%	0.13
Printing and related support activities	0.03%	0.31
Petroleum and coal products	0.10%	2.37
Chemical products	0.05%	5.79
Plastics and rubber products	0.05%	2.67
Wholesale trade	0.03%	4.46
Motor vehicle and parts dealers	0.01%	0.20
Food and beverage stores	0.00%	0.04
General merchandise stores	0.00%	0.12
Other retail	0.01%	0.69
Air transportation	0.04%	0.19
Rail transportation	0.12%	0.00
Water transportation	0.04%	-0.02
Truck transportation	0.03%	1.59
Transit and ground passenger transportation	0.03%	0.15
Pipeline transportation	1.04%	2.17

Other transportation and support activities	0.15%	3.82
Warehousing and storage	0.06%	0.86
Publishing industries, except internet (includes software)	0.02%	0.08
Motion picture and sound recording industries	0.02%	0.10
Broadcasting and telecommunications	0.02%	0.64
Data processing, internet publishing, and other information services	0.05%	0.27
Federal Reserve banks, credit intermediation, and related activities	0.05%	3.43
Securities, commodity contracts, and investments	0.03%	0.29
Insurance carriers and related activities	0.03%	1.67
Funds, trusts, and other financial vehicles	0.00%	0.01
Housing	0.00%	-0.01
Other real estate	0.04%	2.79
Rental and leasing services and lessors of intangible assets	0.05%	1.40
Legal services	0.08%	1.60
Computer systems design and related services	0.03%	0.89
Miscellaneous professional, scientific, and technical services	0.05%	5.24
Management of companies and enterprises	0.06%	2.25
Administrative and support services	0.08%	6.24
Waste management and remediation services	0.04%	0.28
Educational services	0.01%	0.22
Ambulatory health care services	0.00%	-0.04
Hospitals	0.00%	0.02
Nursing and residential care facilities	0.00%	0.07
Social assistance	0.00%	0.04
Performing arts, spectator sports, museums, and related activities	0.02%	0.04
Amusements, gambling, and recreation industries	0.00%	-0.01
Accommodation	0.02%	0.10
Food services and drinking places	0.02%	1.38
Other services, except government	0.01%	0.91
Federal general government (defense)	0.00%	0.04
Federal general government (nondefense)	0.00%	0.03
Federal government enterprises	0.05%	-2.39
State and local general government	0.00%	-0.18
State and local government enterprises	0.04%	-20.19

Table E.20 Historic Inoperability and GDP Loss Vector of Indiana – 2016

Industries	**Inoperability**	**GDP Loss In Millions**
Farms	0.01%	0.32
Forestry, fishing, and related activities	0.04%	0.03
Oil and gas extraction	0.62%	0.74
Mining, except oil and gas	0.24%	1.20
Support activities for mining	0.04%	-0.01
Utilities	1.04%	99.60
Construction	0.02%	3.21
Wood products	0.04%	0.36
Nonmetallic mineral products	0.05%	0.73
Primary metals	0.09%	8.32
Fabricated metal products	0.06%	3.51
Machinery	0.05%	2.62
Computer and electronic products	0.04%	0.22
Electrical equipment, appliances, and components	0.05%	0.25
Motor vehicles, bodies and trailers, and parts	0.01%	4.69
Other transportation equipment	0.01%	-0.03
Furniture and related products	0.02%	0.67
Miscellaneous manufacturing	0.02%	0.72
Food and beverage and tobacco products	0.01%	0.35
Textile mills and textile product mills	0.04%	0.26
Apparel and leather and allied products	0.02%	0.05
Paper products	0.04%	0.21
Printing and related support activities	0.05%	0.81
Petroleum and coal products	0.09%	1.70
Chemical products	0.04%	5.33
Plastics and rubber products	0.04%	1.69
Wholesale trade	0.03%	3.89
Motor vehicle and parts dealers	0.01%	0.39
Food and beverage stores	0.01%	0.14
General merchandise stores	0.00%	-0.03
Other retail	0.01%	0.54
Air transportation	0.03%	0.15
Rail transportation	0.12%	0.00
Water transportation	0.02%	-0.02
Truck transportation	0.03%	1.07
Transit and ground passenger transportation	0.02%	0.09
Pipeline transportation	1.01%	2.09

Other transportation and support activities	0.12%	3.05
Warehousing and storage	0.05%	0.63
Publishing industries, except internet (includes software)	0.02%	0.07
Motion picture and sound recording industries	0.02%	0.09
Broadcasting and telecommunications	0.02%	0.59
Data processing, internet publishing, and other information services	0.04%	0.25
Federal Reserve banks, credit intermediation, and related activities	0.05%	3.03
Securities, commodity contracts, and investments	0.03%	0.28
Insurance carriers and related activities	0.03%	1.80
Funds, trusts, and other financial vehicles	0.00%	0.04
Housing	0.00%	-0.01
Other real estate	0.04%	2.60
Rental and leasing services and lessors of intangible assets	0.04%	1.29
Legal services	0.06%	1.29
Computer systems design and related services	0.03%	0.82
Miscellaneous professional, scientific, and technical services	0.04%	4.77
Management of companies and enterprises	0.06%	2.15
Administrative and support services	0.06%	5.24
Waste management and remediation services	0.04%	0.37
Educational services	0.01%	0.04
Ambulatory health care services	0.00%	0.13
Hospitals	0.00%	0.02
Nursing and residential care facilities	0.00%	0.00
Social assistance	0.00%	0.04
Performing arts, spectator sports, museums, and related activities	0.03%	0.35
Amusements, gambling, and recreation industries	0.00%	-0.01
Accommodation	0.02%	0.22
Food services and drinking places	0.01%	1.30
Other services, except government	0.01%	0.98
Federal general government (defense)	0.00%	0.04
Federal general government (nondefense)	0.00%	0.03
Federal government enterprises	0.05%	-2.21
State and local general government	0.00%	-0.18
State and local government enterprises	0.03%	-20.78

Table E.21 Summary of Historic GDP Loss of Indiana (in Millions)

