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Quantifying restoration costs in the aftermath of an extreme event using system dynamics and dynamic mathematical modeling approaches

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QUANTIFYING RESTORATION COSTS IN THE AFTERMATH OF AN EXTREME EVENT USING SYSTEM DYNAMICS AND DYNAMIC MATHEMATICAL MODELING APPROACHES

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Paper III: Pages 67-94 is a research paper that is intended for submission to Engineering Management Journal.

ABSTRACT

Extreme events such as earthquakes, hurricanes, and the like, lead to devastating effects that may render multiple supply chain critical infrastructure elements inoperable. The economic losses caused by extreme events continue well after the emergency response phase has ended and are a key factor in determining the best path for post-disaster restoration. It is essential to develop efficient restoration and disaster management strategies to ameliorate the losses from such events. This dissertation extends the existing knowledge base on disaster management and restoration through the creation of models and tools that identify the relationship between production losses and restoration costs. The first research contribution is a system dynamics inoperability model that determines inputs, outputs, and flows for roadway networks. This model can be used to identify the connectivity of road segments and better understand how inoperability contributes to economic consequences. The second contribution is an algorithm that integrates critical infrastructure data derived from bottom-up cost estimation technique as part of an object-oriented software tool that can be used to determine the impact of system disruptions. The third contribution is a dynamic mathematical model that establishes a framework to estimate post-disaster restoration costs from a whole system perspective. Engineering managers, city planners, and policy makers can use the methodologies developed in this research to develop effective disaster planning schemas and to prioritize post-disaster restoration operations.

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TABLE OF CONTENTS

Page

LIST OF ILLUSTRATIONS

PAPER III

LIST OF TABLES

NOMENCLATURE

Symbol	Description
GIS	Geographic Information System
SCICI	Supply Chain Interdependent Critical Infrastructure
SCIRC	Supply Chain Infrastructure Restoration Calculator
XML	Extensible Markup Language

1. INTRODUCTION

1.1. BACKGROUND

Extreme events such as earthquakes, hurricanes, or the like, can lead to infrastructure and supply chain failure that may result in considerable economic losses. These economic losses can continue well after the emergency response is terminated. Economic losses can be categorized as direct and indirect losses. Direct losses refer to the costs of rebuilding or restoring the damaged infrastructures. The indirect losses are caused due to business disruption/interruption, temporary unemployment, and the likes (Tirasirichai and Enke 2007). To minimize the indirect economic losses, it is essential to restore all the affected infrastructure elements to make them fully operable. Due to the innate interdependencies between different infrastructure elements, a disturbance in one infrastructure element can produce a ripple effect of failure through other infrastructure elements. According to the Department of Homeland Security (DHS) (DHS, 2018), the incapacitation or destruction of the nation’s critical infrastructures will have a debilitating effect on the national security, national economy, and national public health or safety, or any of these combinations. There is an urgency in developing methodologies that would help to restore critical infrastructure elements rapidly and efficiently. To devise efficient disaster management and restoration strategies, it is critical to understand different factors that render an infrastructure inoperable. There is also a need to incorporate resource requirement data for construction of different critical infrastructures that span across different sectors. Due to the diverse set of functionalities of different critical infrastructures, the analysis of these infrastructures and their resource estimation spreads over multiple disciplines.

This research proposes a framework for quantifying restoration costs in the aftermath of an extreme event. A methodology was developed to model the emergent behavior due to a disruption in the transportation infrastructure and quantify the economic losses associated with such a disruption. Next, a resource requirement data for construction of a wide variety of supply chain interdependent critical infrastructures was derived. Finally, with the use of this data, resources required for restoring multiple infrastructure elements was estimated. The framework thus developed will be helpful in understanding the economic impact of a disaster in the aftermath of an extreme event.

The next section discusses the research that has been done in the literature pertaining to disaster restoration and management.

1.2. LITERATURE REVIEW

Government organizations such as Federal Emergency Management Agency (FEMA), Department of Homeland Security (DHS), and the likes, as well as other organizations, universities and researchers have focused their research on devising strategies to minimize the socioeconomic impact of a disaster. The vast majority of research conducted in the field of disaster restoration and management deals with the economic effects of disaster (Cho et al. 2001; Ham, Kim, and Boyce 2005; Tirasirichai and Enke 2007; Ojha et al. 2018), disaster resilience (Arab et al., 2015; Ramachandran et al., 2015; Zhang et al., 2018), resource allocation strategies (Mackenzie and Zobel 2016; Yang et al 2012), vital supplies distribution strategies (Tzeng et al. 2007; Widener and Horner

2011; Horner and Downs 2010; Hentenryck et al. 2010), evacuation strategies (El-Sergany et al., 2012; Hu et al., 2014; Lambert et al., 2013; Na et al., 2015; Song and Yan, 2016), and devising restoration strategies after an extreme event (Lin et al., 2017; Liu et al., 2014; Ramachandran et al., 2015; Ramachandran et al., 2016). The existing literature deals with single infrastructure elements. Although some studies take into account the interdependencies between different infrastructure elements, the effect of an extreme event is studied from a single infrastructure stand-point.

A lot of work has been done to study the effect of an earthquake on the transportation network and its impact on the overall economy (Cho et al. 2001; Ham, Kim, and Boyce 2005). Tirasirichai and Enke (2007) have used computable general equilibrium model to estimate the indirect costs associated with disruption in the transportation network and study the ripple effects on the economy. Mackenzie and Zobel (2016) have used nonlinear programming to develop a framework for allocating resources to increase the resilience of an electric power network after a disaster. Yang et al (2012) used a multi-objective optimization model for allocating emergency resources after a multi-hazard disaster. They developed a multi-stage resource allocation model to cater to the changing spatial and temporal demand of the rescue supplies. These studies deal with the disaster impact and/restoration from the viewpoint of a single infrastructure element.

Several notable studies have been conducted to develop relief goods distribution strategies. The three main objectives in the literature for supplying disaster relief goods models are, (i) to minimize the travel cost, inventory cost and/or facility location costs, (ii) to minimize the unsatisfied demand at the beneficiaries, and (iii) to minimize the time arrival of goods to the affected people. The components for studying the relief goods distribution system include demand, supply, and transportation (Tzeng et al., 2007). The literature for supplying disaster relief goods includes models dealing with the uncertainty in demand and supply, and relief routing models. Uncertainty is attributed to supply delays and losses (Del La Torre et al., 2012). Widener and Horner (2010) have used a hierarchical capacitated median model and integrated it with a geographical information system to determine the location of relief goods distribution facilities after a disaster. Horner and Downs (2010) developed a model to understand the impact of different design policies on the accessibility of the relief facilities to the beneficiaries. They concluded that the cost structure of the model substantially impacts the arrival time of the vital supplies to the people. Tzeng et al. (2007) used a multi-objective model to develop a relief distribution system to minimize cost, travel time and unsatisfied demand at the beneficiaries. Zhu et al. (2008) developed a two-stage model to minimize the costs associated with the distribution of relief goods distribution. They pre-positioned the vital supplies in the warehouse in the pre-disaster stage and distributed the vital supplies post-disaster stage. One of the problems with their research was that they assumed the demand for the goods to be fixed. Van Hentenryck et al. (2010) developed a single commodity multi-stage hybrid-optimization algorithm to minimize the travel cost and inventory costs while also minimizing the unsatisfied demand at the beneficiaries. Although plenty of work in the literature deals with minimizing costs and time for rerouting, they fail to consider that the beneficiaries might need the supplies even after the commencement of the recovery stage.

While carrying out disaster relief operations, government organizations work along with private entities. Coordination among these private and public entities can be challenging due to ambiguity in their goals and responsibilities. Fikar, Gronalt, and Hirsch

(2016) developed a decision-support system model to simplify the coordination between private and relief organizations to distribute disaster relief goods and minimize the time of arrival of goods at the beneficiaries. For their research, they made use of trucks, off-road and unmanned aerial vehicles to analyze which vehicles would be best suited for last-mile distribution of goods. One of the limitations of their research is that they do not plan for the ambiguity in the availability of vehicles which is necessary for multi-period routing of the relief goods.

Disaster restoration strategies, resource allocation strategies and relief goods strategies rely on multiple critical infrastructure elements. Depending on the severity of the disaster multiple infrastructure elements can be rendered partially or completely inoperable. The amount of resources required for restoration increase tremendously when multiple infrastructures are damaged due to the innate interdependencies between the critical infrastructure elements. The literature fails to consider the impact of failure of multiple critical infrastructures after a disaster.

1.3. RESEARCH OBJECTIVES AND CONTRIBUTIONS

The goal of this research is to develop an analytical tool to understand different factors that render an infrastructure element inoperable and develop a methodology to quantify the cost of restoring damaged infrastructures in the aftermath of an extreme event. disaster restoration. The three contributions from the research are as follows:

Publication 1: A system dynamics approach is used to develop a model to analyze different factors that render a road segment inoperable. The model helps to understand how the traffic pattern changes due to a disruption in the transportation network. This model can be used to identify the connectivity of road segments and better understand how inoperability contributes to economic consequences.

Publication 2: The algorithm developed in this paper integrates critical infrastructure data as part of an object-oriented software tool that can be used to determine the impact of system disruptions. This tool helps to fill the gaps between the search and recover strategies of the agencies carrying out disaster restoration activities such as the Federal Emergency Management Agency (FEMA), and the likes, and constructional techniques under full recovery.

Publication 3: The research objective was to estimate the amount of resources required to restore damaged critical infrastructures. A bottom-up cost estimation technique was used to understand the different construction processes and resources involved in constructing a variety of infrastructures. The types of resources considered for this model included the resources to support the restoration crew, and restore damaged infrastructures.

The methodologies developed in this dissertation can be used by engineering managers, city planners, and policy makers to develop effective disaster planning schemas and to prioritize post-disaster restoration operations.

PAPER

I. MODELING AND SIMULATION OF EMERGENT BEHAVIOR IN TRANSPORTATION INFRASTRUCTURE RESTORATION

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ABSTRACT

Extreme events such as earthquakes, hurricanes, and the likes, result in mass destruction leading to partial or total disruption of various infrastructure and supply chain systems. This causes substantial economic loss. The damaging effects of an extreme event last well after the termination of the emergency response system, and therefore, the development of efficient restoration and disaster management strategies warrant a thorough cost analysis of the critical infrastructure disrupted, and their interdependencies. The economic analyses must account for both direct and indirect losses associated with infrastructure system failure, and thus, the need to model the supply chain interdependent critical infrastructure. The objective of this study is to understand how an extreme event affects the road transportation network. In this study, a system dynamics approach is used to model the transportation road infrastructure system to evaluate the different factors that render road segments inoperable and calculate economic consequences of such inoperability.

1. INTRODUCTION

Economic losses from infrastructure and supply chain failure that result from extreme events such as earthquakes, hurricanes, or the like, are considerable. These losses continue to amass well after emergency response has terminated. To ameliorate the losses from large-scale disasters, it is important to understand the critical infrastructures damaged and to analyze the various interdependencies among them in order to design efficient restoration strategies.

Defining and modeling supply chain interdependent critical infrastructure (SCICI) is a complex problem (Ramachandran et al. 2015; Ramachandran et al. 2016) as disruption of one infrastructure network can produce a ripple effect of failure through other infrastructure networks. This potentially will result in large economic losses. Therefore, understanding the interdependencies between various infrastructure systems is critical to a cost analysis for an infrastructure network failure in the aftermath of a disaster. There are two types of economic losses that result from infrastructure disruption: direct losses and indirect losses. Direct losses include the costs of rebuilding or repairing damaged property, whereas indirect losses include losses due to changes in demand and supply behavior. For instance, if a bridge is damaged by an earthquake, direct loss would include the cost of rebuilding the bridge, whereas indirect cost would include the costs associated with the extra distance and delays that vehicles must endure over a period of time until the damaged bridge is restored. Such indirect losses result, in part, to emergent behavior within the system. The highly interdependent nature of infrastructure elements makes a System Dynamics approach ideal for studying these complex infrastructure networks. A system dynamics approach has the capability to effectively incorporate a large number of variables in its algorithm and model the complex nature of interactions between these variables efficiently. A system dynamics approach uses decision trees and cause and effect relationships among different variables to understand the behavior of a variable due to changes in other variables. This extends to the detection of emerging dependencies. An emergent property of a system is a property that is possessed by the system as a whole but is not possessed by any components of the system individually (Maier 2014). Analyzing traffic patterns due to a major disruption in the transportation infrastructure is a complex problem. For example, if a road segment becomes damaged to the point where at least a part of the traffic flow must be diverted to different routes, this diversion will lead to an increase in the travel costs per vehicle that can depend upon flow rate, volume, topography, route mileage and so on. As the traffic is redirected to alternate routes, the road capacities of these alternates are utilized, which leads to reduced speeds, increases in travel time, and traffic flow congestion. The increased travel costs, travel time, reduced speed for the traffic flow and congestion constitute emergent behavior within the transportation system due to a disruption in one or more road segments.

In this study, a system dynamics model is applied to the transportation network for estimation of traffic disruption costs in the aftermath of a disaster. The causal loop diagram used in system dynamics closely models system behavior. The system dynamics approach is used to model the interdependencies between system variables. In a dynamic system, the value of the variable changes with time and a system dynamics approach makes it possible to update these values accordingly and hence capture these interdependencies. Mittal and Rainey (2015) state that any complex system that exists in the space and time domain demonstrates emergent behavior. The transportation infrastructure system is a complex system that has a spatiotemporal character. A system dynamics approach can be used to study the spatial as well as the temporal nature of the system making system dynamics methodology a good fit to understand the emergent behavior of the system. By means of a causal loop diagram, a visual framework depicting the interdependent nature of the infrastructures involved in the network is presented. Estimations of these costs may serve as an important tool in decision making processes of policy makers for disaster restoration and recovery plans. The degree to which these ripple effects are being realized and the economic losses in which they result are calculated. These ripple effects are ascribed to the emergent behavior of the system as described above. Rerouting vehicles to alternate paths cause decreases in available road capacity which slows down the overall traffic, which in turn leads to increases in travel times and congestion. Such emergent behavior can be understood by analyzing the overall speed of traffic flow post-disruption and comparing it with the overall traffic speed before a disruption in the transportation network. The drivers, when given information about the cost and travel time for each alternate route, can make informed decisions to avoid congestion. This study discusses different scenarios where the cost and time for different alternate routes are calculated. Results from this research will help in understanding the costs of infrastructure failure from how traffic patterns are altered due to a disruption in the transportation network.

The following section gives insight into system dynamics methodology and its applications. In section 3, the model methodology is explained, first with a discussion of how different factors affect available road capacity in general and second, how a system dynamics approach can be used to construct a road transportation disruption model which calculates available road capacity in the aftermath of infrastructure failure. Then, an illustrative example is used to demonstrate the model. The last section presents conclusions, limitations of this model and future work.

2. SYSTEM DYNAMICS APPROACH

System dynamics is a methodological approach to study the dynamics of complex systems involving a large number of variables (Coyle 1996). System dynamics methodology has a qualitative part that visually represents cause and effect relationships between different variables and a quantitative part that parameterizes these relationships. In this methodology, feedback loops describe the parameter interactions within the model. Feedback loops are either positive or negative. Positive loops, also known as reinforcing loops, are ones in which a change (positive or negative) in one variable induces a similar change (positive or negative) in another variable, whereas negative or balancing loops are ones in which a change (positive or negative) in one variable induces an opposite change (negative or positive) in another variable.

System dynamics modeling invokes a four-stage developmental process. The first stage requires a qualitative analysis of the different variables involved in the problem and identifying the cause and effect relationships between these variables. The second stage involves building a causal loop diagram (CLD) that describes the variables under consideration. These variables are connected and typically arrow diagrams are used to describe the cause and effect relationships amongst each other. Each arrowhead will have either a positive or a negative sign. A positive sign on the arrowhead means that an increase in the value of the variable at the tail of the arrow will lead to an increase in the value of the variable at the arrowhead and a decrease in the value of the variable at the tail of the arrow will lead to a decrease in the value of the variable at the arrowhead. A negative sign on the arrowhead means that if the value of the variable at the tail of the arrow decreases then the value of the variable at the arrowhead increases and if the value of the variable at the tail of the arrow increases then the value of the variable at the arrowhead decreases. For instance, in Figure 1, the positive sign on the arrow connecting extra distance to be travelled per vehicle and travel costs per vehicle means that an increase in the distance to be travelled per vehicle leads to an increase in travel costs per vehicle and vice-versa. The third stage in a system dynamics approach involves constructing a model, before finally testing this model in the fourth stage.

Figure 1. Cause and effect relationship

System dynamics finds wide application in economic, business, ecological and population systems due to its ability to model simple linear as well as complex non-linear systems (Sha and Huang 2010; An and Jeng 2005; Sterman 1992). It is also a useful tool to study complex systems involving a large number of variables as well as non-linear feedback loops otherwise considered unmanageable by the conventionally used algorithms such as the critical path method (CPM) and the program evaluation and review technique (PERT) (Sterman 1992). The non-linearity in the complex systems can be attributed to the emergent behavior of the system. The feedback loops in the system dynamics methodology models the dynamic patterns in a complex system and maps out these patterns in terms of their structural relationships. In complex systems, as new information becomes available the behavior of the system might change. A causal loop diagram depicts the cause and effect relationships between different variables to show the complex interactions amongst these variables. The presence of decision trees and cause and effect relationships in system dynamics models make them a popular choice in analyzing social and economic systems (Lyneis, Kenneth, and Sharon 2001). There is a tendency for the users to include more variables than required because of the ease of how cause and effect relationships are mapped in a causal loop diagram. To avoid incorporating excess variables in system dynamics modeling, Li et al. (2009) advocated dividing every model into four subsystems- project, profit, resource and knowledge and allocate variables to these categories, eliminating all variables that do not belong to these subsystems. Alasad et al. (2013) advised using expert knowledge and perceptions of stakeholders to create realistic system dynamics models.

The ability of a system dynamics approach to incorporate different aspects of a problem (economic, infrastructure, etc.) makes it a good fit for this study. System dynamics models have been applied to study many different systems and subsystems. Qing and Mingchao (2011), for example, applied the system dynamics approach to study the economy-environment-resource system in Jiangxi, China to analyze the sustainability of the current development mode and the substitution rate of technology for natural resources.