Industries	**Min**	**Median**	**Max**
Farms	0.14	0.33	0.82
Forestry, fishing, and related activities	-0.01	0.04	0.13
Oil and gas extraction	0.74	1.47	4.31
Mining, except oil and gas	0.94	1.69	2.79
Support activities for mining	-0.01	0.07	0.36
Utilities	93.74	106.92	187.02
Construction	2.31	3.66	9.70
Wood products	0.25	1.17	3.14
Nonmetallic mineral products	0.37	1.40	3.16
Primary metals	7.41	15.47	34.75
Fabricated metal products	3.06	5.05	12.11
Machinery	2.25	3.43	8.37
Computer and electronic products	0.08	0.51	1.34
Electrical equipment, appliances, and components	-0.08	0.26	0.81
Motor vehicles, bodies and trailers, and parts	0.94	5.76	15.48
Other transportation equipment	-0.19	-0.01	0.16
Furniture and related products	-0.56	0.43	1.21
Miscellaneous manufacturing	-0.44	0.58	1.73
Food and beverage and tobacco products	0.00	0.90	1.67
Textile mills and textile product mills	-0.15	0.14	0.48
Apparel and leather and allied products	-0.19	0.04	0.22
Paper products	0.13	1.22	2.38
Printing and related support activities	0.31	1.76	3.22
Petroleum and coal products	1.52	3.29	9.76
Chemical products	5.30	7.92	23.91
Plastics and rubber products	1.32	2.69	6.32
Wholesale trade	3.89	5.86	13.53
Motor vehicle and parts dealers	-0.12	0.31	0.56
Food and beverage stores	-0.17	0.05	0.50
General merchandise stores	-0.25	0.10	0.40
Other retail	0.29	0.69	1.53
Air transportation	0.12	0.23	0.56
Rail transportation	-0.01	-0.01	0.00
Water transportation	-0.05	-0.02	-0.01
Truck transportation	1.03	2.13	5.58
Transit and ground passenger transportation	0.00	0.18	0.54
Pipeline transportation	1.46	3.17	4.41
Other transportation and support activities	1.65	3.11	8.78

Warehousing and storage	0.30	0.84	2.10
Publishing industries, except internet (includes software)	-0.04	0.18	0.37
Motion picture and sound recording industries	-0.05	0.11	0.28
Broadcasting and telecommunications	0.45	1.35	3.70
Data processing, internet publishing, and other information services	0.23	0.38	1.07
Federal Reserve banks, credit intermediation, and related activities	2.36	9.54	24.99
Securities, commodity contracts, and investments	0.26	0.73	2.19
Insurance carriers and related activities	0.94	2.29	5.98
Funds, trusts, and other financial vehicles	-0.05	0.02	0.07
Housing	-0.05	-0.02	-0.01
Other real estate	2.09	4.47	11.18
Rental and leasing services and lessors of intangible assets	1.15	4.24	10.73
Legal services	1.18	2.67	5.93
Computer systems design and related services	0.61	1.26	3.00
Miscellaneous professional, scientific, and technical services	4.39	8.23	20.48
Management of companies and enterprises	1.90	3.29	7.43
Administrative and support services	4.69	7.29	16.36
Waste management and remediation services	0.28	1.02	2.57
Educational services	0.04	0.28	0.53
Ambulatory health care services	-0.11	0.03	0.21
Hospitals	-0.05	0.04	0.19
Nursing and residential care facilities	-0.12	0.00	0.11
Social assistance	-0.05	0.00	0.07
Performing arts, spectator sports, museums, and related activities	0.04	0.33	0.75
Amusements, gambling, and recreation industries	-0.13	0.08	0.33
Accommodation	0.09	0.29	1.11
Food services and drinking places	0.79	2.45	6.33
Other services, except government	0.91	2.03	5.64
Federal general government (defense)	0.04	0.06	0.14
Federal general government (nondefense)	0.03	0.06	0.13
Federal government enterprises	-2.64	-1.86	-0.27
State and local general government	-0.18	-0.07	0.18
State and local government enterprises	-28.58	-18.83	-15.37

Table E.22 Vulnerable Industries in Indiana (in Descending Order)

Rank	Industry	Mean GDP Loss in Millions
1	Utilities	118.79
2	Primary metals	18.31
3	Chemical products	10.48
4	Federal Reserve banks, credit intermediation, and related activities	9.78
5	Miscellaneous professional, scientific, and technical services	9.73
6	Administrative and support services	8.52
7	Wholesale trade	7.15
8	Motor vehicles, bodies and trailers, and parts	7.08
9	Fabricated metal products	6.12
10	Other real estate	5.27
11	Construction	4.60
12	Machinery	4.35
13	Petroleum and coal products	4.32
14	Rental and leasing services and lessors of intangible assets	4.09
15	Management of companies and enterprises	3.88
16	Other transportation and support activities	3.58
17	Plastics and rubber products	3.30
18	Insurance carriers and related activities	3.02
19	Pipeline transportation	2.93
20	Legal services	2.93
21	Food services and drinking places	2.69
22	Truck transportation	2.53
23	Other services, except government	2.28
24	Oil and gas extraction	2.00
25	Mining, except oil and gas	1.74
26	Printing and related support activities	1.62
27	Nonmetallic mineral products	1.54
28	Broadcasting and telecommunications	1.44
29	Computer systems design and related services	1.40
30	Wood products	1.35
31	Paper products	1.21
32	Waste management and remediation services	1.08
33	Warehousing and storage	0.99
34	Securities, commodity contracts, and investments	0.88
35	Other retail	0.80
36	Food and beverage and tobacco products	0.79

37	Miscellaneous manufacturing	0.59
38	Computer and electronic products	0.56
39	Data processing, internet publishing, and other information services	0.46
40	Furniture and related products	0.44
41	Accommodation	0.38
42	Farms	0.37
43	Performing arts, spectator sports, museums, and related activities	0.35
44	Electrical equipment, appliances, and components	0.33
45	Motor vehicle and parts dealers	0.28
46	Air transportation	0.27
47	Educational services	0.27
48	Transit and ground passenger transportation	0.22
49	Publishing industries, except internet (includes software)	0.17
50	Textile mills and textile product mills	0.17
51	Motion picture and sound recording industries	0.13
52	Support activities for mining	0.11
53	Amusements, gambling, and recreation industries	0.09
54	General merchandise stores	0.08
55	Federal general government (defense)	0.07
56	Federal general government (nondefense)	0.06
57	Forestry, fishing, and related activities	0.06
58	Ambulatory health care services	0.05
59	Hospitals	0.05
60	Food and beverage stores	0.05
61	Apparel and leather and allied products	0.04
62	Funds, trusts, and other financial vehicles	0.02
63	Social assistance	0.01
64	Other transportation equipment	0.00
65	Nursing and residential care facilities	0.00
66	Rail transportation	-0.01
67	Water transportation	-0.02
68	Housing	-0.02
69	State and local general government	-0.06
70	Federal government enterprises	-1.74
71	State and local government enterprises	-19.12

APPENDIX F

Benefit Cost Analysis

A utility (henceforth referred as UCo) located in Indiana contributes 15% to the state's total electricity production every year. UCo has 6000 miles of overhead distribution lines, 117 electric substations and 240,000 electric poles within its service territory. The outcome of the vulnerability analysis is shown is Table F.1.