Liu et al. (2011) integrated the transportation systems to improve capital-use efficiency and economic development, and Zheng et al. (2009) integrated metrics such as infrastructure, foreign trade, regional logistics cost, and growth rate of foreign trade, to conclude that investment in aviation logistics is a good way to promote trade and economic development. System dynamics approaches have also been applied to complex construction projects that contain multiple independent systems and highly non-linear feedback loops (Lyneis, Kenneth, and Sharon 2001) , and to port operation systems to improve service time and cost of service (Gui, Zhu, and Lu 2005). Researchers have also combined policy decisions with practical operations to understand and analyze an area's logistics system (Li, Zhang, and Li 2009), and to identify key factors for promoting regional logistics hubs formation (Zhao et al. 2011). System dynamics models have been integrated with business process simulation model to evaluate, design, and optimize the business process, and study the evolution of business over long periods of time (An and Jeng 2005), and with a project management software tool to track project abilities in terms of budget, schedule, and rework hours, and improve planning (Sycamore and Collofello 1999). To evaluate unanticipated problems associated with the emergency medical service system, Su et al. (Su et al. 2008) supplemented their discrete-event emergency medical services simulation model with a system dynamics model to account for the feedback effects of human decisions. Mittal explains how any complex system model is guaranteed to show some emergent behavior for any system that exists in space and time (Mittal and Rainey 2015). To conclude, system dynamics methods have been used in the fields of logistics, economy, business processes, and construction projects just to name a few. The ability of a system dynamics approach to model the spatiotemporal character of a system generates a greater understanding of the emergent behavior arising out of interdependencies within a complex system, in this case, the effects of disruption in a transportation network and its associated indirect costs.

3. METHODOLOGY

Disruption in one part of a transportation system creates a ripple effect throughout other parts of the system, as well as other critical infrastructure systems linked to it. It is therefore necessary to categorize and parameterize the different factors that result from such a disruption. A system dynamics approach can be used to understand the effects of disruption in the transportation system. The qualitative part of system dynamics, i.e. constructing the causal loop diagram, helps to visually depict the causes as well as the effects of disruption in the transportation network. The quantitative part of this approach helps to study the magnitude of the disruption and thereby helps in calculating the economic losses due to the disruption. In this study, the available road capacity is the metric used to quantify the change in traffic patterns due to a disruption and estimate the costs or losses associated with it. The following sub-section explains how different factors affect the road capacity.

3.1. FACTORS AFFECTING AVAILABLE ROAD CAPACITY

The quantitative part of system dynamics deals with parameterizing the relationships between different variables. These relations are defined by a set of equations. Available road capacity refers to the length of the road which is accessible to the vehicle transport. A number of factors affecting the road capacity must be considered when calculating the total road capacity. Table 1 includes the various factors that affect the available road capacity along with the magnitude of the effect. In this section, it is explained how different factors affect the available road capacity.

Table 1. Factors affecting available road capacity

Factors Affecting Available Road Capacity	Road Capacity Lost per Factor
Connectivity issue	$T_{ci} = T_{cil} * T_{cin}$
Road maintenance	$T_{rm} = T_{rml} * T_{rmn}$
Traffic Jams and accidents	$T_{rc} = T_{tjl} * T_{tjn}$
Regulatory enforcement	$T_{re} = T_{rel} * T_{ren}$
Road construction transit	$T_{rcl} * T_{rcl} = T_{grcl} * T_{grcln} + T_{brcl} * T_{brcn} + T_{febrcl} * T_{febrcn} + T_{artl} * T_{artn} + \cdots$
Emergency vehicles	$T_{el} * T_{en} = T_{pcl} * T_{pc} + T_{al} * T_a + T_{fel} * T_{fe} + T_{ttl} * T_{tt}$

1. Connectivity Issue (T_{ci}) – Figure 2 gives the road capacity lost due to connectivity issues. The length of the road capacity lost due to road closure is denoted by T_{ci}. Here, T_{ci} is the product of length of closure, T_{cil}, and the number of lanes closed, T_{cin}.

$$T_{ci} = T_{cil} * T_{cin} \tag{1}$$

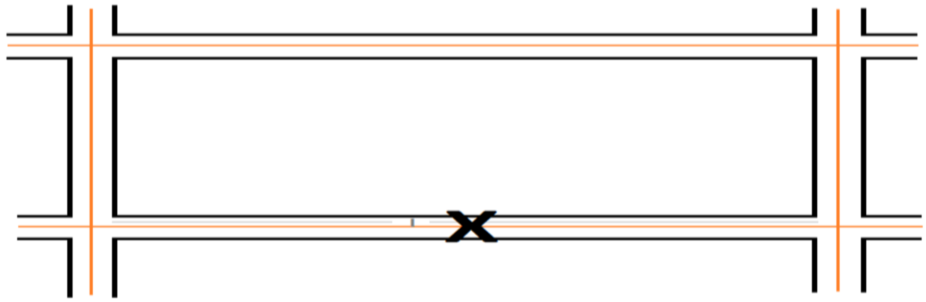

Figure 2. Road capacity lost due to connectivity issue

2. Road maintenance (Trm)– refers to the length of road capacity lost due to ongoing maintenance (Figure 3). The road length used for maintenance is denoted by Trm. Here, Trm is equal to the length of the ongoing road maintenance (Trml) multiplied by the number of lanes closed (Trmn).

$$T_{rm} = T_{rml} * T_{rmn} \quad (2)$$

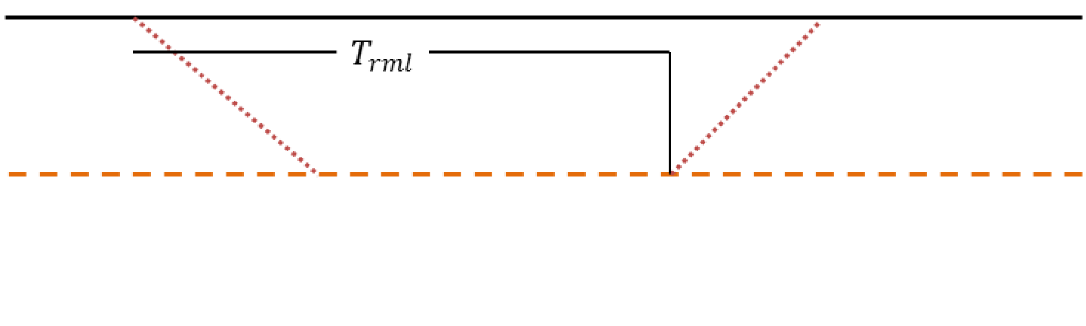

Figure 3. Road capacity used per road maintenance

3. Traffic Jams and Accidents (Ttj) – This is essentially the same parameterization as required for connectivity issues with the major difference being the amount of time for which a segment of road is closed. The road length closed to use by a traffic jam or accident covering all lanes of a road is denoted by Ttjl. Here, Trc refers to the number of lanes (Ttjn) on closed road times multiplied by the length of the closed segment.

$$T_{tj} = T_{tjl} * T_{tjn} \tag{3}$$

4. Regulatory Enforcement event (Tre) - This has the same parameterization as required for road maintenance with the main difference being that the typical length of the lane or partial lane closure is a little over one or two car lengths. The road length of capacity used for regulatory enforcement is denoted by Tre. Here, Tre is equal to the length of closure (Trel) multiplied by the number of lanes closed (Tren).

$$T_{re} = T_{rel} * T_{ren} \tag{4}$$

5. Road Construction Transit (Trc) – the road length used by each road construction vehicle (Trcl) in transit multiplied by the total number of road construction vehicles (Trcn) in transit affects the available road capacity. These road construction vehicles can be further divided into the road lengths used by graders, bulldozers, flat bed semi-tractor trailers, asphalt removers, etc. To calculate the length used by road construction transit, the following equation is used.

$$T_{rcl} * T_{rcn} = T_{grcl} * T_{grcln} + T_{brcl} * T_{brcn} + T_{febrcl} * T_{febrcn} + T_{artl} * T_{artn} + \cdots \tag{5}$$

In the above equation, the road length used by each road construction vehicle is denoted by T_{rcl} and the total number of such vehicles is denoted by T_{rcn}.

6. Emergency vehicles – the road length used by each emergency vehicle (T_{el}) in transit multiplied by the total number of emergency vehicles in transit affects the available road capacity. The length of the road used by emergency vehicles can be further subdivided into the length of the road used by police cars (T_{pc}), ambulances (T_a), fire trucks (T_{fe}) and tow trucks (T_{tt}) separately. The road length used by emergency vehicles is defined by the equation below.

$$T_{el} * T_{en} = T_{pcl} * T_{pc} + T_{al} * T_a + T_{fel} * T_{fe} + T_{ttl} * T_{tt} \quad (6)$$

In the above equation, T_{el} is the length of road required by vehicle for safe transit, and T_e is number of emergency vehicles operating on roads in a given area. Road capacity used equals the length (T_{el}) between the forward and rear buffer zone (the closest distance that the emergency vehicle can approach another vehicle and the closest approach another vehicle can safely have behind the emergency vehicle, respectively). Figure 4 shows the area occupied by an individual emergency vehicle.

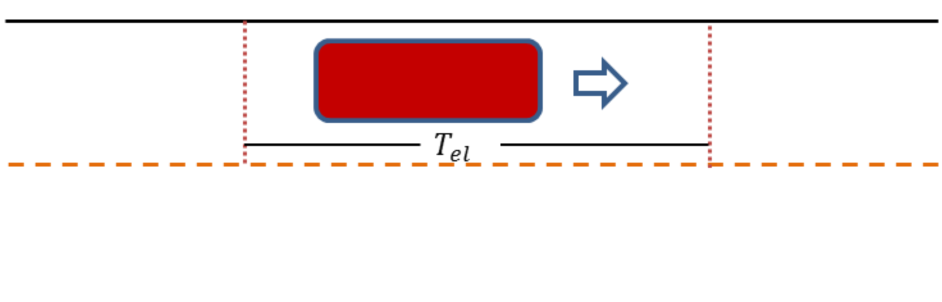

Figure 4. Road capacity used per emergency vehicle

3.2. MODEL EXPLANATION

After identifying the various factors affecting the available road capacity, a causal loop diagram (Figure 5) is created to visually represent the causes leading to a change in the available road capacity and the effects on travel costs when the available road capacity changes. The equations have parameterized the relationship between these variables. Figure 5 shows the different variables affecting available road capacity and their interrelationships. A change in the factors affecting the available road capacity may lead to some degree of inoperability of the road segment. If available road capacity decreases, the average speed per vehicle may decrease which would increase the travel time per vehicle. This leads to an increase in the travel costs per vehicle. For example, if a bridge becomes completely inoperable, there is no capacity available on the stretch of road going to the bridge in both directions and, therefore, traffic must be rerouted which increases the distance travelled per vehicle and hence increases travel times and costs. In another example, if a segment of the road is under construction leading to some loss of capacity (Figure 5) which may decrease the average speed which in turn increases the travel time per vehicle and hence the travel costs. Such changes in the capacity of one road segment may also affect the traffic patterns on the other road segments acting as alternate routes leading further complications to calculating the average cost per vehicle.

To estimate the maximum number of vehicles that can be at the road segment at a given time, capacity of the road has to be calculated. Length of a vehicle is used to calculate the road capacity occupied by a vehicle on the road. Two types of vehicles are considered:

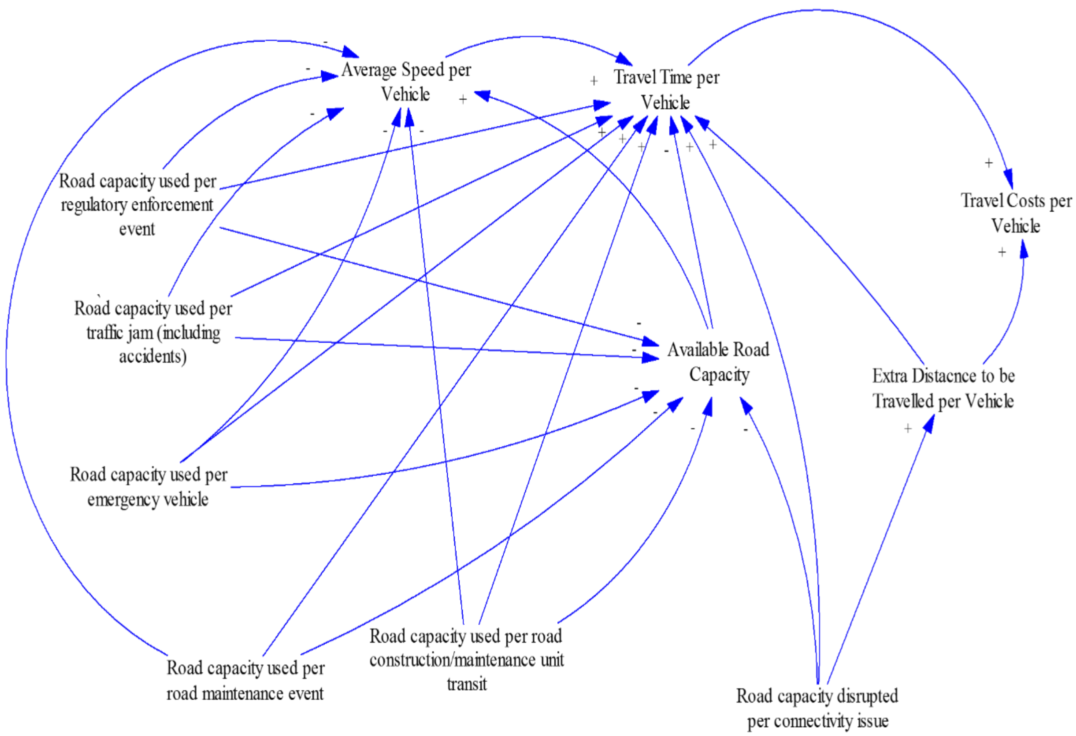

Figure 5. Effect of transportation network disruption on travel costs per vehicle

cars and trucks. A buffer length is included in the length of each vehicle to accommodate the minimum safe distance between each vehicle so as to avoid collisions and maintain the advisory speed limit.Cars are denoted by c and the length of the car is denoted by C_L, and trucks are denoted by t and the surface area of a truck is denoted by T_L. To obtain a single multiplication factor for length of a vehicle, V_L, a composite car/truck ("cruck") is idealized by the following equation is used.

$$V_L = \big((c\% * (C_L + B_C)) + (t\% * (T_L + B_T))\big)\ meters \qquad (7)$$

here, B_C and B_T are the buffer length for cars and trucks respectively. The maximum capacity of a road could be depicted using Figure 6 where each vehicle is maintaining a safe distance from the other vehicle.

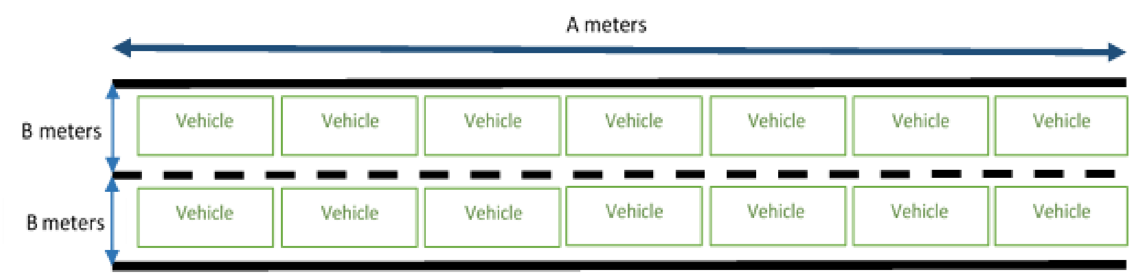

Figure 6. Maximum capacity of the road

The total capacity of the road is equal to the length of a lane (L) multiplied by number of lanes (N_L) as given in equation (8).

$$Total\ Road\ Capacity, T_{RC} = L * N_L \tag{8}$$

Figure 7 depicts various factors affecting the available road capacity and hence, defines the relationship between different variables. To calculate the available road capacity the following equation is used.

$$\textit{Available road capacity}$$
$$= \textit{Total road capacity}$$
$$- \big(\textit{Road capacity lost due to}(\textit{connectivity issue}$$
$$+ \textit{road maintenance} + \textit{regulatory enforcement} + \textit{traffic jams}$$
$$+ \textit{road construction vehicles} + \textit{emergency vehicles})\big)$$
$$- (\textit{Average length of vehicle} * \textit{Number of vehicles}$$

$$T_{ARC} = T_{RC} - \Big((T_{cil} * T_{cin}) + (T_{rml} * T_{rmn}) + \big(T_{tjl} * T_{tjn}\big) + (T_{rel} * T_{ren}) + (T_{rcl} * T_{rcn}) + (T_{el} * T_{en})\Big) - (V_L * N_V) \quad (9)$$

here, vehicle input rate refers to the number of vehicles entering the road segment in a given period of time and vehicle output rate refers to the number of vehicles exiting the road segment in a given period of time. Vehicle input and output rate are the variables that most control traffic flow. For instance, if a road segment is completely inoperable, then the vehicle output rate would be zero vehicles per unit time and the number of vehicles that need to be rerouted are taken from vehicle input rate. If the available capacity of the road is reduced due to a disruption, some of the traffic needs to be diverted to alternate feasible routes. Depending on the amount of traffic being diverted, the available road capacity on the alternate routes may also be affected as the number of vehicles on alternate routes increase. This methodology can be applied to different road segments to study the effect on their available capacity due to an increase in the number of vehicles. The next section includes an example using this methodology and calculating the indirect economic costs.