Table F.1 Vulnerability of Components of Grid

	Overhead Distribution Line	**Substations**	**Poles**
Total Length	6000 Miles	117 Nos	240000 Nos
Vulnerability	1.00%	3.00%	1.00%
Vulnerable	60 Miles	4 Nos	2400 Nos

UCo has collected its historical weather-related power outages data following the database format and performed the analysis with the collected data. The historical data shows an average inoperability of 1% and a standard deviation of 0.2%. UCo has identified 3 risk factors: vegetation related (R_1), equipment related (R_2), and pole related (R_3). Suppose, the outcomes of the analysis with the historical data are as shown in table F.2.

Table F.2 Risk Factors

Risk Factor	**MED**	$\boldsymbol{RF_i}$	$\boldsymbol{q_{R_i}}$	**Relative Proportion**
R_1	3.4	0.72	0.0031	76%
R_2	3.4	0.09	0.0060	18%
R_3	3.4	0.02	0.0090	6%

The table shows that every year UCo has recorded 3.4 MEDs due to severe weather events. Out of all MEDs vegetation related incidents occurred 72% of time and caused an average inoperability of 0.31%, equipment related incidents occurred 9% of time and caused an average of inoperability

0.60% and pole related incidents occurred 2% of time and caused an average of inoperability 0.90%. The relative proportion of the risk factors (θ_{R_i}) were calculated based on equation

$$\theta_{R_i} = \frac{MED \times RF_i \times q_{R_i}}{MED \times \sum_{i=1}^{m} RF_i \times q_{R_i}}$$

The expected GDP loss for the state of Indiana due to 1% inoperability of the utility sector has been derived in section 4.3 and it is \$274.5 million in 2017 values. The expected GDP loss for the state of Indiana due to 1% inoperability in UCo can be calculated following equation

$$Annual\ Economic\ Impact\ due\ to\ R_i = MED \times \sum RF_i \times q_{R_i} \times p\% \times e_{1\%}^{Loss}$$

$$= 3.4 \times (0.72 \times 0.0031 + 0.09 \times 0.0060 + 0.02 \times 0.0090) \times 15\% \times \$274.5\ million$$

The expected annual GDP loss due to 1% inoperability in UCo is \$41.3 million. UCo has identified 4 strategies to mitigate the risk of the annual economic loss. They are selective undergrounding, rerouting the distribution lines to avoid vulnerable zones, elevating the substations to mitigate flood risk and increasing pole strength to make them more robust. The projects are planned to be completed in 5 years and the design life is 20 years. The estimated unit cost of each strategy is shown in table F.3

Table F.3 Unit Cost of Strategies

Risk Factors	**Strategy**	**Unit Cost of Construction**	**O&M Cost**
Vegetation Related	Undergrounding	\$962,000 per Mile	1.39% of Capital Cost
	Rerouting	\$274,857 per Mile	4.77% of Capital Cost
Equipment Related	Elevating Substations	\$2,865,000 per No	1.39% of Capital Cost
Pole Related	Increasing Pole Strength	\$2,500 per No	4.77% of Capital Cost

UCo wants to find the optimal scope of all strategies which will minimize the economic impact of the power outages. It starts with a moderate risk level say 50th percentile. For 50th percentile, the design inoperability is 1%. It has been assumed that the average inoperability follows a normal distribution with mean 1% and standard deviation 0.2%. The risk can be quantified following equation

$$Risk = P(q \leq 1\%) \times 1\% \times 15\% \times \$274.5\ Million = 20.6\ Million$$

$P(q \leq 1\%)$ is equal to 0.5 as q follows a normal distribution with mean 1% and standard deviation 0.2%. The calculated risk is $20.6 million. It has to be distributed across the risk factors and subsequently across the strategies. The relative proportions have already been estimated in table F.2 and the number of strategies associated with each risk factor is shown in table F.3. Therefore, the risk associated with each risk reduction strategies can be found using equation

$$Risk_{RR_i} = \frac{Risk_{R_i}}{n}$$

$$Risk_{R_i} = \theta_{R_i} \times Risk$$

Where, $Risk_{R_i}$ is the risk associated with a risk factor i, n is the number of risk reduction strategies planned for risk factor i and $Risk_{RR_i}$ is the risk associated with each risk reduction strategy planned to mitigate the impact of risk factor i.

Table F.4 Risk Associated with Each Strategy for Risk Level 50th Percentile

Risk Factor	**n**	$\boldsymbol{\theta_{R_i}}$	$\boldsymbol{Risk_{R_i}}$	$\boldsymbol{Risk_{RR_i}}$
Vegetation Related	2	76%	15.7 M	7.8 M
Equipment Related	1	18%	3.7 M	3.7 M
Pole Related	1	6%	1.2 M	1.2 M

The same procedure can be followed to quantify risk at other risk levels. The 60th, 70th, 80th and 90th percentile of the normal distribution with mean 1.0% and SD 0.2% are the design inoperability. For a normal distribution the percentiles are the probabilities. Therefore, the risk at the other risk levels can be calculated as table F.5

Table F.5 Risk Quantification

Risk Percentile	Design Inoperability	Probability	Risk
50%	1.00	0.50	$0.50 \times 1\% \times 15\% \times \$274.5\ Million$ = 20.6 M
60%	1.05	0.60	$0.60 \times 1.05\% \times 15\% \times \$274.5\ Million$ = 26.0 M
70%	1.10	0.70	$0.70 \times 1.10\% \times 15\% \times \$274.5\ Million$ = 31.8 M
80%	1.17	0.80	$0.80 \times 1.17\% \times 15\% \times \$274.5\ Million$ = 38.5 M
90%	1.26	0.90	$0.90 \times 1.26\% \times 15\% \times \$274.5\ Million$ = 46.6 M

Once, the risk is quantified at each risk level, it can be used to derive the risk associated with each risk factor at all risk level. This risk associated with each risk factor is used in the BCA as a cost component.

Table F.6 Risk Associated with Each Strategy for Risk Level 60th Percentile

Risk Factor	n	$\boldsymbol{\theta_{R_i}}$	$\boldsymbol{Risk_{R_i}}$	$\boldsymbol{Risk_{RR_i}}$
Vegetation Related	2	76%	19.7 M	9.8 M
Equipment Related	1	18%	4.7 M	4.7 M
Pole Related	1	6%	1.6 M	1.6 M

Table F.7 Risk Associated with Each Strategy for Risk Level 70th Percentile

Risk Factor	n	$\boldsymbol{\theta_{R_i}}$	$\boldsymbol{Risk_{R_i}}$	$\boldsymbol{Risk_{RR_i}}$
Vegetation Related	2	76%	24.2 M	12.1 M
Equipment Related	1	18%	5.7 M	5.7 M
Pole Related	1	6%	1.9 M	1.9 M

Table F.8 Risk Associated with Each Strategy for Risk Level 80th Percentile

Risk Factor	n	$\boldsymbol{\theta_{R_i}}$	$\boldsymbol{Risk_{R_i}}$	$\boldsymbol{Risk_{RR_i}}$
Vegetation Related	2	76%	29.2 M	14.6 M
Equipment Related	1	18%	6.9 M	6.9 M
Pole Related	1	6%	2.3 M	2.3 M

Table F.9 Risk Associated with Each Strategy for Risk Level 90th Percentile

Risk Factor	n	$\boldsymbol{\theta_{R_i}}$	$\boldsymbol{Risk_{R_i}}$	$\boldsymbol{Risk_{RR_i}}$
Vegetation Related	2	76%	35.4 M	17.7 M
Equipment Related	1	18%	8.4 M	8.4 M
Pole Related	1	6%	2.8 M	2.8 M

The planned scope of work for the 4 strategies are shown in table F.10. It is assumed that same amount of work will be done each year during the construction period which is 5 years.