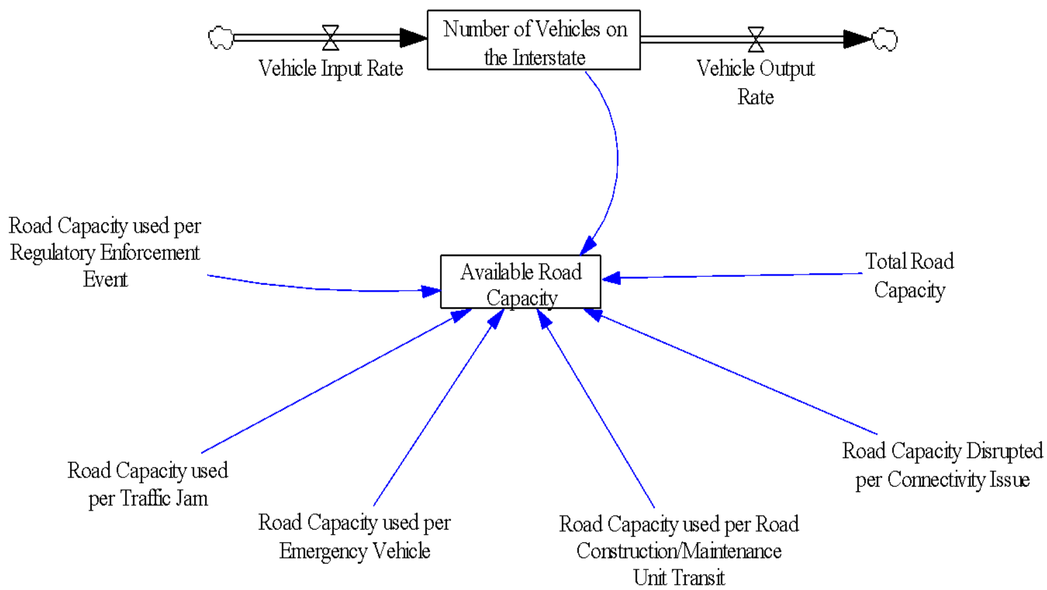

Figure 7. Factors affecting the available road capacity

4. ILLUSTRATIVE EXAMPLE

For this study, a single bridge (the Eads Bridge over the Mississippi River) in St. Louis, Missouri metro area is considered damaged. For simplicity, only the east bound traffic flow on the bridge is modeled. Eads Bridge has two east bound lanes and it is asserted that both these lanes are closed due to road maintenance. With this inoperability of the road, vehicles have to be rerouted. Alternate paths (two neighboring bridges) are chosen for these vehicles. The alternate paths are prioritized based on the minimum indirect costs. The alternate paths selected for the traffic to flow from the west side of the Mississippi river to the east side are by using the adjacent bridges to the north (The Martin Luther King Bridge (alternate path 1)) and south (The Poplar Street Bridge (alternate path

2)) of the Eads Bridge. The length of the Eads bridge is approximately 1600 meters (1 mile). Both the alternate paths have two lanes for the traffic going from the west side of the Mississippi river to the east side. Using the methodology above, indirect economic loss associated with a change in traffic pattern due to disruption in a road segment is calculated. The main objective of this illustrative example is use the methodology to determine the alternate path the vehicle (cruck) will be rerouted to and average cost per vehicle for covering the extra distance.

Determining which alternate path a vehicle should take depends on the available road capacity of each alternate path. To calculate the available road capacity, the average length of the vehicle is calculated using equation (7), an example of which is shown in equation (10). Here, out of total traffic, 83.33% are cars and 16.67% are trucks. This case is based on representative data from Missouri Department of Transportation (MoDOT 2017). The safe following distance for a car is one car length for every 5 miles per hour and the safe following distance for a truck is two and a half times of the length of the car for every 5 miles per hour. This velocity dependence requires that a change in the speed of the vehicle leads to a change in the buffer length of the vehicle. Therefore, the average length occupied by a vehicle changes with the speed. Table 2 gives the value for the average length of a car and a truck and the value for the safe following distance when the vehicles are travelling at 55 miles per hour.

$$V_L = \Big((83.33\% * (4 + 44) + \big(16.67\% * (16 + 110)\big)\Big)\ meters \qquad (10)$$

$$V_L = 61\ meters$$

The average length occupied by a vehicle when travelling at 45 miles per hour and 32.5 miles per hour are calculated and the results are shown in Table 3.

Table 2. Average length and buffer length for vehicles travelling at 55mph

Vehicle Type	Average Length (meters)	Buffer Length (meters) when travelling at 55 mph
Car	4 meters	44 meters
Truck	16 meters	110 meters

Table 3. Average length of vehicle based on the speed at which the traffic is flowing

	When the vehicle is travelling at 45mph	When the vehicle is travelling at 32.5mph
Buffer Length for Car	36 meters	26 meters
Buffer Length for Truck	90 meters	65 meters
Length of Cruck, V_L	51 meters	38.5 meters

Once the length of the cruck is calculated, the next step is to calculate the available road capacity for the alternate routes. The available road capacity is calculated, given that there are 30 vehicles already present on alternate route 1 and 45 vehicles already present on alternate route 2. The values for the length of the alternate paths and the number of vehicles already on the alternate paths are also given in Table 4. It is assumed that there is no disruption on either of the alternate paths and the only factor affecting the available road capacity is the number of vehicles that are originally on that route.

Table 4. Number of vehicles on alternate paths and length of alternate paths

Route	Number of Vehicles Already on the Route	Distance
Path 1 (Martin Luther King Bridge Route)	30	4200 meters (2.6 miles)
Path 2 (Poplar Street Bridge Route)	45	7100 meters (4.4 miles)

Based on equation (9), available road capacity for alternate path 1 and path 2 when the vehicle is travelling at 55 miles per hour is calculated using equation (11). Since both the alternate paths have two lanes the available road capacity for the two alternate paths will be calculated as below.

For alternate path 1, $T_{ARC} = (4200 * 2) - (61 * 30)$

$$T_{ARC} = 6570\ meters \tag{11}$$

Similarly, the available road capacity for alternate path 2 is calculated as shown in equation (12).

Similarly, the available road capacity for alternate path 1 and alternate path 2 are calculated when the vehicle is travelling at 45 miles per hour and 32.5 miles per hour and the results are shown in Table 5.

For alternate path 2, $T_{ARC} = (7100 * 2) - (61 * 45)$

$$T_{ARC} = 11455 \ meters \tag{12}$$

Table 5. Available road capacity on alternate routes for vehicles travelling at different speeds

	Alternate path 1	Alternate path 2
Available Road Capacity when the vehicle is travelling at 55mph	6570 meters	11455 meters
Available Road Capacity when the vehicle is travelling at 45mph	6870 meters	11905 meters
Available Road Capacity when the vehicle is travelling at 32.5mph	7245 meters	12467.5 meters

After calculating the available road capacity for the alternate paths, the next step is to calculate the number of vehicles that can be rerouted to these alternate paths using equation (13).

$$Number\ of\ vehicles/crucks\ that\ can\ be\ rerouted\ to\ the\ path = \frac{T_{ARC}}{V_L} \tag{13}$$

Using equation (13) the number of vehicles that can be rerouted to alternate path 1 and alternate path 2 are calculated for the vehicles travelling at 55 miles per hour, 45 miles per hour and 32.5 miles per hour. The available road capacity for each alternate path and the number of vehicles that can be rerouted to that alternate path is given in Table 6.

Table 6. Available road capacity

Average speed of the vehicle	Number of vehicles that can be rerouted to path 1	Number of vehicles that can rerouted to path 2
55 mph	107	187
45 mph	134	233
32.5 mph	188	323

The travel costs per mile due to rerouting are calculated as shown in equation (14).

$$C = (c\% * G) + (t\% * D) \quad (14)$$

Here, C denotes the average cost per mile per vehicle and G denotes the fuel price per mile per car and D denotes the price of fuel per mile per truck. Given a gasoline price per gallon of \$2.08 and diesel price per gallon of \$2.18, and average miles per gallon (mpg) for a truck is 6 miles per gallon and average mpg for a car is 23.6 miles per gallon, then the average cost per mile per vehicle is calculated using equation (14) is as follows.

$$C = \left(83.33\% * \left(\frac{\$2.08}{23.6\ miles}\right)\right) + \left(16.67\% * \left(\frac{\$2.18}{6\ miles}\right)\right) \quad (15)$$

$$= \$0.13\ per\ mile\ per\ vehicle$$

Indirect costs due to rerouting would include the cost incurred due to extra miles travelled and the extra time a cruck has to travel. The total indirect costs are given by equation (16).

$$Total\ Indirect\ cost\ per\ cruck \tag{16}$$
$$= Cost\ due\ to\ extra\ miles\ travelled\ per\ cruck$$
$$+ Costs\ due\ to\ extra\ time\ a\ cruck\ must\ travel$$

The cost incurred due to extra miles travelled per cruck is given by equation (17).

$$Indirect\ cost\ incurred\ due\ to\ extra\ miles\ travelled\ per\ cruck \tag{17}$$
$$= C * Extra\ distance\ travelled$$

Since the extra distance travelled per cruck is equal to the difference between the length of the alternate path and the length of the original path that a cruck would follow if there is no disruption. Hence, equation (17) can be rewritten as equation (18).

$$Indirect\ cost\ incurred\ due\ to\ extra\ miles\ travelled\ per\ cruck$$
$$= C * (Length\ of\ alternate\ route \tag{18}$$
$$- Length\ of\ original\ route)$$

Using equation (18), the indirect cost incurred due to extra distance travelled by a cruck for the two alternate routes are calculated in equations (19) and (20).

$$Indirect\ cost\ per\ cruck\ due\ to\ extra\ distance\ travelled\ using$$
$$alternate\ path\ 1 = \$0.13 * (2.6\ miles - 1\ mile) = \$0.20\ per\ cruck \tag{19}$$
$$Indirect\ cost\ per\ cruck\ due\ to\ extra\ distance\ travelled\ using$$
$$alternate\ path\ 2 = \$0.13 * (4.4\ miles - 1\ mile) = \$0.44\ per\ cruck \tag{20}$$

Similarly, the indirect costs incurred due to the extra time a cruck takes due to rerouting can be calculated using equation (21).

$$Indirect\ cost\ due\ to\ extra\ time\ a\ cruck\ must\ travel = C_T * \left(\left(\frac{Distance\ of\ alternate\ route}{Speed\ on\ the\ alternate\ route}\right) - \left(\frac{Distance\ of\ original\ route}{Speed\ on\ the\ original\ route}\right)\right) \quad (21)$$

here, C_T is the cost factor of travel time. For this example, cost factor of travel time is considered to be the minimum wage in St. Louis, Missouri which is $7.70/hour. However, the cost factor of travel time can be varied depending on the traveler's destination, field of work, etc. The speed on the original route is considered to be 55 mph.

For this illustrative example, it is assumed that 140 vehicles have to be rerouted from Eads Bridge at a given moment of time. For this example we have three cases, i.e. vehicles travelling at 55 mph, 45 mph and 32.5 mph. These cases are explained below.

Case 1: When the vehicles are travelling at 55 miles per hour on alternate path 1.

From the results shown in Table 6, alternate path 1 has a capacity to accommodate 107 more vehicles travelling at 55 miles per hour. This implies that other 33 vehicles will have to be rerouted to alternate path 2.

Using equation (18), the indirect cost due to the extra distance travelled per cruck for rerouting 107 vehicles through alternate path 1 and 33 vehicles through alternate path 2 are $21.4 and $14.52 respectively. The indirect costs due to extra time these crucks must travel are $23.97 for 107 crucks on alternate route 1 and $15.71 for the 33 crucks on alternate route 2. Therefore, the total indirect cost due to rerouting these 140 vehicles would be $75.60.

Case 2: When the vehicles are travelling at 45 miles per hour on alternate path 1.

Table 6 shows that alternate path 1 has a capacity to accommodate 134 vehicles travelling at 45 miles per hour. This implies that the other 6 vehicles will have to be rerouted to alternate path 2. Using equation (18), the indirect cost due to the extra distance travelled per cruck for rerouting 134 vehicles through alternate path 1 is $26.80 and 6 vehicles through alternate path 2 is $2.64. Indirect cost due to extra time a cruck must travel are found out to be $40.86 and $3.68 for alternate route 1 and 2 respectively, using equation (21). This implies the total indirect costs due to rerouting 140 vehicles would be $73.93.

Case 3: When the vehicles are travelling at 32.5 miles per hour on alternate path 1.

From the results shown in Table 6, alternate path 1 has a capacity to accommodate 188 more vehicles travelling at 32.5 miles per hour. This implies that all 140 vehicles will be rerouted to path 1. Using equation (18), the indirect cost due to the extra distance travelled per cruck for rerouting all 140 vehicles through alternate path 1 is equal to $28. Indirect cost due to extra time a cruck must travel is found out to be $66.64 for 140 crucks on alternate route 1, using equation (21). This implies the total indirect costs due to rerouting 140 vehicles would be $94.64.

After analyzing the results from the above three cases, case 2 (vehicles travelling at 45mph) is preferred to be the best case as the indirect costs are minimum for this case. Even though the result in case 3 shows that the vehicles will have to follow the shortest distance, it is not a preferred option as the time penalty associated with this methodology makes case 3 one of the most expensive options.

This methodology has been applied for rerouting 140 vehicles, but the methodology is flexible and scalable. As more vehicles and more alternate routes are added the equations can simply be adjusted. The indirect economic losses for a large number of vehicles can be calculated using the results from equation (16), (19) and (21) depending on the alternate route that is followed by the vehicle. Figure 8 is a speed versus cost graph that shows the cost of rerouting 140 and 280 vehicles along the two alternate routes considered in the above example. The same procedure is followed to calculate the indirect economic loss for rerouting 280 vehicles as shown in the above example.

The indirect cost of rerouting 280 vehicles is calculated using the same methodology used in the example. For the case when the vehicular traffic is flowing at a speed of 55 mph, the indirect cost due to the extra distance travelled per cruck for rerouting 107 vehicles through alternate path 1 is $21.4 and 173 vehicles through alternate path 2 is $76.12. Indirect cost due to extra time a cruck must travel are found out to be $23.97 and $82.5 for alternate route 1 and 2 respectively. This implies the total indirect cost due to rerouting 280 vehicles when the traffic is flowing at a speed of 55 mph is equal to $203.84. Similarly, when the vehicular traffic is flowing at a speed of 45 mph, the indirect cost due to extra distance travelled and extra time added for rerouting 280 vehicles is $91.04 and $130.34 resulting in a total indirect cost of $221.38. For the case when the vehicular traffic is flowing at a speed of 32.5 mph, the indirect cost due to extra distance travelled and extra time added for rerouting 280 vehicles is $78.08 and $172.51 resulting in a total indirect cost of $250.59. From the results of this example, the best scenario for rerouting 280 vehicles would be the case when the traffic is flowing at 55 mph as it is the least expensive option. As seen from the two examples, the amount of added travel time influences the decision along with the extra distance that needs to be travelled. As number of vehicles keep increasing, it will be necessary to add additional alternative routes so as to accommodate them. The benefit of this approach lies in its ability to account for lost time while selecting the most cost-effective alternative.

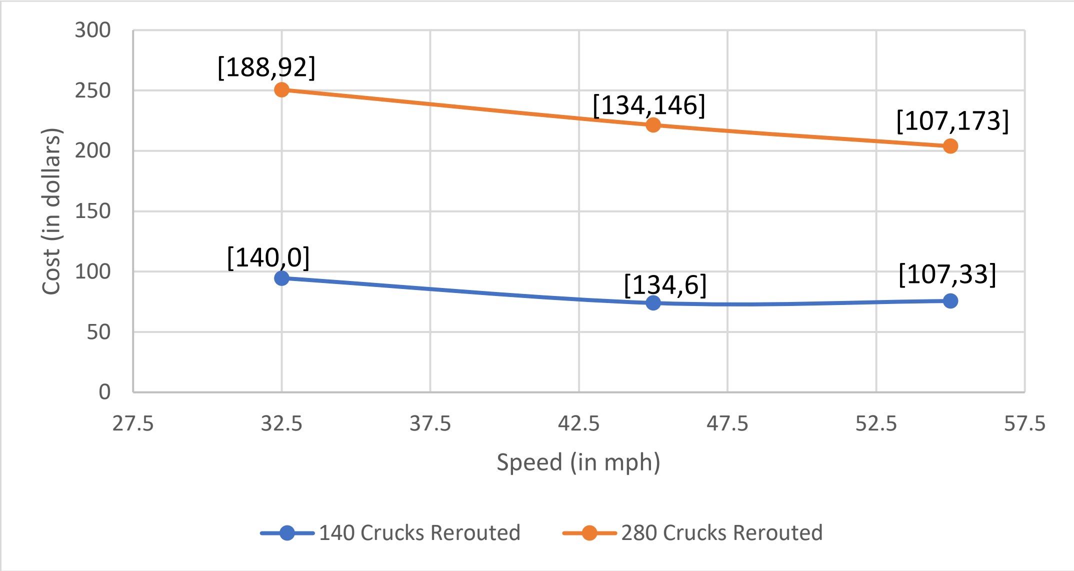

Figure 8. Speed vs cost graph when 140 and 280 vehicles are rerouted on the two alternate paths. The blue line shows the results when 140 crucks are rerouted and the orange line shows the results when 280 crucks are rerouted. The first and second numbers in brackets on the graph are the number of vehicles on alternate route 1 and 2 respectively

5. CONCLUSION AND FUTURE WORK

The objective of this study is to create a methodology to model the emergent behavior during a disruption in the transportation system and that calculates economic losses due to such a disruption. A causal loop diagram visually represents the different factors that affect available road capacity and travel costs. A causal loop diagram mapping the interdependencies between system variables provides greater insight into the spatiotemporal character of the transportation network system. This model also posits equations that allow the user to calculate available road capacity and to determine the number of vehicles that need to be rerouted to alternate paths. This in turn allows for the calculation of indirect losses associated with that traffic being rerouted. These indirect costs are, in part due to emergent behavior within the alternate transportation system, include costs due to extra distance travelled per vehicle as well as costs due to the extra time a vehicle had to travel due to the disruption in the transportation network. With the traffic being rerouted to alternate routes, the available road capacities on these routes are reduced as more and more vehicles utilize them. This, in turn, affects traffic speed and causes congestion, thereby increasing the indirect costs due to extra travel time each vehicle must endure. To demonstrate the methodology, an illustrative example based on bridges crossing the Mississippi River in St. Louis is used where the two east bound lanes of the Eads Bridge are under maintenance. Two alternate paths are examined and the extra cost per vehicle is calculated for these alternate paths. This methodology calculates the most cost-efficient traffic reorientation scenario.

This methodology can be applied to other transportation networks with alternate paths added as needed. Care should be taken when increasing the number of paths as this will likely result in a non-linear increase in the number of options evaluated. This could be alleviated either through the application of heuristics or a self-organizing approach. The cost per vehicle per alternate path can be calculated and multiplied by the number of vehicles going through those alternate paths to calculate the indirect economic losses. This research can further be extended to estimate the extent of disruption of the transportation network that will not only necessitate a higher freight transportation load on rail, water and air networks but also make them a more viable option by minimizing economic losses.

This approach could be modified to investigate the factors leading indirect costs due to the inoperability for other critical infrastructure systems such as power, water, and communications. A system dynamics model is advantageous for determining the factors that render such infrastructure systems inoperable. Understanding these factors allows the design of strategies and solutions to abate the economic losses owing to the inoperability of the infrastructure system. Systems dynamics methods also allow the modelling of the spatiotemporal character of a system and therefore yield a greater insight to the emergent behavior arising out of interdependencies within a complex system. By using a common method to evaluate indirect losses it can simplify the integration of the data into a larger evaluation framework.