Table F.9 Planned Scope of Work

Strategy	**Unit**	**Planned Scope**
Selective Undergrounding	per Mile	x1
Rerouting	per Mile	x2
Elevating Substations	Per No	x3
Pole Strengthening	Per No	x4

Benefit has been defined as the reduction of economic loss due to implementation of the risk reduction strategies. In this research it has been assumed that the relationship between vulnerable components and annual economic loss is linear. If V is the vulnerable portion of the grid which is triggering risk factor i then the linearity assumption considers that each unit of V contributes equally to the annual economic impact. Therefore, if the strategy is planned for x unit, it will reduce the impact by x/V percentage. For example, let us assume that a utility has identified 100 miles of its distribution lines as vulnerable causing vegetation related risk. Suppose, the annual economic impact of vegetation related risk has been estimated using equation 70 to be $100 million a year. Therefore, based on the linearity assumption each mile of the vulnerable distribution line causes an economic loss of $1 million a year. Now, if the utility plans 10 miles of undergrounding, that will reduce the annual economic loss by $10 million a year. Economic impact due to a risk factor i is calculated by equation

$$Annual\ Economic\ Impact\ due\ to\ R_i = MED \times RF_i \times q_{R_i} \times p\% \times e_{1\%}^{Loss}$$

$$Annual\ Economic\ Impact\ due\ to\ R_1 = 3.4 \times 0.72 \times 0.0031 \times 15\% \times 274.5\ Million$$
$$= \$31.2\ Million$$

$$Annual\ Economic\ Impact\ due\ to\ R_2 = 3.4 \times 0.09 \times 0.0060 \times 15\% \times 274.5\ Million$$
$$= \$7.6\ Million$$

$$Annual\ Economic\ Impact\ due\ to\ R_3 = 3.4 \times 0.02 \times 0.0090 \times 15\% \times 274.5\ Million$$
$$= \$2.5\ Million$$

Table F.10 Unit Benefit of Strategies

Risk Factor	**Vulnerability**	**Economic Impact**	**Unit Impact**
Vegetation Related	60 Miles	31.2 Million	$=\frac{\$31.2\ Million}{60\ Miles} = \$520{,}781\ per\ Mile$
Equipment Related	4 Nos	7.6 Million	$=\frac{\$7.6\ Million}{4\ Nos} = \$1{,}889{,}933\ per\ No$
Pole Related	2400 Nos	2.5 Million	$=\frac{\$2.5\ Million}{2{,}400\ Nos} = \$1{,}050\ per\ No$

Cash Flow Analysis

The construction period for the new projects has been considered for 5 years. So, for the first 5 years, the annual cost is the sum of the construction cost and the operation and maintenance (O&M) cost. Once the construction period is over, there will only be O&M cost for the rest of the design life. It should be noted that the O&M cost will gradually increase as construction progresses until the end of construction period. Once, the construction is over, the O&M cost will be estimated for the full scope of the reduction strategy. The risk derived table F.4 to F.9, is used as the cost component. The derived risk for each risk reduction strategy has been used consistently for all the years. The discount rate has been assumed to be 5%.

Strategy 1: Selective Undergrounding

Table F.11 Cash Flow Analysis for Selective Undergrounding (Risk Level 50th Percentile)

Year	Risk	Cost (Capital)	O&M	Benefit
1	7783079	962000x1	13372x1	520781x1
2	7783079	962000x1	26744x1	1041563x1
3	7783079	962000x1	40115x1	1562344x1
4	7783079	962000x1	53487x1	2083126x1
5	7783079	962000x1	66859x1	2603907x1
6	7783079	0	66859x1	2603907x1
7	7783079	0	66859x1	2603907x1
8	7783079	0	66859x1	2603907x1
9	7783079	0	66859x1	2603907x1
10	7783079	0	66859x1	2603907x1
11	7783079	0	66859x1	2603907x1
12	7783079	0	66859x1	2603907x1
13	7783079	0	66859x1	2603907x1
14	7783079	0	66859x1	2603907x1
15	7783079	0	66859x1	2603907x1
16	7783079	0	66859x1	2603907x1
17	7783079	0	66859x1	2603907x1
18	7783079	0	66859x1	2603907x1
19	7783079	0	66859x1	2603907x1
20	7783079	0	66859x1	2603907x1
NPV	96994371	4164957x1	711782x1	27721226x1

$$BCR = \frac{NPV\ of\ Benefit}{NPV\ of\ Cost + NPV\ of\ Risk} = \frac{27721226x1}{4164957x1 + 711782x1 + 96994371} \geq 1$$

$$x1 \geq 4.3$$

Table F.12 Cash Flow Analysis for Selective Undergrounding (Risk Level 60th Percentile)

Year	Risk	Cost (Capital)	O&M	Benefit
1	9812932	962000x1	13372x1	520781x1
2	9812932	962000x1	26744x1	1041563x1
3	9812932	962000x1	40115x1	1562344x1
4	9812932	962000x1	53487x1	2083126x1
5	9812932	962000x1	66859x1	2603907x1
6	9812932	0	66859x1	2603907x1
7	9812932	0	66859x1	2603907x1
8	9812932	0	66859x1	2603907x1
9	9812932	0	66859x1	2603907x1
10	9812932	0	66859x1	2603907x1
11	9812932	0	66859x1	2603907x1
12	9812932	0	66859x1	2603907x1
13	9812932	0	66859x1	2603907x1
14	9812932	0	66859x1	2603907x1
15	9812932	0	66859x1	2603907x1
16	9812932	0	66859x1	2603907x1
17	9812932	0	66859x1	2603907x1
18	9812932	0	66859x1	2603907x1
19	9812932	0	66859x1	2603907x1
20	9812932	0	66859x1	2603907x1
NPV	122290823	4164957x1	711782x1	27721226x1

$$BCR = \frac{NPV\ of\ Benefit}{NPV\ of\ Cost + NPV\ of\ Risk} = \frac{27721226x1}{4164957x1 + 711782x1 + 122290823} \geq 1$$

$$x1 \geq 5.4$$

Table F.13 Cash Flow Analysis for Selective Undergrounding (Risk Level 70th Percentile)

Year	Risk	Cost (Capital)	O&M	Benefit
1	12039117	962000x1	13372x1	520781x1
2	12039117	962000x1	26744x1	1041563x1
3	12039117	962000x1	40115x1	1562344x1
4	12039117	962000x1	53487x1	2083126x1
5	12039117	962000x1	66859x1	2603907x1
6	12039117	0	66859x1	2603907x1
7	12039117	0	66859x1	2603907x1
8	12039117	0	66859x1	2603907x1
9	12039117	0	66859x1	2603907x1
10	12039117	0	66859x1	2603907x1
11	12039117	0	66859x1	2603907x1
12	12039117	0	66859x1	2603907x1
13	12039117	0	66859x1	2603907x1
14	12039117	0	66859x1	2603907x1
15	12039117	0	66859x1	2603907x1
16	12039117	0	66859x1	2603907x1
17	12039117	0	66859x1	2603907x1
18	12039117	0	66859x1	2603907x1
19	12039117	0	66859x1	2603907x1
20	12039117	0	66859x1	2603907x1
NPV	150034011	4164957x1	711782x1	27721226x1

$$BCR = \frac{NPV\ of\ Benefit}{NPV\ of\ Cost + NPV\ of\ Risk} = \frac{27721226x1}{4164957x1 + 711782x1 + 150034011} \geq 1$$

$$x1 \geq 6.6$$

Table F.14 Cash Flow Analysis for Selective Undergrounding (Risk Level 80th Percentile)

Year	Risk	Cost (Capital)	O&M	Benefit
1	14549056	962000x1	13372x1	520781x1
2	14549056	962000x1	26744x1	1041563x1
3	14549056	962000x1	40115x1	1562344x1
4	14549056	962000x1	53487x1	2083126x1
5	14549056	962000x1	66859x1	2603907x1
6	14549056	0	66859x1	2603907x1
7	14549056	0	66859x1	2603907x1
8	14549056	0	66859x1	2603907x1
9	14549056	0	66859x1	2603907x1
10	14549056	0	66859x1	2603907x1
11	14549056	0	66859x1	2603907x1
12	14549056	0	66859x1	2603907x1
13	14549056	0	66859x1	2603907x1
14	14549056	0	66859x1	2603907x1
15	14549056	0	66859x1	2603907x1
16	14549056	0	66859x1	2603907x1
17	14549056	0	66859x1	2603907x1
18	14549056	0	66859x1	2603907x1
19	14549056	0	66859x1	2603907x1
20	14549056	0	66859x1	2603907x1
NPV	181313401	4164957x1	711782x1	27721226x1

$$BCR = \frac{NPV\ of\ Benefit}{NPV\ of\ Cost + NPV\ of\ Risk} = \frac{27721226x1}{4164957x1 + 711782x1 + 181313401} \geq 1$$

$$x1 \geq 7.9$$

Table F.15 Cash Flow Analysis for Selective Undergrounding (Risk Level 90th Percentile)

Year	Risk	Cost (Capital)	O&M	Benefit
1	17600333	962000x1	13372x1	520781x1
2	17600333	962000x1	26744x1	1041563x1
3	17600333	962000x1	40115x1	1562344x1
4	17600333	962000x1	53487x1	2083126x1
5	17600333	962000x1	66859x1	2603907x1
6	17600333	0	66859x1	2603907x1
7	17600333	0	66859x1	2603907x1
8	17600333	0	66859x1	2603907x1
9	17600333	0	66859x1	2603907x1
10	17600333	0	66859x1	2603907x1
11	17600333	0	66859x1	2603907x1
12	17600333	0	66859x1	2603907x1
13	17600333	0	66859x1	2603907x1
14	17600333	0	66859x1	2603907x1
15	17600333	0	66859x1	2603907x1
16	17600333	0	66859x1	2603907x1
17	17600333	0	66859x1	2603907x1
18	17600333	0	66859x1	2603907x1
19	17600333	0	66859x1	2603907x1
20	17600333	0	66859x1	2603907x1
NPV	219339051	4164957x1	711782x1	27721226x1

$$BCR = \frac{NPV\ of\ Benefit}{NPV\ of\ Cost + NPV\ of\ Risk} = \frac{27721226x1}{4164957x1 + 711782x1 + 219339051} \geq 1$$

$$x1 \geq 9.6$$

Strategy 2: Rerouting of Overhead Distribution Lines

Table F.16 Cash Flow Analysis for Rerouting (Risk Level 50th Percentile)

Year	Risk	Cost (Capital)	O&M	Benefit
1	7783079	274857x2	13111x2	520781x2
2	7783079	274857x2	26221x2	1041563x2
3	7783079	274857x2	39332x2	1562344x2
4	7783079	274857x2	52443x2	2083126x2
5	7783079	274857x2	65553x2	2603907x2
6	7783079	0	65553x2	2603907x2
7	7783079	0	65553x2	2603907x2
8	7783079	0	65553x2	2603907x2
9	7783079	0	65553x2	2603907x2
10	7783079	0	65553x2	2603907x2
11	7783079	0	65553x2	2603907x2
12	7783079	0	65553x2	2603907x2
13	7783079	0	65553x2	2603907x2
14	7783079	0	65553x2	2603907x2
15	7783079	0	65553x2	2603907x2
16	7783079	0	65553x2	2603907x2
17	7783079	0	65553x2	2603907x2
18	7783079	0	65553x2	2603907x2
19	7783079	0	65553x2	2603907x2
20	7783079	0	65553x2	2603907x2
NPV	96994371	1189987x2	697882x2	27721226x2

$$BCR = \frac{NPV\ of\ Benefit}{NPV\ of\ Cost + NPV\ of\ Risk} = \frac{27721226x2}{1189981x1 + 697882x1 + 96994371} \geq 1$$

$$x2 \geq 3.8$$

Table F.17 Cash Flow Analysis for Rerouting (Risk Level 60th Percentile)

Year	Risk	Cost (Capital)	O&M	Benefit
1	9812932	274857x2	13111x2	520781x2
2	9812932	274857x2	26221x2	1041563x2
3	9812932	274857x2	39332x2	1562344x2
4	9812932	274857x2	52443x2	2083126x2
5	9812932	274857x2	65553x2	2603907x2
6	9812932	0	65553x2	2603907x2
7	9812932	0	65553x2	2603907x2
8	9812932	0	65553x2	2603907x2
9	9812932	0	65553x2	2603907x2
10	9812932	0	65553x2	2603907x2
11	9812932	0	65553x2	2603907x2
12	9812932	0	65553x2	2603907x2
13	9812932	0	65553x2	2603907x2
14	9812932	0	65553x2	2603907x2
15	9812932	0	65553x2	2603907x2
16	9812932	0	65553x2	2603907x2
17	9812932	0	65553x2	2603907x2
18	9812932	0	65553x2	2603907x2
19	9812932	0	65553x2	2603907x2
20	9812932	0	65553x2	2603907x2
NPV	122290823	1189987x2	697882x2	27721226x2

$$BCR = \frac{NPV\ of\ Benefit}{NPV\ of\ Cost + NPV\ of\ Risk} = \frac{27721226x2}{1189981x1 + 697882x1 + 122290823} \geq 1$$

$$x2 \geq 4.7$$

Table F.18 Cash Flow Analysis for Rerouting (Risk Level 70th Percentile)