The example evaluated in this study is a steady state representation of the number of vehicles that are present on each bridge at any particular point in time. This methodology can model different states and time steps to map the emergent behavior arising out of the transportation system. Expanding this to include a discrete event simulation (Zeigler and Muzy 2016) would allow for capturing some of the dynamic effects of the traffic building up to reach capacity. This model assumes that the information about rerouting is shared with individual drivers, thereby guiding emergent behavior to minimize congestion. Introducing human behavior effects into the model will allow the exploration of the willingness of drivers to accept different routes. This study is focused on a particular area of a particular transportation system. This work will be expanded to include the other infrastructure elements mentioned into a holistic representation to give decision makers better and more representative information regarding how best to restore critical infrastructure systems.

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II. SUPPLY CHAIN INFRASTRUCTURE RESTORATION CALCULATOR SOFTWARE TOOL: DEVELOPER GUIDE AND USER MANUAL

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ABSTRACT

This report describes a software tool that calculates costs associated with the reconstruction of supply chain interdependent critical infrastructure in the advent of a catastrophic failure by either outside forces (extreme events) or internal forces (fatigue). This tool fills a gap between search and recover strategies of the Federal Emergency Management Agency (FEMA) and construction techniques under full recovery. In addition to overall construction costs, the tool calculates reconstruction needs in terms of personnel and their required support. From these estimates, total costs (or the cost of each element to be restored) can be calculated. Estimates are based upon historic reconstruction data, although decision-managers do have the choice of entering their own input data to tailor the results to a local area.

1. INTRODUCTION

Supply Chain Interdependent Critical Infrastructure (SCICI) has been defined as those elements of the national infrastructure which are so vital that their incapacity or destruction would have a debilitating impact on the defense or economic security of the United States

(Department of Homeland Security, 1996). Modeling SCICI restoration is a challenging problem (Ramachandran et al. 2015; Ramachandran et al. 2016). The innate interdependencies between various critical infrastructures add to the complexity of the system. Extreme events such as earthquakes, hurricanes, and the like, can disrupt various critical infrastructures leading to considerable economic losses. Based on the severity of the extreme event, one or multiple infrastructures can be rendered partially or completely inoperable.

This report presents a developer's guide and a user tutorial for a supply chain infrastructure restoration calculator (SCIRC) tool that estimates the amount of resources required to restore infrastructure networks. This tool was developed as part of a joint effort between the Center of Excellence in Geospatial Information Sciences (CEGIS) at the U.S. Geological Survey and the Engineering Management and Systems Engineering Department at the Missouri University of Science and Technology. For this report, resources include: potable water, gray water, food, sanitation facilities, housing, transportation and other basic requirements of restoration crews along with the supplies (such as power, fuel, materials, and costs) required for restoring these infrastructures. It is important to estimate the amount of resources required to restore disrupted critical infrastructures to devise efficient disaster restoration and management strategies. This tool can be used by city planners and policy makers to calculate the amount of resources required for restoring one or multiple infrastructures to its normal operating state and for budgeting and prioritizing post-disaster restoration operations.

The SCIRC tool is written as open-source software in the Python programming language and uses a bottom-up cost estimation technique to collect data associated with each infrastructure facility. These data include the amount of resources required to build a unit of each infrastructure element. For example, the amount of power, fuel, potable water, storage area, man-hours, food, materials, gray water, solid waste and black water required to build one square foot of a high school. These data are collected for each of the infrastructure elements represented in the SCIRC tool. The estimation of cost, material, and number of restoration crew necessary for disaster recovery is a unique feature of the SCIRC tool. Once this information is available, policy makers will be able to make more efficient decisions regarding the allocation of the resources for disaster restoration.

2. SOFTWARE

The SCIRC tool is written in the Python 2.7 programming language. The SCIRC algorithm (Figure 1) is designed to solve a system of equations to simultaneously determine resource requirements using established methods (Nottage and Corns, 2011). The SCIRC tool application queries the user to input the number of units of an infrastructure element that needs to be restored and then returns the amount of resources required for restoration, or in the advent of a large-scale disaster, the user can also calculate the amount of resources required to restore multiple infrastructure elements.

The SCIRC tool includes five tabs:

1. Facilities Affected – This tab includes a list of infrastructure elements from which the user can choose one or many to restore. The thirty infrastructure elements that are included in the software along with their units are listed in Table 1.

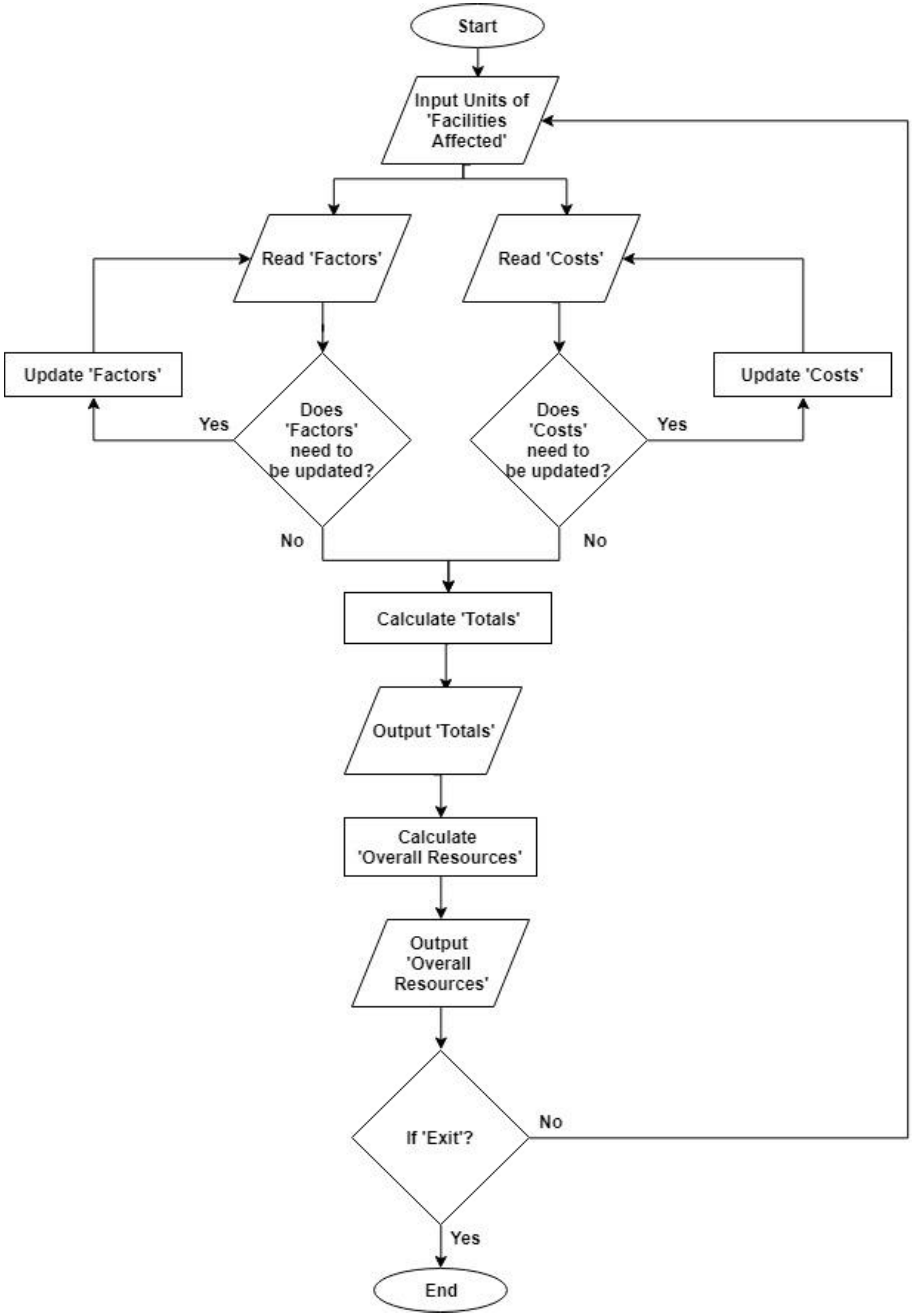

Figure 1. Algorithm for the SCIRC tool

2. Factors – This tab delineates the different resources required to restore each unit of a selected infrastructure element. The user selects an element from the drop-down menu available in the factors tab to determine the amount of resources required to build a unit of that element. While standard values for the resources required to restore one unit of an element are default values in the software, the tool does provides the user with an option to change these values in the factors tab based on their expertise or locale. Different types of resources, along with their units, are listed in Table 2.

3. Totals – This tab lists the amount of each resource required to restore the infrastructure elements specified by the user. The user selects an element from the drop-down menu in the totals tab to calculate the amount of resources needed to restore the specified number of elements. Along with the resources included in the Factors tab, the Totals tab also includes a total cost estimate, specifically the summation of all costs of the required restoration resources.

4. Costs – This tab lists the unit costs of each resource. The values in the cost tab are pre-fed in the software. The software provides the user with an option to update the costs in the application. It is important to note that the costs of resources provided in the costs tab refers to the cost of one unit of each resource, whereas the cost provided in the totals tab refers to the total cost of restoring a specified number of units of an infrastructure element as specified by the user.

5. Overall Resources – This tab lists the resources required to restore all the infrastructure elements specified by the user. The tab sums the individual resources required to restore each of the elements and reports the totals. In other words, if the user inputs in the Facilities Affected tab a request to restore one infrastructure element, the

Overall Resources tab will return the resources required to restore that element, whereas if the user requests restoration of ten occurrences of a given infrastructure element in the Facilities Affected tab, the Overall Resources tab will provide the amount of resources required to restore these ten elements.

Table 1. List of facilities included in the software. The table includes the description for each facility and the units that each facility is measured in

FACILITIES	DESCRIPTION	UNITS
Electrical Distribution	Electrical power lines to deliver electricity	miles
Coal Power Plant	Coal-based power plants for electrical generation	kW
Nuclear Power Plant	Nuclear power based power plants for electrical generation	kW
Wind Farm	Wind turbines based power plants for electrical generation	kW
Natural Gas Distribution	Steel pipes (10 inch diameter) used for natural gas distribution	miles
Water Distribution	Network of pipes used to distribute water for domestic and commercial use	miles
Water Purification	Water treatment plants to purify water	gal
Sewage Treatment	Wastewater treatment plants	gal
Warehouse	Warehouse to store goods, supplies and the likes.	sq. ft.
Wireless Towers	Cell towers in a cellular network	units
Wired Networks	Optical cable lines for fiber optic internet connection	miles
Communication Centers	Emergency response centers	sq. ft.
Hospital Facilities	Super specialty multi-bed healthcare facility	sq. ft.
Fire Stations	Facilities with fire engine, fire fighters, and fire retardant materials and equipment, and the likes.	sq. ft.
Police Stations	Facilities accommodating police personnel	sq. ft.
Railway Networks	Railway track lines to transport goods and ferry people	miles

Table 1. List of facilities included in the software. The table includes the description for each facility and the units that each facility is measured in (Continued)

Railway Bridges	Bridges used by railways to transport goods and passengers over roads, ravines, and the likes.	sq. ft.
Roadway Bridges	Bridges used by motor vehicles to transport goods and passengers over roads, rivers, and the likes.	sq. ft.
Elementary Schools	From kindergarten through grade 6	sq. ft.
Middle Schools	From grade 7 through grade 9	sq. ft.
High Schools	From grade 10 through grade 12	sq. ft.
Air Freight Facilities	Facilities to ship and receive air cargo	sq. ft.
Air Passenger Facilities	Domestic and International Airports	sq. ft.
Arterial Roads	Major and minor roads passing through a town/city	sq. ft.
Water Freight Facilities	Facilities to ship and receive cargo using riverboats and barges	sq. ft.
Interstates	Highways connecting two or more states	sq. ft.
Traffic Signals	Standard traffic signal poles	units
Street Lights	Standard street lighting poles	units
Rail Freight Facilities	Facilities to ship and receive cargo using railways	sq. ft.
Rail Passenger Facilities	Railway station to transport passengers	sq. ft.

Table 2. List of resources. The table includes a description for each resource and the units in which the resource is measured

FACTORS	DESCRIPTION	UNITS
Power (F_{i1})	Electric power needed for restoration tools and operations	kW per unit of the facility
Fuel (F_{i2})	Amount of gas needed to run power generator, tools, and construction equipment	gallon per unit of the facility
Potable Water (F_{i3})	Amount of clean drinking water needed by the restoration crew	gallon per unit of the facility
Storage Area (Fi4)	Storage space used by restoration crew to store goods, tools, and the likes.	square foot per unit of the facility
Man-hours (Fi5)	Labor hours spent by personnel working on restoration activities	hours per unit of the facility
Gray Water (Fi6)	Water used for restoration and construction activities	gallon per unit of the facility
Black Water (Fi7)	Wastewater containing fecal matter	gallon per unit of the facility
Solid Waste (Fi8)	Garbage, construction waste and the likes.	pound per unit of the facility
Food (Fi9)	Amount of food items needed by the restoration crew	pound per unit of the facility
Materials (Fi10)	Construction material required to construct respective facilities	US Dollars per unit of the facility

3. MATHEMATICAL FRAMEWORK FOR THE APPLICATION

The user specifies the amount of units of one or more infrastructure elements that need to be restored. If the user wanted to restore ‘x’ units of the element i, the resources are denoted by j, and the SCIRC tool would multiply the number of units, x, with each resource in the “Factors” tab for the element i. Equations (1) – (10) in Table 3 give the formula for calculating the total amount of each resource required to restore an element i. Equation (11) in Table 3 refers to the total cost of restoring x units of element i. C_j in equation 1 denotes the cost of one unit of resource j.

Following the equations described above, "Totals" for multiple elements are calculated. Equation (12) calculates the overall resources, OR_{ij}. Here, i refers to the element and j refers to the resources included in the "Overall Resources" tab.

$$OR_{ij} = \sum_{i=1}^{30} T_{ij} \quad \forall\, j = 1,2,3, \ldots \ldots, 11 \tag{12}$$

Table 3. Mathematical equations for "Totals" tab

T_{i1} – Refers to the amount of power required to restore x units of facility i	$T_{i1} = x * F_{i1}$ eq. (1)
T_{i2} – Refers to the amount of fuel required to restore x units of facility i	$T_{i2} = x * F_{i2}$ eq. (2)
T_{i3} – Refers to the amount of potable water required to restore x units of facility i	$T_{i3} = x * F_{i3}$ eq. (3)
T_{i4} – Refers to the amount of storage area required to restore x units of facility i	$T_{i4} = x * F_{i4}$ eq. (4)
T_{i5} – Refers to the amount of man-hours required to restore x units of facility i	$T_{i5} = x * F_{i5}$ eq. (5)
T_{i6} – Refers to the amount of gray water required to restore x units of facility i	$T_{i6} = x * F_{i6}$ eq. (6)
T_{i7} – Refers to the amount of black water generated while restoring x units of facility i	$T_{i7} = x * F_{i7}$ eq. (7)
T_{i8} – Refers to the amount of solid waste generated while restoring x units of facility i	$T_{i8} = x * F_{i8}$ eq. (8)
T_{i9} – Refers to the amount of food required to restore x units of facility i	$T_{i9} = x * F_{i9}$ eq. (9)
T_{i10} – Refers to the amount of materials required to restore x units of facility i	$T_{i10} = x * F_{i10}$ eq. (10)
T_{i11} – Refers to the total cost incurred to restore x units of facility i	$T_{i11} = \sum_{j=1}^{10}(T_{ij} * C_j)$ eq. (11)

If there is only a single occurrence of an element to be restored, then the values in the "Totals" tab and "Overall resources" tab remain the same. If multiple occurrences or elements are to be restored, the “Overall Resources” tab shows the total amount of resources required to restore all occurrences for all elements.

4. INSTALLATION

The SCIRC tool is stored as a Python 2.7 executable file for the ease of the user. This application requires minimal effort for installation. The application is provided as an executable file format. The user can download the file from the link https://communities.geoplatform.gov/disasters/supply-chain-infrastructure-restoration/ (GeoPlatform: Disasters, 2019). Once downloaded, the user must double-click the saved file and select the ‘Run’ option in the dialog box. The user can now choose the location where they want to install this tool. After the software has been installed, the user can now double-click on the executable file to run the application. The user’s computer must meet the minimum system requirements before installing and running the SCIRC application. The system requirements are shown in Table 4.

Table 4. System requirements to run SCIRC

CPU	1 gigahertz (GHz) or 32-bit(x86) or 64-bit (x64) processor
RAM	1 GB (32-bit) or 2 GB (64-bit)
Disk Space	60 MB
Operating System	Microsoft Windows version 7 or newer

5. TUTORIAL

Launching the application: To launch the application, double-click on the SCIRC executable file (SCIRC.bat).

User Interface: Once the application is launched, the user will see the main interface page of the software (Figure 2). The tabs Facilities Affected, Factors, Totals, and Costs are accessible as the top field of the table, while the Overall Resources tab is accessible in the horizontal bar positioned after the first bank of I/O boxes.

Input: The user can input values for the desired infrastructure element in the box adjacent to that element (Figure 3). For example, to calculate the amount of resources required to restore 487,000 square feet of "High School" the user should:

1. Click on the box adjacent to "High School".
2. Input the value '487,000' in the box and press 'Enter' key on the keyboard.

The user can also input values for multiple facilities using the above steps. The user can click on the 'Reset' button at any time to make all the values in the Facilities Affected tab zero.

Output: Once the user has input the values in the Facilities Affected tab, the output can be seen in both Overall Resources and Totals Tab (Figure 4). The user accesses the amount of resources required to restore an individual element as follows:

1. Click on the Totals tab.
2. Click on the Select Facility drop-down menu.

3. Click on the element that the user wants to select from the drop-down menu. The amount of resources required to restore the user-specified units of the select facility can be viewed now (Figure 5).