Year	Risk	Cost (Capital)	O&M	Benefit
1	12039117	274857x2	13111x2	520781x2
2	12039117	274857x2	26221x2	1041563x2
3	12039117	274857x2	39332x2	1562344x2
4	12039117	274857x2	52443x2	2083126x2
5	12039117	274857x2	65553x2	2603907x2
6	12039117	0	65553x2	2603907x2
7	12039117	0	65553x2	2603907x2
8	12039117	0	65553x2	2603907x2
9	12039117	0	65553x2	2603907x2
10	12039117	0	65553x2	2603907x2
11	12039117	0	65553x2	2603907x2
12	12039117	0	65553x2	2603907x2
13	12039117	0	65553x2	2603907x2
14	12039117	0	65553x2	2603907x2
15	12039117	0	65553x2	2603907x2
16	12039117	0	65553x2	2603907x2
17	12039117	0	65553x2	2603907x2
18	12039117	0	65553x2	2603907x2
19	12039117	0	65553x2	2603907x2
20	12039117	0	65553x2	2603907x2
NPV	150034011	1189987x2	697882x2	27721226x2

$$BCR = \frac{NPV\ of\ Benefit}{NPV\ of\ Cost + NPV\ of\ Risk} = \frac{27721226x2}{1189981x1 + 697882x1 + 150034011} \geq 1$$

$$x2 \geq 5.8$$

Table F.19 Cash Flow Analysis for Rerouting (Risk Level 80th Percentile)

Year	Risk	Cost (Capital)	O&M	Benefit
1	14549056	274857x2	13111x2	520781x2
2	14549056	274857x2	26221x2	1041563x2
3	14549056	274857x2	39332x2	1562344x2
4	14549056	274857x2	52443x2	2083126x2
5	14549056	274857x2	65553x2	2603907x2
6	14549056	0	65553x2	2603907x2
7	14549056	0	65553x2	2603907x2
8	14549056	0	65553x2	2603907x2
9	14549056	0	65553x2	2603907x2
10	14549056	0	65553x2	2603907x2
11	14549056	0	65553x2	2603907x2
12	14549056	0	65553x2	2603907x2
13	14549056	0	65553x2	2603907x2
14	14549056	0	65553x2	2603907x2
15	14549056	0	65553x2	2603907x2
16	14549056	0	65553x2	2603907x2
17	14549056	0	65553x2	2603907x2
18	14549056	0	65553x2	2603907x2
19	14549056	0	65553x2	2603907x2
20	14549056	0	65553x2	2603907x2
NPV	181313401	1189987x2	697882x2	27721226x2

$$BCR = \frac{NPV\ of\ Benefit}{NPV\ of\ Cost + NPV\ of\ Risk} = \frac{27721226x2}{1189981x1 + 697882x1 + 181313401} \geq 1$$

$$x2 \geq 7.0$$

Table F.20 Cash Flow Analysis for Rerouting (Risk Level 90th Percentile)

Year	Risk	Cost (Capital)	O&M	Benefit
1	17600333	274857x2	13111x2	520781x2
2	17600333	274857x2	26221x2	1041563x2
3	17600333	274857x2	39332x2	1562344x2
4	17600333	274857x2	52443x2	2083126x2
5	17600333	274857x2	65553x2	2603907x2
6	17600333	0	65553x2	2603907x2
7	17600333	0	65553x2	2603907x2
8	17600333	0	65553x2	2603907x2
9	17600333	0	65553x2	2603907x2
10	17600333	0	65553x2	2603907x2
11	17600333	0	65553x2	2603907x2
12	17600333	0	65553x2	2603907x2
13	17600333	0	65553x2	2603907x2
14	17600333	0	65553x2	2603907x2
15	17600333	0	65553x2	2603907x2
16	17600333	0	65553x2	2603907x2
17	17600333	0	65553x2	2603907x2
18	17600333	0	65553x2	2603907x2
19	17600333	0	65553x2	2603907x2
20	17600333	0	65553x2	2603907x2
NPV	219339051	1189987x2	697882x2	27721226x2

$$BCR = \frac{NPV\ of\ Benefit}{NPV\ of\ Cost + NPV\ of\ Risk} = \frac{27721226x2}{1189981x1 + 697882x1 + 219339051} \geq 1$$

$$x2 \geq 8.5$$

Strategy 3: Elevating Substations

Table F.21 Cash Flow Analysis for Substation Elevation (Risk Level 50_{th} Percentile)

Year	Risk	Cost (Capital)	O&M	Benefit
1	3766006	2865000x3	39824x3	1889933x3
2	3766006	2865000x3	79647x3	3779865x3
3	3766006	2865000x3	119471x3	5669798x3
4	3766006	2865000x3	159294x3	7559730x3
5	3766006	2865000x3	199118x3	9449663x3
6	3766006	0	199118x3	9449663x3
7	3766006	0	199118x3	9449663x3
8	3766006	0	199118x3	9449663x3
9	3766006	0	199118x3	9449663x3
10	3766006	0	199118x3	9449663x3
11	3766006	0	199118x3	9449663x3
12	3766006	0	199118x3	9449663x3
13	3766006	0	199118x3	9449663x3
14	3766006	0	199118x3	9449663x3
15	3766006	0	199118x3	9449663x3
16	3766006	0	199118x3	9449663x3
17	3766006	0	199118x3	9449663x3
18	3766006	0	199118x3	9449663x3
19	3766006	0	199118x3	9449663x3
20	3766006	0	199118x3	9449663x3
NPV	46932760	12403951x3	2119807x3	100601224x3

$$BCR = \frac{NPV\ of\ Benefit}{NPV\ of\ Cost + NPV\ of\ Risk} = \frac{100601224x3}{12403951x3 + 2119807x3 + 46932760} \geq 1$$

$$x3 \geq 0.5$$

Table F.22 Cash Flow Analysis for Substation Elevation (Risk Level 60th Percentile)