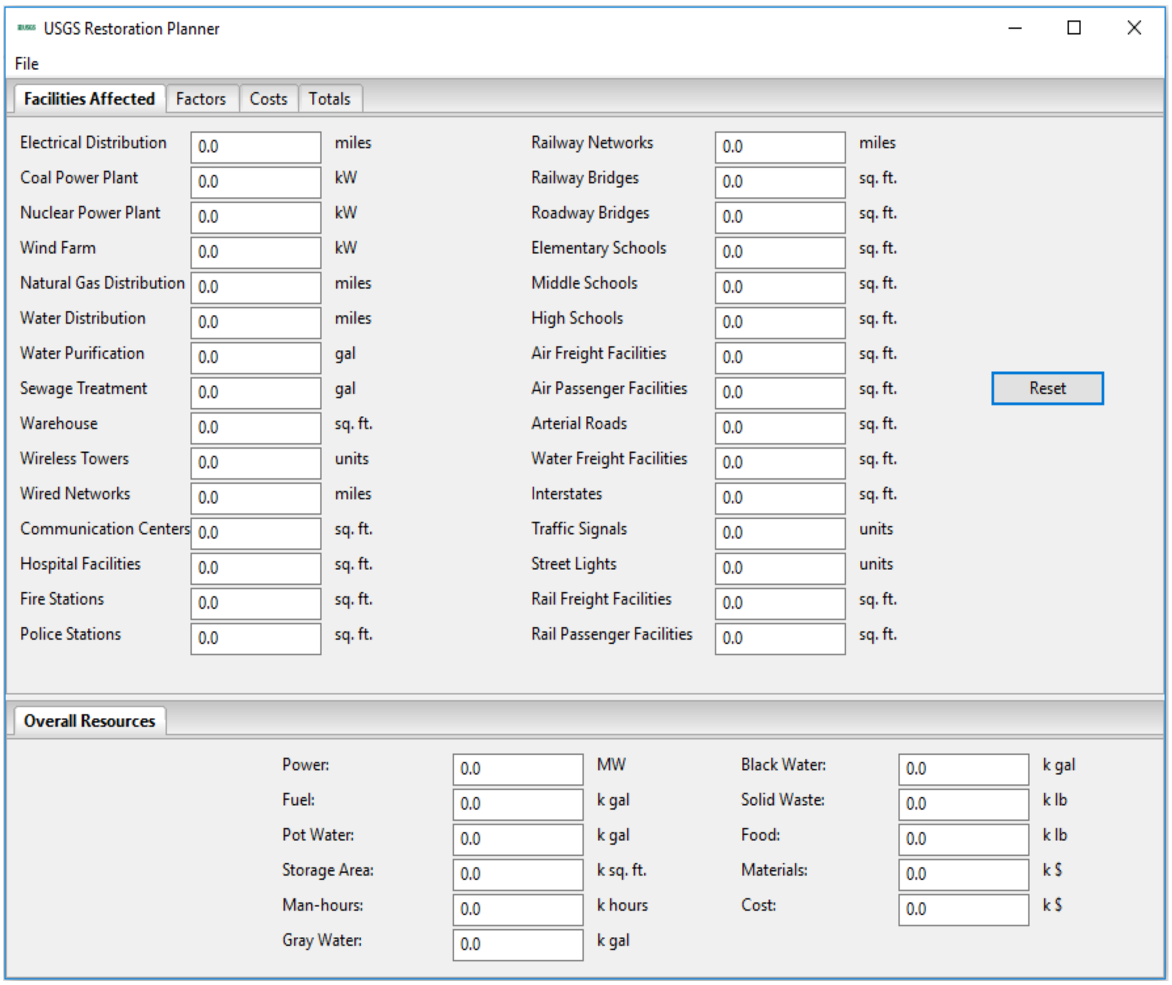

Figure 2. User interface as seen when the application is launched

Flexibility of the application: Based on the need and/or expertise of the user, the user may want to change the values in the Factors and Costs tabs. The Factors tab gives the amount of resources required to restore one occurrence of an individual infrastructure element. The Costs tab provides the restoration cost of one occurrence of each necessary resource.

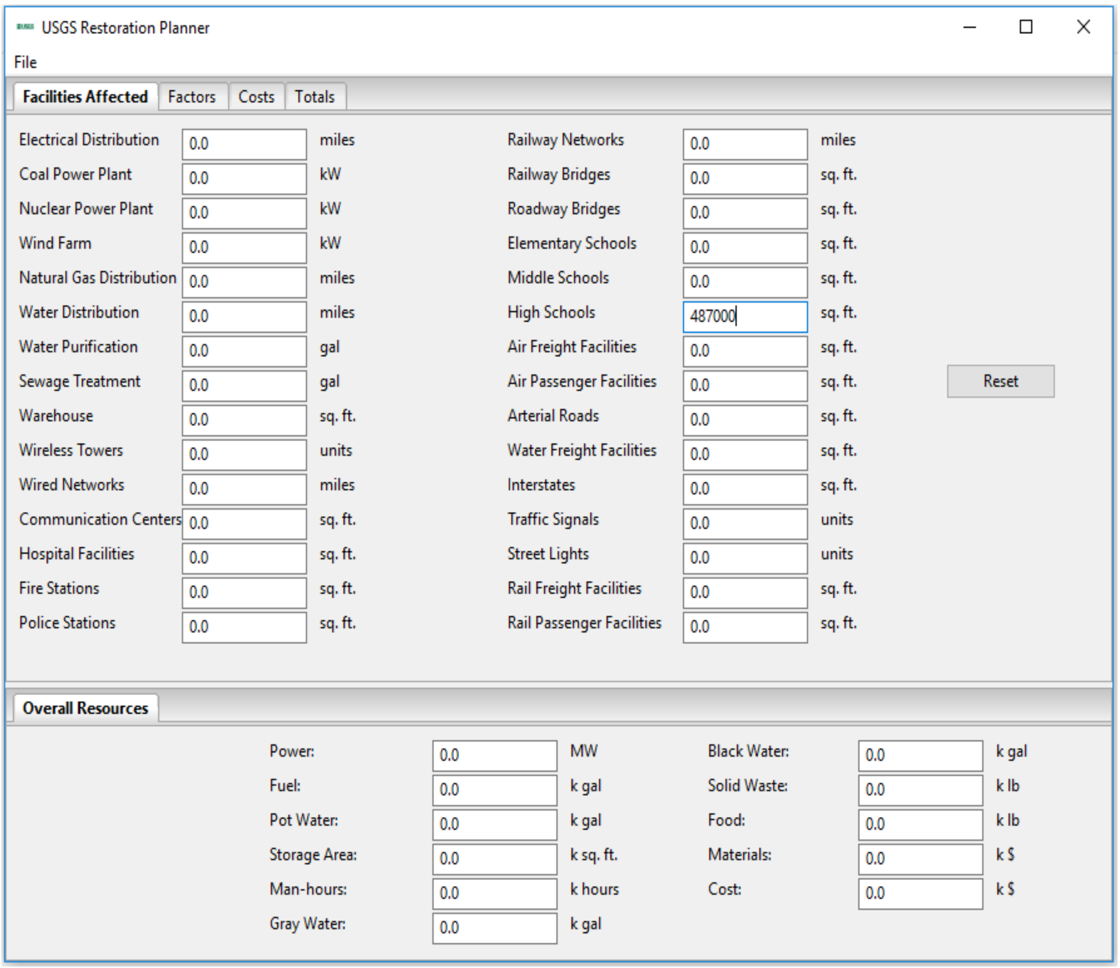

Figure 3. The user entering the value in the box adjacent to high schools

To modify the values in Factors tab, follow the steps below:

1. Click on the Factors tab and select an infrastructure element from the drop-down menu (Figure 6) for which the value should be modified (For example, High School).

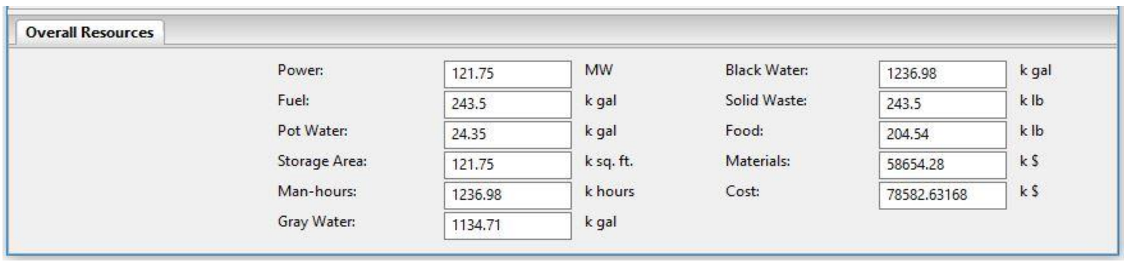

Figure 4. Overall resources tab. The user can view the amount of resources required to restore one or more facilities here

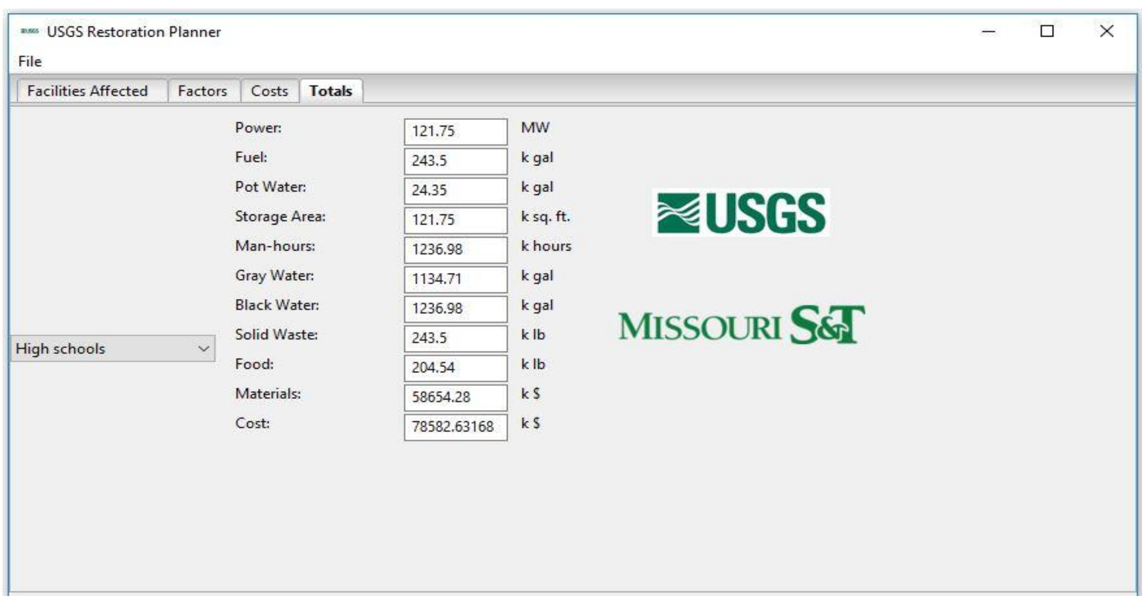

Figure 5. Totals tab. The user can select a facility from the drop-down menu and view the amount of resources required to restore an individual facility

2. Click on the box adjacent to the resource for which the value needs to be modified (For example, Man-hours).
3. Delete the value in the box by pressing the ‘Backspace’ or ‘Delete’ key on the keyboard.
4. Enter the value in the text box using the keyboard and press ‘Enter’.

To modify the values in Costs tab, follow the steps below:

1. Click on the Costs tab.
2. Click on the box adjacent to the resource for which the cost needs to be modified (For example, Man-hours).
3. Delete the value in the box by pressing the ‘Backspace’ or ‘Delete’ key on the keyboard.
4. Enter the value in the box using the keyboard and press ‘Enter’.

Saving and opening a file: The user can save the results in an XML formatted file.

The saved file can be opened in the application.

To save a file follow the steps listed below:

1. Click on the File menu.
2. Click on Save As and type the file name in the ‘Save file as’ dialog box. Note that the file must be saved in an XML format.
3. Click on Save to save the file.

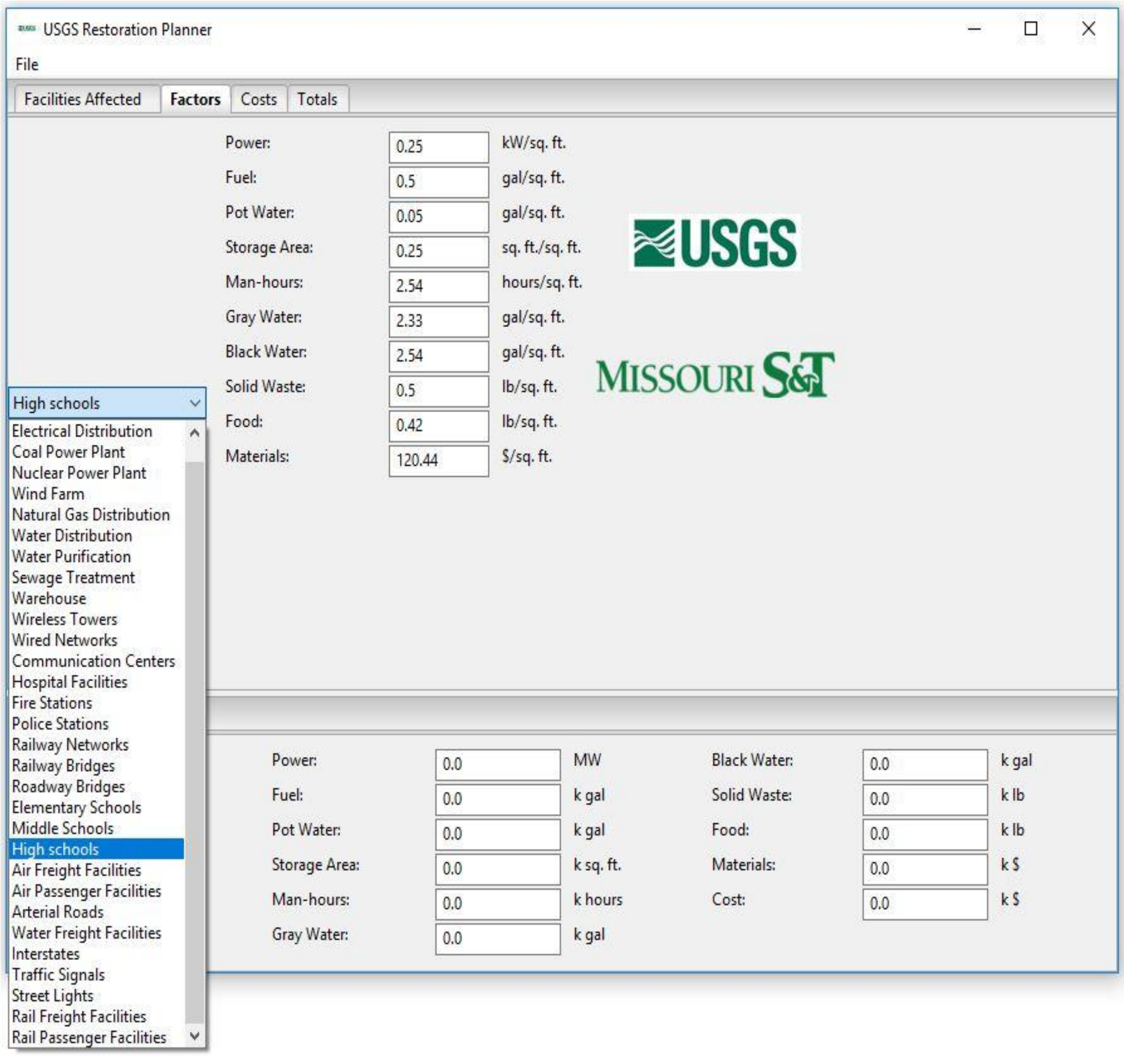

Figure 6. Factors tab. The user can select a infrastructure element from the drop-down menu and modify the value of one or more resources for that facility in this tab

To open a saved file, use the following steps:

1. Click on the File menu.
2. Click on Open to view the 'Choose a file' dialog box.
3. Select the file and click on Open. The selected file will be opened in the application.

6. RESULTS

SCIRC calculates the resources required for restoring multiple facilities after catastrophic failure. Unlike traditional commercial software, this application also calculates the amount of resources required for the restoration crew while they perform the restoration operations. The total cost provided by this software does not include overhead expenses such as accounting fees, advertising, legal fees, and profits. The cost and amount of supplies required by the restoration crew, however, are calculated. Table 5 provides a detailed comparison between the actual cost, (the actual cost of restoring elements using data from reconstruction after a tornadic event) and the cost of restoring a facility using the SCIRC tool along with the percentage difference between the actual and calculated cost for restoring a facility. A list of facilities that have been validated using these data is presented in Table 5.

Table 5. Percentage cost difference between the actual and calculated costs for restoring a given facility

Facilities Affected	**Unit of Facilities Affected**	**Actual Cost, $**	**SCIRC Cost, $**	**Percentage Cost Difference**
Hospital	900,000 sq. ft.	168,000,000	168,531,674	-0.16%
High School	487,000 sq. ft.	89,740,786	97,137,331	8.24%
Elementary School	66,500 sq. ft.	10,800,000	11,251,868	4.18%
Middle School	125,800 sq. ft.	24,320,000	24,381,387	0.25%
Fire Station	7,500 sq. ft.	755,108	786,838	4.20%
Warehouse	10,000 sq. ft.	880,000	852,924	-3.08%
Police Station	5,000 sq. ft.	567,286	674,264	18.86%
Wired Networks	1 mile	16,632	16,695	0.38%

Table 5. Percentage cost difference between the actual and calculated costs for restoring a given facility (Continued)

Railway Networks	1 mile	1,585,000	1,318,523	-16.81%
Traffic Signals	1 each	32,760	36,181	10.44%
Street Lights	1 each	5,200	5,342	2.73%

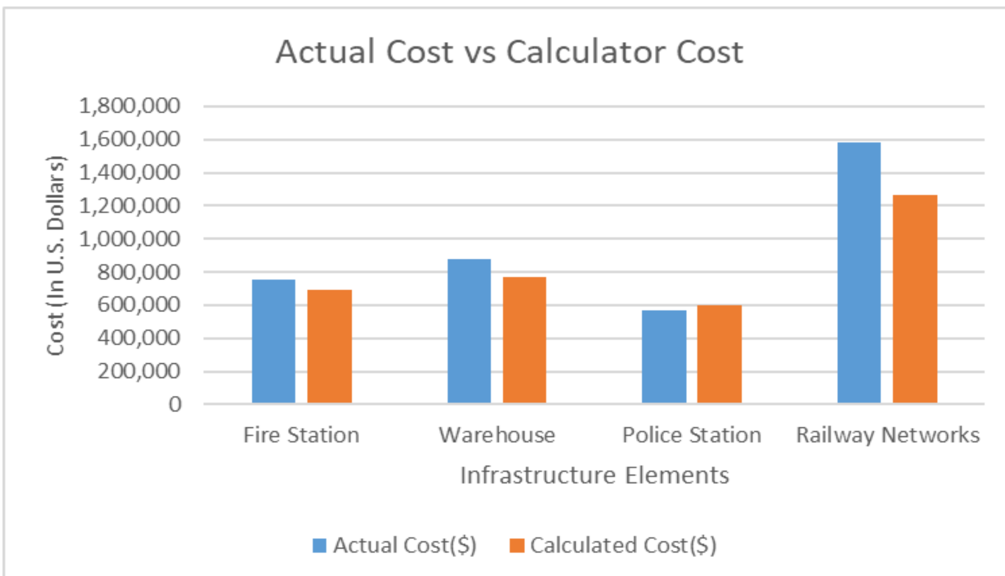

Figure 7. Actual cost vs SCIRC cost for fire station, warehouse, police station and railway networks

The actual and SCIRC costs for hospitals, high schools, elementary schools and middle schools are given in Figure 8. Note that the cost used for validation does not include the cost of equipment used within these facilities. For instance, the cost of restoring a hospital does not include the cost of equipping it with X-Ray, CT scan, MRI and similar medical equipment. Also, the costs of furniture, computers, gym equipment and similar products required for day to day operation of the facility are not included in the total cost. Since hourly wage for a restoration crew member varies with the nature of work, an average hourly wage of $30 is assumed across all facilities for the restoration crew member.