Year	Risk	Cost (Capital)	O&M	Benefit
1	4748193	2865000x3	39824x3	1889933x3
2	4748193	2865000x3	79647x3	3779865x3
3	4748193	2865000x3	119471x3	5669798x3
4	4748193	2865000x3	159294x3	7559730x3
5	4748193	2865000x3	199118x3	9449663x3
6	4748193	0	199118x3	9449663x3
7	4748193	0	199118x3	9449663x3
8	4748193	0	199118x3	9449663x3
9	4748193	0	199118x3	9449663x3
10	4748193	0	199118x3	9449663x3
11	4748193	0	199118x3	9449663x3
12	4748193	0	199118x3	9449663x3
13	4748193	0	199118x3	9449663x3
14	4748193	0	199118x3	9449663x3
15	4748193	0	199118x3	9449663x3
16	4748193	0	199118x3	9449663x3
17	4748193	0	199118x3	9449663x3
18	4748193	0	199118x3	9449663x3
19	4748193	0	199118x3	9449663x3
20	4748193	0	199118x3	9449663x3
NPV	59172979	12403951x3	2119807x3	100601224x3

$$BCR = \frac{NPV\ of\ Benefit}{NPV\ of\ Cost + NPV\ of\ Risk} = \frac{100601224x3}{12403951x3 + 2119807x3 + 59172979} \geq 1$$

$$x3 \geq 0.7$$

Table F.23 Cash Flow Analysis for Substation Elevation (Risk Level 70th Percentile)

Year	Risk	Cost (Capital)	O&M	Benefit
1	5825379	2865000x3	39824x3	1889933x3
2	5825379	2865000x3	79647x3	3779865x3
3	5825379	2865000x3	119471x3	5669798x3
4	5825379	2865000x3	159294x3	7559730x3
5	5825379	2865000x3	199118x3	9449663x3
6	5825379	0	199118x3	9449663x3
7	5825379	0	199118x3	9449663x3
8	5825379	0	199118x3	9449663x3
9	5825379	0	199118x3	9449663x3
10	5825379	0	199118x3	9449663x3
11	5825379	0	199118x3	9449663x3
12	5825379	0	199118x3	9449663x3
13	5825379	0	199118x3	9449663x3
14	5825379	0	199118x3	9449663x3
15	5825379	0	199118x3	9449663x3
16	5825379	0	199118x3	9449663x3
17	5825379	0	199118x3	9449663x3
18	5825379	0	199118x3	9449663x3
19	5825379	0	199118x3	9449663x3
20	5825379	0	199118x3	9449663x3
NPV	72597102	12403951x3	2119807x3	100601224x3

$$BCR = \frac{NPV\ of\ Benefit}{NPV\ of\ Cost + NPV\ of\ Risk} = \frac{100601224x3}{12403951x3 + 2119807x3 + 72597102} \geq 1$$

$$x3 \geq 0.8$$

Table F.24 Cash Flow Analysis for Substation Elevation (Risk Level 80th Percentile)

Year	Risk	Cost (Capital)	O&M	Benefit
1	7039866	2865000x3	39824x3	1889933x3
2	7039866	2865000x3	79647x3	3779865x3
3	7039866	2865000x3	119471x3	5669798x3
4	7039866	2865000x3	159294x3	7559730x3
5	7039866	2865000x3	199118x3	9449663x3
6	7039866	0	199118x3	9449663x3
7	7039866	0	199118x3	9449663x3
8	7039866	0	199118x3	9449663x3
9	7039866	0	199118x3	9449663x3
10	7039866	0	199118x3	9449663x3
11	7039866	0	199118x3	9449663x3
12	7039866	0	199118x3	9449663x3
13	7039866	0	199118x3	9449663x3
14	7039866	0	199118x3	9449663x3
15	7039866	0	199118x3	9449663x3
16	7039866	0	199118x3	9449663x3
17	7039866	0	199118x3	9449663x3
18	7039866	0	199118x3	9449663x3
19	7039866	0	199118x3	9449663x3
20	7039866	0	199118x3	9449663x3
NPV	87732291	12403951x3	2119807x3	100601224x3

$$BCR = \frac{NPV\ of\ Benefit}{NPV\ of\ Cost + NPV\ of\ Risk} = \frac{100601224x3}{12403951x3 + 2119807x3 + 87732291} \geq 1$$

$$x3 \geq 1.0$$

Table F.25 Cash Flow Analysis for Substation Elevation (Risk Level 90th Percentile)

Year	Risk	Cost (Capital)	O&M	Benefit
1	8516290	2865000x3	39824x3	1889933x3
2	8516290	2865000x3	79647x3	3779865x3
3	8516290	2865000x3	119471x3	5669798x3
4	8516290	2865000x3	159294x3	7559730x3
5	8516290	2865000x3	199118x3	9449663x3
6	8516290	0	199118x3	9449663x3
7	8516290	0	199118x3	9449663x3
8	8516290	0	199118x3	9449663x3
9	8516290	0	199118x3	9449663x3
10	8516290	0	199118x3	9449663x3
11	8516290	0	199118x3	9449663x3
12	8516290	0	199118x3	9449663x3
13	8516290	0	199118x3	9449663x3
14	8516290	0	199118x3	9449663x3
15	8516290	0	199118x3	9449663x3
16	8516290	0	199118x3	9449663x3
17	8516290	0	199118x3	9449663x3
18	8516290	0	199118x3	9449663x3
19	8516290	0	199118x3	9449663x3
20	8516290	0	199118x3	9449663x3
NPV	106131799	12403951x3	2119807x3	100601224x3

$$BCR = \frac{NPV\ of\ Benefit}{NPV\ of\ Cost + NPV\ of\ Risk} = \frac{100601224x3}{12403951x3 + 2119807x3 + 106131799} \geq 1$$

$$x3 \geq 1.2$$

Strategy 4: Strengthening of Poles

Table F.26 Cash Flow Analysis for Pole Strengthening (Risk Level 50th Percentile)

Year	Risk	Cost (Capital)	O&M	Benefit
1	1255335	2500x4	119x4	1050x4
2	1255335	2500x4	239x4	2100x4
3	1255335	2500x4	358x4	3150x4
4	1255335	2500x4	477x4	4200x4
5	1255335	2500x4	596x4	5250x4
6	1255335	0	596x4	5250x4
7	1255335	0	596x4	5250x4
8	1255335	0	596x4	5250x4
9	1255335	0	596x4	5250x4
10	1255335	0	596x4	5250x4
11	1255335	0	596x4	5250x4
12	1255335	0	596x4	5250x4
13	1255335	0	596x4	5250x4
14	1255335	0	596x4	5250x4
15	1255335	0	596x4	5250x4
16	1255335	0	596x4	5250x4
17	1255335	0	596x4	5250x4
18	1255335	0	596x4	5250x4
19	1255335	0	596x4	5250x4
20	1255335	0	596x4	5250x4
NPV	15644253	10824x4	6348x4	55890x4

$$BCR = \frac{NPV\ of\ Benefit}{NPV\ of\ Cost + NPV\ of\ Risk} = \frac{55890x4}{10824x4 + 6348x4 + 15644253} \geq 1$$

$$x4 \geq 404.1$$

Table F.27 Cash Flow Analysis for Pole Strengthening (Risk Level 60th Percentile)