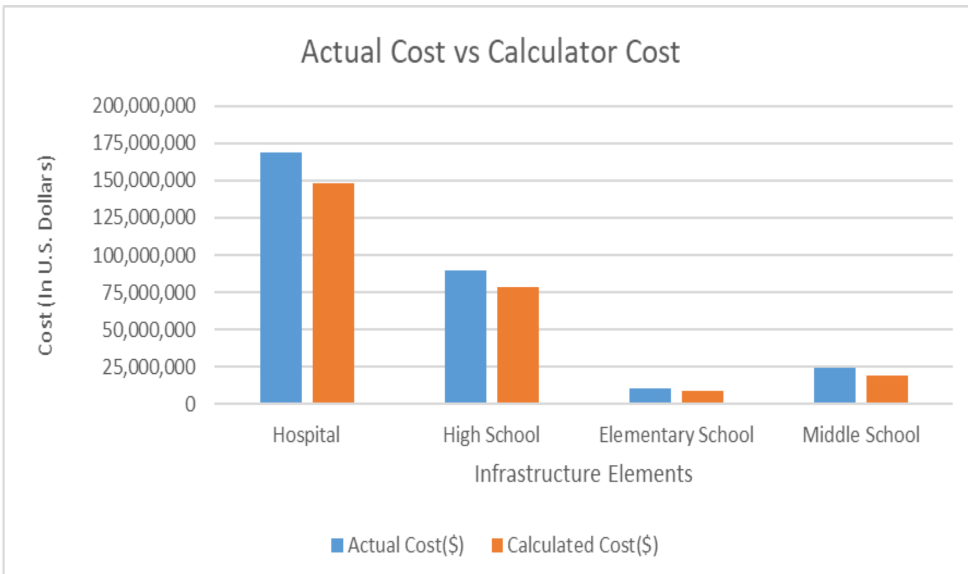

Figure 8. Actual cost vs SCIRC cost for hospital, high school, elementary school and middle school

Actual and SCIRC cost values of wired networks, traffic signals and street lights are given in Figure 9. For wired networks, the cost of optical fiber cable as well as the cost of installation of these optical fiber cables is included in the cost used for validating the results obtained from the SCIRC tool. The cost used to validate a traffic signal includes the cost of replacing one signalized post and mast arm, the cost of controller cabinet as well as the cost of installing the traffic signal. For street lights, the cost includes the cost of the light poles, bracket arms, controller, sensor, high pressure sodium lamp, and wiring and installation of the street light.

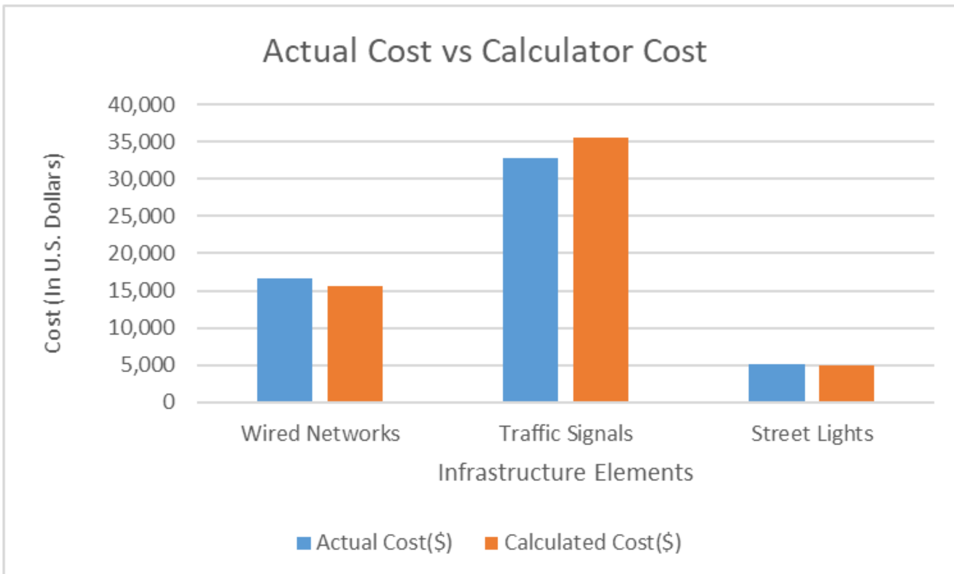

Figure 9. Actual cost vs SCIRC cost for wired networks, traffic signals and street lights

7. VALIDATION PARAMETERS

The default values used by the SCIRC tool to calculate resource costs were gathered from government and industry sources indicative for the mid-western United States (EIA, 2018; EPA, 2018; MWEA, 2018; Boesler, 2013; Jiang, 2011). In some cases, default data (presented in Appendix I and II) were derived from a combination of cost estimates from other projected resource needs. In areas of the country where costs vary significantly from the mid-western values, the user can and should substitute local prices for the default values in the "Costs" tab.

Calculated results from the SCIRIC tool are validated against real-world data published in after-action reports following the F-5 tornado that devastated Joplin, Missouri on 22 May 2011. Facility costs were generally taken directly from published project reports, although some of the infrastructure elements available in the SCIRIC tool are distinct from cost categories in the published reports. In these cases, cost data are either derived or taken from state or federal reports for labor costs or from alternate published sources, such as construction bids and agency websites. Table 6 lists the facilities along with the references from where the data has been extracted for validation. Standard construction bids include a 20% cost overrun in their cost markup. Because of this, a relative error range of ±20% is used as the acceptable error range. This goodness of fit incorporates industry practice and existing protocols for cost analysis (U.S. GAO, 2009).

Table 6. A list of references used to validate different infrastructure elements

Facilities Affected	**References**
Hospital Facilities	"Mercy Joplin Quick Facts." Mercy. Accessed July 22, 2018. https://www.mercy.net/newsroom/mercy-hospital-joplin-quick-facts/.
High Schools	"Filter Projects." DLR Group. Accessed July 22, 2018. http://www.dlrgroup.com/work/joplin-high-school/.
Elementary Schools	"Soaring Heights Elementary School." Hollis Miller. Accessed July 22, 2018. https://www.hollisandmiller.com/portfolio-posts/soaring-heights-elementary-school/.
Middle Schools	"East Middle School." Hollis Miller. Accessed July 22, 2018. https://www.hollisandmiller.com/portfolio-posts/east-middle-school/.

Table 6. A list of references used to validate different infrastructure elements (Continued)

Fire Stations	"Commercial Cost Estimate." Commercial Construction Cost Calculator. Accessed July 22, 2018. http://www.buildingjournal.com/commercial-estimating.html.
Warehouse	"International Warehouse/Logistics Center Costs." Compass International. Accessed July 22, 2018. https://www.compassinternational.net/international-warehouse-logistics-center-costs/.
Police Stations	"Commercial Cost Estimate." Commercial Construction Cost Calculator. Accessed July 22, 2018. http://www.buildingjournal.com/commercial-estimating.html.
Wired Networks	"Knowledge Resources." RITA | ITS | Costs: Unit Cost Components for Fiber Optic Cable Installation. Accessed July 22, 2018. https://www.itscosts.its.dot.gov/its/benecost.nsf/DisplayRUCByUnitCostElementUnadjusted?ReadForm&UnitCostElement=Fiber Optic Cable Installation &Subsystem=Roadside Telecommunications.
Railway Networks	"2017 Railroad Engineering & Construction Costs." Compass International. Accessed July 22, 2018. https://www.compassinternational.net/railroad-engineering-construction-cost-benchmarks/.
Traffic Signals	Harper, Jennifer. "MoDOT Traffic Division." E-mail. July 18, 2018.
Street Lights	"Lindon City Street Lights Questions And Answers." PDF file. Accessed July 22 2018. https://siterepository.s3.amazonaws.com/00442201006240906424493.pdf.

8. DISCUSSION

The SCIRC tool extends industry cost estimating tools in several ways. It is specifically designed to consider interdependencies and includes ratios that calculate how changes in one system or sub-system results in changes in other systems. It provides a holistic analytical capability to map the level of resources and manpower required to restore damaged systems. This integrated approach allows a unique mechanism for considering the cost-benefit of full restoration and can be used to determine whether rebuild or new construction options are the best choice.

SCIRC provides the user with the information about the amount of resources required to restore one or multiple facilities. The user can input the number occurrences of each infrastructure element that needs to be restored after an extreme event and the software calculates the amount of resources required for restoration. Quantifying the extent of damage caused by a disaster is crucial to restoration planning. This tool can be applied to a region affected by a disaster. Based on the severity of the disaster, the extent of damage to various infrastructure elements can be analyzed. If a hundred thousand square feet of a hospital, five miles of an interstate and hundred traffic signals are destroyed due to a tornado, the user can input the values for these destroyed infrastructures in the SCIRC tool and calculate the amount of resources that will be required to restore these infrastructures. The SCIRC provides a macro level view of the amount of resources required to restore an entire infrastructure network. The tool also provides information regarding the number of man-hours required to carry out restoration activities. This information can be used to calculate the number of personnel required for carrying out restoration operations and is useful in quantifying the amount of resources that would be required by the restoration crews while performing restoration operations. City planners and policy makers can use this tool for budgeting and prioritizing post-disaster operations. Organizations overseeing restoration efforts and budget planning can use this tool to devise efficient disaster restoration strategies. Although the SCIRC tool can be used to calculate the direct costs associated with restoring different infrastructure elements, it is not very helpful for calculating the indirect costs accrued after one or multiple infrastructures are damaged due to an extreme event.

The software is flexible, it can be used to calculate the amount of resources required to restore multiple infrastructure elements and has the ability to be applied to different regions. Whereas most tools are specific to a single infrastructure, the SCIRC calculates the resources required for construction of multiple infrastructure elements of multiple types as required by a restoration scenario. A limitation of this software is that additional infrastructure elements cannot be added to the tool. Also, this tool lacks a feature to automatically update the value of costs based on different regions. However, the factors and costs can be manually updated by an individual based on their expertise and knowledge. The future work will allow the user to automatically update the value of costs by selecting the geographic region. Ultimately it would be possible to link the SCIRC tool with a GIS framework such as The National Map in order to calculate the amount of resources required to restore infrastructure elements by selecting a specific area on the map on a near-real time basis.

9. SUMMARY

The SCIRC calculates the amount of resources required to restore one or more infrastructure elements after failure. The software calculates the total amount of resources required to restore one or more occurrences for each selected infrastructure element along with the cost of each resource. The SCIRC can calculate results for thirty different infrastructure elements (Table 1). The SCIRC calculates costs based upon a standardized average base for the country, but the user can tailor cost to a specific region by inputting the cost data manually. A unique contribution of the SCIRC is the ability to account for the resources required by restoration crews as well as the material resources necessary to restore the entire infrastructure network. The output from this software can be used by city planners and policy makers to devise efficient strategies for post-disaster restoration operations.

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III. BOTTOM-UP RESOURCE AND COST ESTIMATION FOR RESTORATION OF INTERDEPENDENT CRITICAL INFRASTRUCTURE

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ABSTRACT

Extreme events can damage or destroy multiple supply chain interdependent critical infrastructures elements. Although much research has focused on developing efficient restoration strategies, and/or making critical infrastructures more resilient, there remains a need to adequately address the resources necessary to restore such damage. The methodology developed in this research estimates both the resources required to support the repair personnel, and restore different infrastructure elements. This method uses a dynamic mathematical model that establishes a framework to estimate post-disaster restoration costs from a whole system perspective. This model is validated with a case study of the resources required to restore multiple infrastructures that were damaged by the EF-5 tornado that struck Joplin, Missouri on May 22, 2011. Engineering managers, city planners, and policy makers can use the methodologies developed in this research to develop effective disaster planning schemas and to prioritize post-disaster restoration operations.

Keywords: Bottom-up Cost Estimation, Critical Infrastructures, Disaster Restoration, Resource Estimation

1. INTRODUCTION

In the aftermath of an extreme event, significant elements of critical infrastructure will be damaged or destroyed. The long term effect of this destruction on the area and its economy will depend on the rapidity of the restoration of these infrastructure elements. A key factor in the rapid restoration of infrastructure is planning the allocation and availability of needed resources. This research develops a dynamic mathematical model that is used to create an algorithm capable of estimating the resources necessary to restore a wide range of infrastructure elements following an extreme event. The algorithm has been coded into a Supply Chain Infrastructure Resource Calculator (SCIRC) that is available for public use.

Unlike traditional approaches, the algorithm developed for this research estimates both the resources required to restore damaged or destroyed infrastructure elements as well as the resources required to support the crew performing the restoration activities. Three categories of resources are considered as part of the dynamic mathematical model. These resources are necessary for reconstructing infrastructure elements, these are: construction resources (power, fuel, storage area, man-hours, and materials), crew needs (power, fuel, potable water, and food), and waste materials (gray water, solid waste, and black water). For example, the power and fuel resources are required for operating construction processes as well as for supporting the crew in the affected area where they are performing restoration activities. Demands for fuel and power must also include a fuel estimate also requires getting the crew to and from the work site each day and a power estimate for crew support during the restoration timespan (e.g. heating or cooling, food storage, and such).

According to the Department of Homeland Security (DHS) (DHS, 2018), the incapacitation or destruction of the nation's critical infrastructures will have a debilitating effect on the national security, national economy, and national public health or safety, or any combination. Disaster management and restoration research largely ha modeled the effect of an extreme event on a single infrastructure, however in a disaster, many critical infrastructure systems are damaged or destroyed. The frequency of extreme weather events has been increasing globally (European Academies' Science Advisory Council, 2018), and many researchers, government organizations and independent agencies have focused their attention in developing models that would help create efficient restoration strategies, and/or make critical infrastructures more resilient (Zhang, Kong, & Simonovic, 2018; Lin, & Wang, 2017; Mackenzie & Zobel, 2016; Ramachandran, Long, Shoberg, Corns, & Carlo, 2016; 2015a ; 2015b; Arab et al., 2015; Liu, Li, Zio, & Kang, 2014). Studies on post-disaster infrastructure restoration can generally be classified as belonging to one of seven broad categories:

(i) the economic effects of a disaster (Cho, Gordon, Moore II, Richardson, Shinozuka, & Chang, 2001; Ham, Kim, & Boyce, 2005),

(ii) techniques to make infrastructure more resilient, facilitating a quicker restoration time line (Arab et al., 2015; Ramachandran et al., 2015b; Zhang, Kong, & Simonovic, 2018),

(iii) supplying relief goods and emergency rescue resources to the affected population (Tzeng, Cheng, & Huang, 2007; Widener & Horner, 2011; Yang, Zhou, Gao, & Liu, 2013; Horner & Downs, 2010; Van Hentenryck, Bent, & Coffrin, 2010),

(iv) evacuating people before and after a disaster from the affected area (El-Sergany, & Alam, 2012; Hu, Sheu, & Xiao, 2014; Lambert et al., 2013; Na, & Banerjee, 2015; Song & Yan, 2016),

(v) modeling restoration strategies after an extreme event (Lin, & Wang, 2017; Liu et al., 2014; Ramachandran et al., 2015a; 2016), and

(vi) effects of extreme events on mental health (McFarlane & Williams, 2012; North, 2014; Wilson-Genderson, Heid, & Pruchno, 2018).

These studies largely fail to address the resources required to restore infrastructure on a macro-level. In a macro-level view, multiple infrastructure elements are considered *en masse* and the resources required for restoration of all infrastructure elements are estimated as such. For example, the amount of resources required for restoring multiple damaged infrastructure systems throughout a city would constitute a macro-level view. Such an approach provides the city planners and policy makers with better estimates of the resources needed to devise efficient restoration strategies.

The open source SCIRC calculator based on the algorithm described in this study has been written in the Python 2.7 programming language and includes a wide variety of resources and infrastructure elements (described below). The output provided by the SCIRC calculator can be used by city planners, policy makers, and organizations performing restoration activities for budgeting and prioritizing post-disaster operations. The SCIRC calculator and user manual (Ojha, Kanwar, Long, Shoberg, & Corns, 2019) can be accessed at the federal government geospatial web site GeoPlatform (Geoplatform: Disasters, 2019) at the URL: https://communities.geoplatform.gov/disasters/supply-chain-infrastructure-restoration/. This model is validated by estimating the resources required to restore different infrastructures that were devastated by an EF-5 tornado in Joplin, Missouri on May 22, 2011. Figure 1 shows the path of the EF-5 tornado that devastated Joplin, Missouri on May 22, 2011. The aftermath of this tornado left 553 non-residential buildings, including a hospital, two fire stations, and ten local public schools as well as approximately 7500 residential buildings damaged or destroyed (Kuligowski, Lombardo, Phan, Levitan, and Jorgensen, 2014). Model estimates are then compared with the reported restoration resources used and the costs incurred. The threats posed by extreme events warrant the need for a framework that can estimate the amount of resources required to restore multiple infrastructure elements.

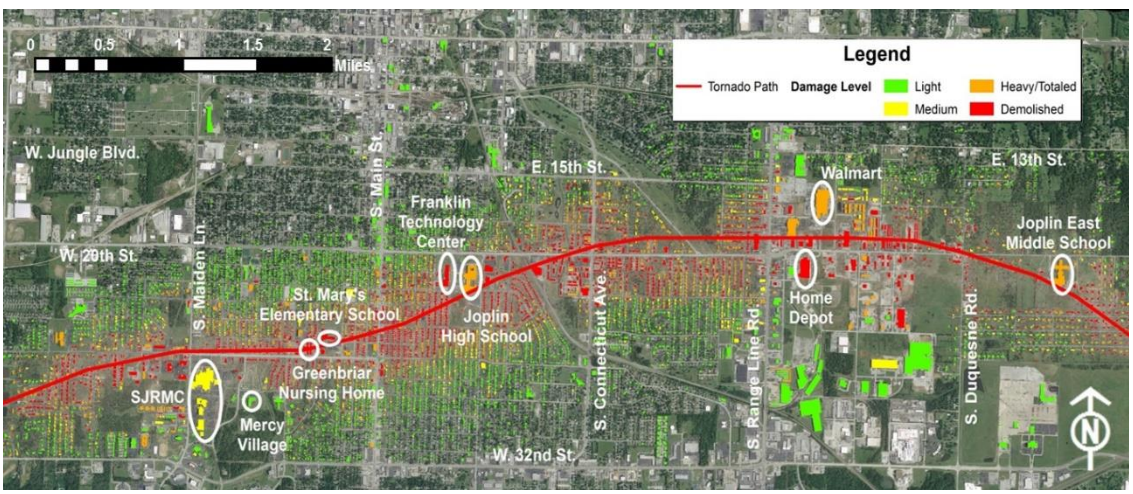

Figure 1. The tornado path for the EF-5 tornado that devastated Joplin, Missouri on May 22, 2011. The image is taken from Levitan, 2016

The methodology used for creating the mathematical framework, as well as the techniques used for data acquisition are discussed in the following section. The methodology has been applied to a case study, and the results and their validation are also presented. The implications of the developed model with respect to the engineering manager and future work is discussed in the final two sections of this paper.

2. METHODOLOGY

For this research, a bottom-up cost estimation technique is used to calculate the amount of resources required to build a given infrastructure. Thirty infrastructure elements are evaluated (Table 1) in this research. These elements belong to a wide range of critical infrastructure sectors and require a variety of construction processes. For instance, building a powerplant requires different construction processes than installing a street lamp. Each construction process uses its own set of equipment and materials. The thirty infrastructure elements selected in this research span different sectors including commercial facilities, communications, emergency services, energy, government facilities, health care and public health, information technology, transportation systems, and water and wastewater systems, and are considered sufficient to show the proof of concept as they include a wide variety of construction processes.

Table 1. A list of infrastructure elements along with the units in which their damage is measured

INFRASTRUCTURE ELEMENTS	**DESCRIPTION**	**UNITS**
Electrical Distribution	Electrical power lines to deliver electricity	Miles

Table 1. A list of infrastructure elements along with the units in which their damage is measured (Continued)

Coal Power Plant	Coal-based power plants for electrical generation	kW
Nuclear Power Plant	Nuclear-based power plants for electrical generation	kW
Water Distribution	A network of pipes used to distribute water for domestic and commercial use	miles
Water Purification	Water treatment plants to purify water	gal
Sewage Treatment	Wastewater treatment plants	gal
Warehouse	Warehouse to store goods, supplies and the likes.	sq. ft.
Wireless Towers	Cell towers in a cellular network	units
Wired Networks	Optical cable lines for fiber optic internet connection	miles
Communication Centers	Emergency response centers	sq. ft.
Hospital Facilities	Super specialty multi-bed healthcare facility	sq. ft.
Fire Stations	Facilities with fire engine, firefighters, and fire-retardant materials and equipment, and the likes.	sq. ft.
Police Stations	Facilities accommodating police personnel	sq. ft.
Railway Networks	Railway track lines to transport goods and ferry people	miles
Railway Bridges	Bridges used by railways to transport goods and passengers over roads, ravines, and the likes.	sq. ft.
Roadway Bridges	Bridges used by motor vehicles to transport goods and passengers over roads, rivers, and the likes.	sq. ft.
Elementary Schools	From kindergarten through grade 6	sq. ft.
Middle Schools	From grade 7 through grade 9	sq. ft.
High Schools	From grade 10 through grade 12	sq. ft.
Air Freight Facilities	Facilities to ship and receive air cargo	sq. ft.
Air Passenger Facilities	Domestic and International Airports	sq. ft.
Arterial Roads	Major and minor roads passing through a town/city	sq. ft.
Water Freight Facilities	Facilities to ship and receive cargo using riverboats and barges	sq. ft.
Interstates	Highways connecting two or more states	sq. ft.
Traffic Signals	Standard traffic signal poles	units
Street Lights	Standard street lighting poles	units
Rail Freight Facilities	Facilities to ship and receive cargo using railways	sq. ft.
Rail Passenger Facilities	Railway station to transport passengers	sq. ft.

2.1. MATHEMATICAL FRAMEWORK FOR THE MODEL

Since the construction processes vary with the type of infrastructure being restored, construction processes are analyzed independently for each infrastructure element. Using a bottom-up cost estimation technique, each construction process is analyzed and the amount of resources such as materials, power, fuel, man-hours, and storage area required, as well as the gray water, solid waste, and black water generated are estimated. After determining which materials are necessary for restoration, the cost of these materials can then be calculated. Each piece of equipment uses a given amount of power and/or fuel to perform its activity. The number of man-hours required to construct an infrastructure element can be used to calculate the amount of potable water and food required. For example, if a person drinks 0.2 gallons of water per hour and works for five hours, the total amount of potable water needed would be a gallon. Similarly, other resources are also calculated using a similar set of coefficients in a set of linear equations. Expert advice and historical data are used to determine these coefficients. Once the coefficients are estimated, the total cost of resources is calculated and compared with data available in the literature. The process described above for collecting data is represented in Figure 2.

To calculate the total amount of resources required to restore ‘x’ units of an infrastructure element, the number of units (x) of the infrastructure element to be restored was multiplied by the amount of resources required to restore one unit of that infrastructure element as shown in equation 1.

$$T_{ij} = x * R_{ij} \quad (1)$$

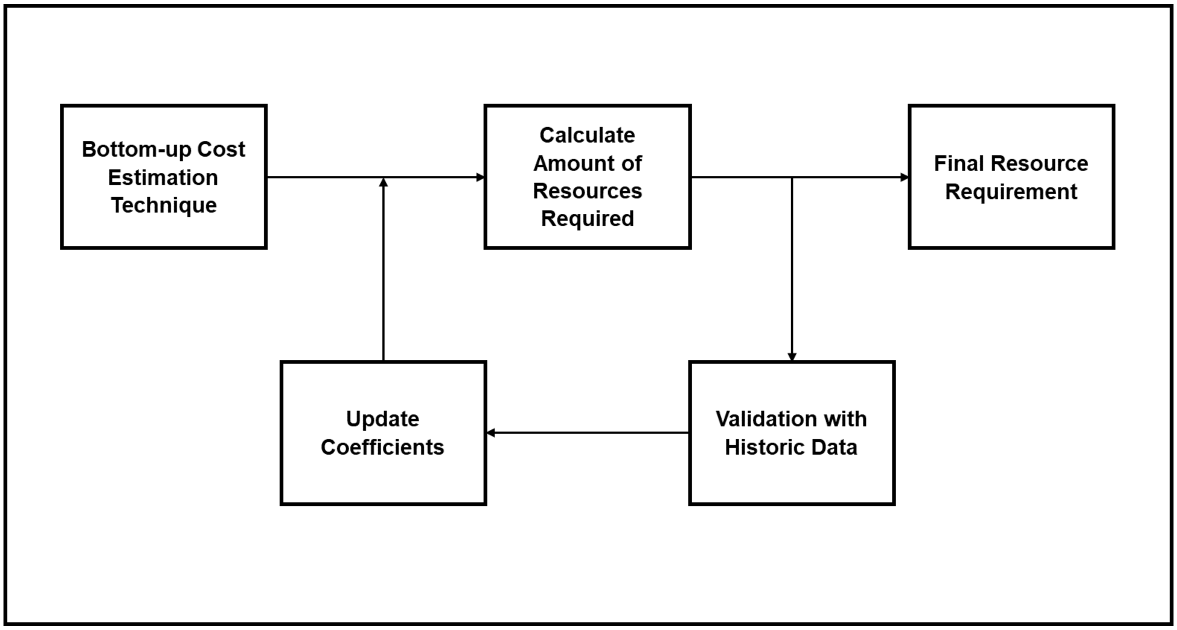

Figure 2. Algorithm for deriving the amount of resources required to restore one unit of an infrastructure element

here, T_{ij} refers to the amount of resource j required to restore x units of infrastructure element i and, R_{ij} refers to the amount of resource j required to restore one unit of infrastructure element i.

The total cost required to restore an infrastructure element i was calculated using equation 2.

$$(TC)_i = \sum_{j=1}^{10} (T_{ij} * C_j) \tag{2}$$

In equation (2), $(TC)_i$ refers to the total cost incurred to restore x units of infrastructure element i and, C_j refers to the cost of one unit of resource j.

The overall resources required to restore multiple facilities was calculated using equation (3).

$$OR_j = \sum_{i=1}^{30} T_{ij} \quad \forall\, j = 1,2,3, \ldots \ldots, 10 \tag{3}$$

In equation (3), OR_j refers to the amount of resource j required to restore multiple infrastructure elements included in the framework. Here, i goes from 1 to 30 which is the number of infrastructure elements, and j is the number of parameters associated with restoration resources.

The overall cost, denoted by OC, refers to the total cost that would be required to restore multiple facilities was calculated using equation (4).

$$OC = \sum_{i=1}^{30} (TC)_i \tag{4}$$

The mathematical model created calculates the amount of resources required to restore one unit of each infrastructure element. Note that the resources estimated in this model are for the reconstruction of the infrastructure elements only and not for their operation. These resources include:

1. Power (kiloWatts (kW) per unit of the infrastructure element): Electricity required to rebuild infrastructure elements.
2. Fuel (gallon per unit of the infrastructure element): Amount of gas needed to run power generator, tools, and construction equipment to build an infrastructure element.
3. Potable water (gallon per unit of the infrastructure element): Amount of clean drinkable water required by the restoration crew.

4. Storage area (square feet per unit of the infrastructure element): Storage space used by restoration crew to store materials, tools, and the likes.
5. Man-hours (hours per unit of the infrastructure element): Amount of labor hours required to rebuild an infrastructure element.
6. Gray water (gallon per unit of the infrastructure element): Amount of water generated by the crew while performing restoration activities.
7. Black water (gallon per unit of the infrastructure element): Amount of waste water containing human waste generated while performing restoration activities.
8. Solid waste (pound per unit of the infrastructure element): Amount of garbage and solid construction waste generated while performing restoration activities.
9. Food (pound per unit of the infrastructure element): Amount of food consumed by the restoration crew
10. Materials (U.S. Dollars per unit of the infrastructure element): Dollar amount of construction material required to construct respective facilities.

This research extends the work of Poreddy, Corns, Long, & Soylemezoglu (2016) with respect to how resources are defined and used as part of the restoration algorithm. As such, the amount of food, potable water, gray water, black water, and solid waste are dependent on the number of man-hours it takes to build one unit of an infrastructure element. The units for these resources are normalized per unit of the infrastructure element.

2.2. DATA FOR THE MODEL

Table 2 consists of the amount of resources required to restore one unit of an infrastructure element. The data for potable water, gray water, solid waste, food, and a portion of the power and fuel required for restoring the infrastructure elements are based on the man-hours required to restore the infrastructure elements. Storage area, materials, and the other portion of power and fuel are derived by analyzing the construction processes involved in reconstruction. The cost of materials, and labor-hours for building hospitals, high schools, middle schools, elementary schools, fire stations, police stations, and warehouses are derived from a square foot estimator tool (RSMeans, 2018). Cost of fuel, waste water treatment, potable water, and electricity were derived from several resources (United States Energy Information Administration (EIA), 2018; Environmental Protection Agency (EPA), 2018; Boesler, 2013; Ohio Environmental Protection Agency, 2010; Michigan Water Environment Association (MWEA), 2009). The costs used in this research is indicative of mid-western United States. The cost of resources varies depending on the geographic region, and hence must be changed while applying the framework to different regions.

2.3. SIGNIFICANCE OF THE SUPPLY CHAIN INFRASTRUCTURE RESTORATION CALCULATOR

The SCIRC software package (Geoplatform: Disasters, 2019) is based on the mathematical algorithm developed in this research. The resource requirement data for restoration derived in this research is used as the dataset input in the software. The supply chain infrastructure restoration calculator adds a significant contribution to the existing disaster restoration literature:

1. The combination of resources required to restore multiple infrastructure elements can be calculated using the restoration calculator.

Table 2. Amount of individual resources required per unit of restoration metric

Infrastructure Element	Power KW/ unit	Fuel gal/ unit	Potable Water gal/ unit	Storage square feet/unit	Man Hours hours/ unit	Gray Water gal/ unit	Black Water gal/ unit	Solid Waste lb/ unit	Food lb/ unit	Materials $/unit
Electric Distribution	4404.09	4079.79	72.92	15000	3500	3208.33	3500	700	583.33	145000
Coal Power Plant	7.14	3.58	0.0375	9.5	1.8	1.65	1.8	0.36	0.3	3200
Nuclear Power Plant	11.73	6.40	0.048	10	2.3	2.11	2.3	0.46	0.38	3800
Wind Farm	7.37	4.97	0.42	9	2	1.83	2	0.4	0.33	1500
Natural Gas Distribution	674.75	794.83	8.33	12500	400	366.67	400	80	66.67	70000
Water Distribution	574.75	494.83	8.33	5000	400	366.67	400	80	66.67	5000
Water Purification	0.32	0.27	0.002	1	0.1	0.092	0.1	0.02	0.017	2
Sewage Treatment	0.42	0.22	0.002	1.2	0.1	0.092	0.1	0.02	0.017	2
Warehouse	1.21	0.49	0.012	0.1	0.6	0.55	0.6	0.12	0.11	66.72
Wireless Towers	2394.95	658.97	1.67	500	80	73.33	80	16	13.33	184000
Wired Networks	2481.80	300.80	1.44	6000	68.92	63.18	68.92	13.78	11.49	10665.23
Communication Centers	1.32	1.16	0.019	0.5	0.9	0.825	0.9	0.18	0.15	92.97
Hospital Facilities	2.08	1.64	0.03	0.5	1.54	1.41	1.54	0.308	0.26	138.6

Table 2. Amount of individual resources required per unit of restoration metric (Continued)

Fire Stations	1.27	1.13	0.02	0.5	0.86	0.79	0.86	0.17	0.14	77.02
Police Stations	1.41	1.22	0.02	0.5	0.98	0.9	0.98	0.19	0.16	103.3
Railway Networks	4904.09	4079.79	80	15000	3500	3200	3500	715	580	1200000
Railway Bridges	0.66	0.69	0.009	1.319	0.469	0.429	0.469	0.094	0.078	972.22
Roadway Bridges	0.20	0.17	0.003	0.546	0.148	0.136	0.148	0.029	0.025	156.14
Elementary Schools	3.32	2.41	0.05	0.25	2.59	2.37	2.59	0.51	0.43	88.65
Middle Schools	3.28	2.38	0.05	0.25	2.55	2.33	2.55	0.51	0.42	114.49
High Schools	3.26	2.37	0.05	0.25	2.54	2.33	2.54	0.5	0.42	120.44
Air Transportation facility	4.37	8.97	0.042	1	2	1.83	2	0.4	0.33	75
Air Passenger Facilities	6.06	14.71	0.62	1.5	3	2.75	3	0.6	0.5	155
Arterial Roads	0.03	0.03	0.001	0.114	0.024	0.022	0.024	0.005	0.004	7.58
Water Freight Facilities	4.37	8.47	0.42	0.5	2	1.83	2	0.4	0.33	75
Interstates	0.03	0.03	0.001	0.094	0.02	0.018	0.02	0.004	0.003	14.04
Traffic Signals	78.41	83.17	0.94	75	45	41.25	45	9	7.5	34630
Street Lights	32.88	27.31	0.49	50	23.49	21.53	23.49	4.7	3.92	4572.3
Rail Freight Facilities	4.37	8.47	0.042	0.5	2	1.83	2	0.4	0.33	75
Rail Passenger Facilities	5.96	14.21	0.625	1	3	2.75	3	0.6	0.5	130

2. A subject matter expert with the knowledge of the outputs and inputs of different infrastructure elements can use the results from the mathematical model to understand the interdependencies between them. The output from the mathematical model provides a list of resources required for restoring a number of infrastructure elements. Subject matter experts can use this information to analyze which infrastructure produces resources that are the same as the resources required by another infrastructure for its restoration.

3. Unlike traditional models that study the economic effects of a disaster and calculate the economic losses associated with it, this model calculates the amount of resources required to restore various infrastructure elements along with the resources required by the restoration crew to perform the restoration operations.

4. Data can be modified in the calculator based on the expertise and knowledge of the user as well as the geographic region under consideration.

5. The results from the calculator can be used to develop efficient resource allocation resources. The output of the model provides the amount of resources required to restore different infrastructure elements. City planners and engineering managers can use this information to prioritize the sequence of restoration of different infrastructure elements based on the availability of the resources and the criticality of the infrastructure.

The lack of readily available input data, which serves as the basis for how costs and allocations are generated, serves as a challenge for the implementation of the mathematical model. Therefore, much of the required data must be derived from other sources.

3. CASE STUDY: MAY 22, 2011 TORNADO IN JOPLIN, MISSOURI

This section describes a case study that includes a brief overview of the study area, a list of infrastructures that were damaged due to a tornado, results from the model and validation of the results.

The costs calculated using the model developed in this research were compared with the data from the case study. The data used for validation in the case study is derived from published reports, construction bids, and agency websites. Table 3 lists the infrastructure elements and the sources from where the data was derived for the case study. The data used as the input in the mathematical model is independent from the data used in the case study for validation.

The study area chosen is Joplin, Missouri which was devastated by an EF-5 tornado on May 22, 2011. According to the U.S. Census Bureau (2010), the population of Joplin at the time was estimated to be 50,150. Joplin is located in the southwest corner of Missouri and is a commercial, medical, and cultural hub for this region (Kuligowski et al., 2014). The destruction caused by the tornado not only affected the people from Joplin but also the population living in the surrounding region. The tornado's path through Joplin was up to 1 mile wide and 6 miles long and was on the ground for approximately 15 minutes (Kuligowski et al., 2014). An estimated 20,820 people were directly impacted by the tornado (U.S. Census Bureau, 2011). The tornado caused 161 fatalities and more than 1,000 injuries, and damaged or destroyed 553 business and approximately 7500 residential structures (Kuligowski et al., 2014). The list of damaged structures included one major hospital (St. John's Regional Medical Center), ten schools out of which six schools (Joplin

High School, Joplin East Middle School, Franklin Technology center, Irwing Elementary School, St. Mary’s Catholic Elementary School, and Emerson Elementary School) were severely damaged, two fire stations (No. 2 and No. 4), Duquesne police station, a large number of commercial facilities, traffic signals, street lights, and wired networks (Kuligowski et al., 2014). These infrastructure elements are used to validate the mathematical model.

Table 3 lists the infrastructure elements affected, their scale, the cost of damaged facilities, the calculated costs using the mathematical model, the percentage cost difference between the costs Joplin and those calculated from the mathematical model, and the sources from where the data was derived for the case study. The overhead expenses such as architectural fees, contractor fees, legal fees, advertising, and profits are not calculated in this model. It is important to note that the resources that are calculated are those resources required for the construction of the infrastructure elements and not their operation. An average hourly wage of $30 is assumed for the labor costs.