Year	Risk	Cost (Capital)	O&M	Benefit
1	1582731	2500x4	119x4	1050x4
2	1582731	2500x4	239x4	2100x4
3	1582731	2500x4	358x4	3150x4
4	1582731	2500x4	477x4	4200x4
5	1582731	2500x4	596x4	5250x4
6	1582731	0	596x4	5250x4
7	1582731	0	596x4	5250x4
8	1582731	0	596x4	5250x4
9	1582731	0	596x4	5250x4
10	1582731	0	596x4	5250x4
11	1582731	0	596x4	5250x4
12	1582731	0	596x4	5250x4
13	1582731	0	596x4	5250x4
14	1582731	0	596x4	5250x4
15	1582731	0	596x4	5250x4
16	1582731	0	596x4	5250x4
17	1582731	0	596x4	5250x4
18	1582731	0	596x4	5250x4
19	1582731	0	596x4	5250x4
20	1582731	0	596x4	5250x4
NPV	19724326	10824x4	6348x4	55890x4

$$BCR = \frac{NPV\ of\ Benefit}{NPV\ of\ Cost + NPV\ of\ Risk} = \frac{55890x4}{10824x4 + 6348x4 + 19724326} \geq 1$$

$$x4 \geq 509.4$$

Table F.28 Cash Flow Analysis for Pole Strengthening (Risk Level 70th Percentile)

Year	Risk	Cost (Capital)	O&M	Benefit
1	1941793	2500x4	119x4	1050x4
2	1941793	2500x4	239x4	2100x4
3	1941793	2500x4	358x4	3150x4
4	1941793	2500x4	477x4	4200x4
5	1941793	2500x4	596x4	5250x4
6	1941793	0	596x4	5250x4
7	1941793	0	596x4	5250x4
8	1941793	0	596x4	5250x4
9	1941793	0	596x4	5250x4
10	1941793	0	596x4	5250x4
11	1941793	0	596x4	5250x4
12	1941793	0	596x4	5250x4
13	1941793	0	596x4	5250x4
14	1941793	0	596x4	5250x4
15	1941793	0	596x4	5250x4
16	1941793	0	596x4	5250x4
17	1941793	0	596x4	5250x4
18	1941793	0	596x4	5250x4
19	1941793	0	596x4	5250x4
20	1941793	0	596x4	5250x4
NPV	24199034	10824x4	6348x4	55890x4

$$BCR = \frac{NPV\ of\ Benefit}{NPV\ of\ Cost + NPV\ of\ Risk} = \frac{55890x4}{10824x4 + 6348x4 + 24199034} \geq 1$$

$$x4 \geq 625.0$$

Table F.29 Cash Flow Analysis for Pole Strengthening (Risk Level 80th Percentile)

Year	Risk	Cost (Capital)	O&M	Benefit
1	2346622	2500x4	119x4	1050x4
2	2346622	2500x4	239x4	2100x4
3	2346622	2500x4	358x4	3150x4
4	2346622	2500x4	477x4	4200x4
5	2346622	2500x4	596x4	5250x4
6	2346622	0	596x4	5250x4
7	2346622	0	596x4	5250x4
8	2346622	0	596x4	5250x4
9	2346622	0	596x4	5250x4
10	2346622	0	596x4	5250x4
11	2346622	0	596x4	5250x4
12	2346622	0	596x4	5250x4
13	2346622	0	596x4	5250x4
14	2346622	0	596x4	5250x4
15	2346622	0	596x4	5250x4
16	2346622	0	596x4	5250x4
17	2346622	0	596x4	5250x4
18	2346622	0	596x4	5250x4
19	2346622	0	596x4	5250x4
20	2346622	0	596x4	5250x4
NPV	29244097	10824x4	6348x4	55890x4

$$BCR = \frac{NPV\ of\ Benefit}{NPV\ of\ Cost + NPV\ of\ Risk} = \frac{55890x4}{10824x4 + 6348x4 + 29244097} \geq 1$$

$$x4 \geq 755.3$$

Table F.30 Cash Flow Analysis for Pole Strengthening (Risk Level 90th Percentile)

Year	Risk	Cost (Capital)	O&M	Benefit
1	2838763	2500x4	119x4	1050x4
2	2838763	2500x4	239x4	2100x4
3	2838763	2500x4	358x4	3150x4
4	2838763	2500x4	477x4	4200x4
5	2838763	2500x4	596x4	5250x4
6	2838763	0	596x4	5250x4
7	2838763	0	596x4	5250x4
8	2838763	0	596x4	5250x4
9	2838763	0	596x4	5250x4
10	2838763	0	596x4	5250x4
11	2838763	0	596x4	5250x4
12	2838763	0	596x4	5250x4
13	2838763	0	596x4	5250x4
14	2838763	0	596x4	5250x4
15	2838763	0	596x4	5250x4
16	2838763	0	596x4	5250x4
17	2838763	0	596x4	5250x4
18	2838763	0	596x4	5250x4
19	2838763	0	596x4	5250x4
20	2838763	0	596x4	5250x4
NPV	35377266	10824x4	6348x4	55890x4

$$BCR = \frac{NPV\ of\ Benefit}{NPV\ of\ Cost + NPV\ of\ Risk} = \frac{55890x4}{10824x4 + 6348x4 + 35377266} \geq 1$$

$$x4 \geq 913.7$$

The minimum budget required for each risk level can be derived as the sum product of the minimum scope of work of each strategy and the unit cost as shown in table F.3.

Table F.31 Minimum Scope of Work and Budget for Each Risk Level

Risk Level	Strategy 1	Strategy 2	Strategy 3	Strategy 4	Min Budget
50%	4.3	3.8	0.5	404.1	38,382,194
60%	5.4	4.7	0.7	509.4	48,443,018
70%	6.6	5.8	0.8	625.0	59,456,218
80%	7.9	7.0	1.0	755.3	71,855,317
90%	9.6	8.5	1.2	913.7	86,884,805

For optimization, the objective function is calculated as the sum of the NPV of benefits from the 4 strategies. For example, at 50th percentile level

- the NPV of benefit from strategy 1 is 27721226x1 (Table F.11)
- the NPV of benefit from strategy 2 is 27721226x2 (Table F.16)
- the NPV of benefit from strategy 3 is 100601224x3 (Table F.21)
- the NPV of benefit from strategy 4 is 55890x4 (Table F.26)

Therefore, the objective function is

$$\text{Max } (27721226x1 + 27721226x2 + 100601224x3 + 55890x4)$$