3.1. VALIDATION

Figure 3 is a graphical representation of the calculated costs and actual costs compared in Table 3. Calculated costs estimate the cost of rebuilding the infrastructure element and, as such, does not include the equipment and furniture used in these infrastructure elements. For example, the costs of medical equipment such as X-ray machines, MRI machine, beds, and other medical equipment are not included in the cost of rebuilding a hospital.

Table 3. Comparison of costs calculated from the mathematical model versus case study data. Number of units of infrastructure element affected, and the actual cost of construction for these select infrastructure elements are derived from: Hospital Facilities (Mercy, 2015); High School (DLR Group,2014); Elementary School (Hollis & Miller, 2018a); Middle School (Hollis & Miller, 2018b); Fire Station (Commercial Construction Cost Calculator, 2009a); Warehouse (Compass International, 2016); Police Station (Commercial Construction Cost Calculator, 2009); Wired Networks (United States Department of Transportation, 2018); Traffic Signals (Harper, 2018); Street Lights (Amazon AWS Lindon City Street Lights Questions And Answers , 2008)

Infrastructure Elements Affected	**Unit of Infrastructure Elements Affected**	**Actual Cost, $**	**SCIRC Cost, $**	**Percentage Cost Difference**
Hospital[1]	900,000 sq. ft.	168,000,000	172,000,000	2%
High School[2]	487,000 sq. ft.	89,740,786	100,000,000	11%
Elementary School[3]	66,500 sq. ft.	10,800,000	12,000,000	11%
Middle School[4]	125,800 sq. ft.	24,320,000	25,000,000	3%
Fire Station[5]	7,500 sq. ft.	755,108	800,000	6%
Warehouse[6]	10,000 sq. ft.	880,000	870,000	-1%
Police Station[7]	5,000 sq. ft.	567,286	680,000	19%
Wired Networks[8]	1 mile	16,632	17,000	2%
Traffic Signals[9]	1 each	32,760	36,000	10%
Street Lights[10]	1 each	5,200	5,400	4%

The costs calculated using the model developed in this research fall within a relative error range of less than ±20% which is acceptable according to the industry practices and existing protocols for cost analysis (U.S. GAO, 2009). Table 3 lists the percentage costs differences between the calculated costs and the costs from the published materials. The reason behind the cost estimates obtained from the model being higher than the actual costs (with the minor exception of warehouses) can be attributed to the inclusion of resource requirements to support the personnel. Other contributing factors leading to the differences in the costs are the efficiency as well as the type of equipment, and the hourly wages paid to personnel by different contractors performing the construction processes.

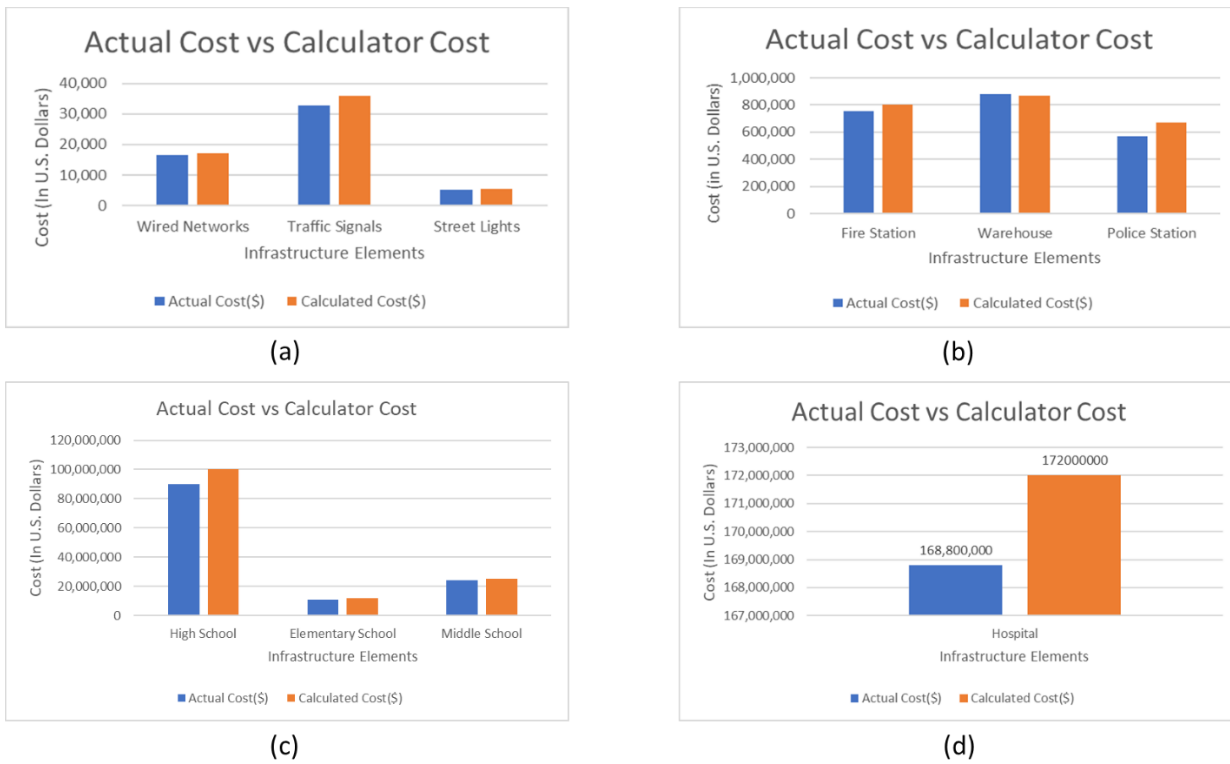

Figure 3. Comparison of costs (orange) estimated by the model with data from the case study (blue). Graph (a) compares costs for wired networks, traffic signals, and street lights. Graph (b) compares costs for the fire station, warehouse and police station. Graph (c) compares costs for high school, elementary school, and middle school. Graph (d) compares the cost for hospital

4. IMPLICATIONS FOR THE ENGINEERING MANAGER

This research presents a model that estimates the amount of resources necessary to restore multiple infrastructure elements. While a substantial amount of research has been done in understanding the long-term economic effects of a disaster (Cho et al., 2001; Ham et al., 2005; Tirasirichai & Enke, 2007; Ojha, Corns, Shoberg, Qin, & Long, 2018) and allocation of resources for rescue operations (Mackenzie & Zobel, 2016; Yang et al., 2013), methodologies for determining the amount of resources required to restore large-scale critical infrastructure systems are less well explored. The SCIRC tool created from the algorithms presented here can be very useful in such explorations. To develop the model presented in this research, a bottom-up cost estimation technique was used to derive data for the amount of resources required for restoration. Unlike traditional models in the literature, this research involved multiple infrastructure elements whose interconnectivity is essential for the effective functioning of modern society. The tool was written in Python programming language and the software (Geoplatform: Disasters, 2019) along with the user manual (Ojha et al., 2019) can be accessed at the URL https://communities.geoplatform.gov/disasters/supply-chain-infrastructure-restoration/. The user can input the number of units of the particular infrastructure damaged to calculate the resources required to restore it. For instance, if the user inputs the destruction of a hundred thousand square feet of a hospital, ten miles of arterial roads and hundred street lights due to a tornado, then the SCIRC tool will calculate the amount of resources required for restoration.

Most conventional cost estimation tools can only be applied to specific infrastructure elements to estimate the cost of construction. The SCIRC software tool can be used to calculate the cost as well as the amount of resources required to restore multiple infrastructure elements. The SCIRC tool developed in this study has a limited number of infrastructure elements (30), but additional elements can be added to the tool following the same methodology. Also, the user can manually update the values of factors and costs based on their knowledge and expertise (Ojha et al., 2019). In addition to providing a macro-level view of the amount of resources required, it also provides estimates on the number of man-hours required for restoration. This information can further be used to suggest the number of personnel needed to perform the activities. Thus, the SCIRC tool can be used by city planners and policy makers to prepare budget estimates and prioritize operations after a disaster. Engineering managers can use their knowledge about the outputs produced by each infrastructure and combine it with the results (amount of resources required to restore several infrastructure elements) obtained from the model to prioritize infrastructure restoration efforts. For example, the engineering manager can opt to restore the electrical power lines supplying electricity to the warehouse before restoring the warehouse itself to minimize fuel costs required to power the on-site generators. This model will be helpful to visualize the resource requirement before beginning the restoration process.

5. FUTURE WORK

This model is a first step in developing a framework to automatically integrate resource requirement data for multiple infrastructure elements in real-time. There are several avenues open for future work. The model can be further developed to estimate the amount of resources required to restore a portion of the infrastructure rather than the entire infrastructure. For instance, if only the roof of a warehouse is damaged, the model can be further developed to calculate the amount of resources required to repair the roof of the warehouse. This can be achieved by including all the construction processes in the model that are involved in the construction of an infrastructure. The type of crew, equipment and material can also be categorized based on the construction process included in the model. The crew and equipment can be allocated to different infrastructures based on the construction phase. This way, maximum utilization can be achieved with limited resources. Including different crew types in the model will also help to get better estimates of cost as the hourly wage will be based on the type of the crew.

The interdependent nature of the critical infrastructures means that the services provided by one infrastructure may be required by another infrastructure for its effective functioning. For an infrastructure element to be fully operable, the infrastructure element it is dependent upon should be able to provide the required services. The model developed in this research can be further extended by including the average amount of time it takes to complete each construction process. This feature can be used to calculate the amount of time required to restore an entire infrastructure element.

The SCIRC software can be further developed to connect with a GIS framework such as The National Map of the U.S. Geological Survey. The idea of linking the software with a GIS framework is to let the user click on infrastructure elements on the map to estimate the amount of resources required for restoring that infrastructure in near-real time. For this, the model will need to be further developed to update the costs of resources based on the geographic location.

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SECTION

2. CONCLUSIONS AND FUTURE WORK

The conclusion of this dissertation along with potential avenues for future work are discussed in this chapter. The main objective of this dissertation was to develop analytical tools for minimizing the economic losses associated with a disruption in transportation network and estimate the resources required for restoring different infrastructure elements. Results from this dissertation can help policy makers and city planners to devise efficient restoration strategies and prioritize budgeting for post-disaster operations.

One of the contributions developed a framework to model the emergent behavior during a disruption in the transportation system and minimize the indirect costs associated with rerouting of vehicles. The increased travel costs, travel time, reduced speed for traffic flow on alternate routes and traffic congestion were identified as the emergent behavior within the transportation system due to a disruption in one or more road segments. A system dynamics approach was used to identify and analyze different factors that affect the available road capacity, and map the interdependencies between these factors. This model was applied to a steady state representation of the eastbound traffic flow present at the Eads bridge over the Mississippi River in St. Louis at any particular point in time. The model developed was used to understand how the traffic pattern evolved after a disruption in the transportation network. The change in the available road capacity of the alternate routes when vehicles were rerouted onto them was observed. The model can also be used to identify the possible junctions where an increase in the traffic count may lead to congestion. The research developed a model that can better assist transport planners and practitioners to prioritize the order in which different sections of the transportation network should be repaired in order to minimize the overall indirect costs associated with rerouting due to the extra time and distance a vehicle must travel.

The other important contribution of this research was developing the supply chain infrastructure restoration calculator (SCIRC) to estimate the amount of resources required to restore different infrastructure elements. The SCIRC tool was written in python programming language. A bottom-up cost estimation technique was used to gather construction data for each infrastructure element. The resources considered for restoring an infrastructure element were (i) power, fuel, storage area, man-hours, and materials required for construction of the infrastructure element, (ii) potable water and fuel required by the restoration crew, and (iii) gray water, solid waste and black water generated by the restoration crew. Unlike most conventional cost estimation tools, the SCIRC tool is not limited to a single infrastructure and can be used to calculate the resources required to restore multiple infrastructure elements. Multiple infrastructures were included in the SCIRC tool as several infrastructure elements can be damaged based on the severity of the disaster. The model developed is flexible and can be applied to different geographic regions. To validate the model, the results from the model were compared with the data gathered from reports after the devastation caused by the EF-5 tornado in Joplin, Missouri on May 22, 2011. The costs calculated using this model fall within a relative error range of less than ±20% which is considered acceptable according to the industry practices and existing protocols for cost analysis (U.S. GAO, 2009). City planners, policy makers and organizations carrying out disaster restoration operations can use this model to estimate the amount of resources required to restore the entire infrastructure network. They can also use this tool to devise efficient disaster restoration strategies and prioritize post-disaster restoration operations.

The model to minimize the transportation indirect costs associated with a disruption in the transportation network can be further developed by introducing human behavior effects to determine the driver's route choice. An approach similar to this model, can be used to identify different factors that make other critical infrastructures inoperable. A causal loop diagram, similar to the one used in this research, can be used to map the interdependencies between different factors that can render an infrastructure inoperable and understand the emergent behavior that may arise out of the complex system.

Future work for the SCIRC tool will include updating the cost of resources automatically by selecting the geographic region. The SCIRC tool can be further developed to link with a GIS framework such as The National Map of the U.S. Geological Survey to let the user click on the infrastructure elements on the map and estimate the amount of resources required in near-real time. This will be of a great help to the organizations and the agencies carrying out the post-disaster restoration activities.

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APPENDIX A.

DEFAULT PARAMETERS FOR FACILITY FACTORS (PER UNIT OF RESTORATION METRICS)

Table A: Default parameters for Facility factors (per unit of restoration metric)

Facility	Power KW/ unit	Fuel gal/ unit	Potable Water gal/ unit	Storage square feet/unit	Man Hours hours/ unit	Gray Water gal/ unit	Black Water gal/ unit	Solid Waste lb/ unit	Food lb/ unit	Mater ials $/unit
Electric Distribution	250	1500	72.92	15000	3500	3208.33	3500	700	583.33	1450 00
Coal Power Plant	5	2.25	0.0375	9.5	1.8	1.65	1.8	0.36	0.3	3200
Nuclear Power Plant	9	4.7	0.048	10	2.3	2.11	2.3	0.46	0.38	3800
Wind Farm	5	3.5	0.42	9	2	1.83	2	0.4	0.33	1500
Natural Gas Distribution	200	500	8.33	12500	400	366.67	400	80	66.67	7000 0
Water Distribution	100	200	8.33	5000	400	366.67	400	80	66.67	5000
Water Purification	0.2	0.2	0.002	1	0.1	0.092	0.1	0.02	0.017	2
Sewage Treatment	0.3	0.15	0.002	1.2	0.1	0.092	0.1	0.02	0.017	2
Warehouse	0.5	0.05	0.012	0.1	0.6	0.55	0.6	0.12	0.11	66.72
Wireless Towers	2300	600	1.67	500	80	73.33	80	16	13.33	1840 00
Wired Networks	2400	250	1.44	6000	68.92	63.18	68.92	13.78	11.49	1066 5.23
Communication Centers	0.25	0.5	0.019	0.5	0.9	0.825	0.9	0.18	0.15	92.97

Table A: Default parameters for Facility factors (per unit of restoration metric) (Continued)

Hospital Facilities	0.25	0.5	0.03	0.5	1.54	1.41	1.54	0.308	0.26	138.6
Fire Stations	0.25	0.5	0.02	0.5	0.86	0.79	0.86	0.17	0.14	77.02
Police Stations	0.25	0.5	0.02	0.5	0.98	0.9	0.98	0.19	0.16	103.3
Railway Networks	750	1500	80	15000	3500	3200	3500	715	580	1200000
Railway Bridges	0.104	0.34	0.009	1.319	0.469	0.429	0.469	0.094	0.078	972.22
Roadway Bridges	0.022	0.063	0.003	0.546	0.148	0.136	0.148	0.029	0.025	156.14
Elementary Schools	0.25	0.5	0.05	0.25	2.59	2.37	2.59	0.51	0.43	88.65
Middle Schools	0.25	0.5	0.05	0.25	2.55	2.33	2.55	0.51	0.42	114.49
High Schools	0.25	0.5	0.05	0.25	2.54	2.33	2.54	0.5	0.42	120.44
Air Transportation facility	2	7.5	0.042	1	2	1.83	2	0.4	0.33	75
Air Passenger Facilities	2.5	12.5	0.62	1.5	3	2.75	3	0.6	0.5	155
Arterial Roads	0.003	0.014	0.001	0.114	0.024	0.022	0.024	0.005	0.004	7.58
Water Freight Facilities	2	7	0.42	0.5	2	1.83	2	0.4	0.33	75
Interstates	0.003	0.012	0.001	0.094	0.02	0.018	0.02	0.004	0.003	14.04
Traffic Signals	25	50	0.94	75	45	41.25	45	9	7.5	34630

Table A: Default parameters for Facility factors (per unit of restoration metric) (Continued)

Street Lights	5	10	0.49	50	23.49	21.53	23.49	4.7	3.92	4572.3
Rail Passenger Facilities	2.4	12	0.625	1	3	2.75	3	0.6	0.5	130

APPENDIX B.

DEFAULT COSTS (MIDWESTERN SCALE) FOR RESTORATION ACTIVITIES

Table B: Default costs (Midwestern scale) for restoration activities

Facility	Units	Costs
Power	$/Kw	0.097
Fuel	$/gal	2.781
Potable Water	$/gal	0.004
Storage Area	$/sq. ft.	0.5
Man-Hours	$/hr	30.0
Gray Water	$/gal	0.003
Black Water	$/gal	0.005
Solid Waste	$/lb	0.002
Food	$/lb	3.0

VITA

Akhilesh Ojha was born in Chandigarh, India. He finished his schooling from Chandigarh, and graduated from Panjab University, India with a Bachelor's of Engineering in Biotechnology and Master of Business Administration Degree in Marketing and Finance. He started his Master's degree in Engineering Management at Missouri University of Science and Technology (Rolla) in August 2013 and graduated in December 2014. He began his PhD program in Engineering Management at the Missouri University of Science and Technology in August, 2015. Akhilesh Ojha received his PhD in Engineering Management from Missouri University of Science and Technology in May, 2019. His research interest areas included Disaster Restoration, Supply Chain Management, Operations Research and Marketing. He was a student member of AAG, ISERC, and ASEM. He was a teaching assistant for the courses Operations Management Science, and Managing Engineering and Technology and an instructor for Supply Chain Management systems. Akhilesh also held a Graduate Research Assistant under Dr. Suzanna Long where he worked on quantifying restoration costs in the aftermath of an extreme event using system dynamics and dynamic mathematical modeling approaches, and quantifying economic benefits of investment in railroad projects.