Development of a Civil Infrastructure Resilience Assessment Framework

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ABSTRACT: Recent disruptive events, such as earthquakes or floods, have caused severe damage to civil infrastructural systems. Thus, there is a need to extend the focus of traditional design practices to consider resilience-based design approaches which can help in defining preventive actions and measures to mitigate the consequences caused by such disruptive events. This paper presents a Civil Infrastructure Resilience Assessment Framework (CIRAF) to assess the seismic fragility and resilience of a single or interconnected civil infrastructural systems following a disruptive event. Once the information regarding the infrastructural system, hazards, fragility databases, components' damage state correlation, recovery models, and upgrade models are identified, then the framework can be used to quantify the loss of functionality, recovery time, repair cost, and overall resilience following an extreme event. Bayesian models are used to evaluate the probability of failure of a system, which consists of layers of sub-systems and components. A state-of-the-art engineering tool is also developed using the framework that would enable the stakeholders to compare different upgrade strategies through an easy to use web interface and thus easing the decision-making process. A simplified infrastructural system consisting of 3 components is illustrated in this paper using the CIRAF framework.

1. INTRODUCTION

Disasters arising from natural hazards, conflicts, and man-made events have impacted communities worldwide. It is almost virtually impossible to prevent the damage arising from these unpredictable threats. Some examples of the tragic incidents that have happened in the recent past are the 2011 Fukushima-Daiichi Disaster, 2005 Hurricane Katrina, and 2017 Bangladesh Floods. These events have shown that communities are vulnerable to extreme events and they not only affects lives but also cause severe damage to the civil infrastructure. Current building design codes primarily focuses on minimizing the loss of lives and do not give much importance to disaster resilience – the ability of the system to recover from a catastrophic event (*Almufti et al.*, 2013). To understand resilience of a civil infrastructural system, it is necessary to understand how the failure or decrease of functionality impacts the performance of the system. Therefore, there is a need to extend the focus of traditional design practices to include resilience-based design techniques which can help in defining preventive actions and measures to mitigate their effect.

In recent decades, considerable efforts have been made to develop a framework to quantify resilience of a civil infrastructural system. These studies have leveraged various techniques to perform vulnerability analysis, correlation of interconnected components, loss estimation, and performance analysis. For example, *Ruiying et al*. (2017), *Kilanitis et al*. (2018) and *Tokgoz et al*.

(2013) have focused on sampling-based techniques such as Monte Carlo simulations, to evaluate the vulnerability or demand values in the event of a particular disaster. *Chang et al*. (2007) have used Matrix-based System Reliability methods to compute system reliability whereas *Gehl et al*. (2016) and *Bensi et al*. (2015) have presented a novel way of correlating components' fragility in an infrastructural system using Bayesian methods. These Bayesian methods are useful in describing the structural and functional relationship and can also be used to compare systems-of-systems (e.g. network of hospitals within a city).

Quantification of direct and indirect losses are critical while assessing resilience. The direct and indirect losses, however, are highly dependent on the type of infrastructural system. For example, *Kilanitis et al*. (2018) focused on traffic flow losses in transportation system while in a hospital network, *Cimellaro et al*. (2010b) have expressed losses as a function of the health of a population before and after the event. In an ideal scenario, a framework should be able to accommodate all different types of losses. In reality, though, it is not practically possible to define every possible losses quantitatively. Thus, some parameters have to be neglected to make the model more straightforward and computationally efficient.

In this research, an attempt has been made to develop a generic framework and open-ended tool that can be applied to most of the civil infrastructural systems by using Bayesian networks, fragility curves, etc. The broader vision to provide owners and stakeholders with a framework to implement Resilience-Based Design beyond Standard Code-Based Design for enhancing the capacity of the community to withstand and recover from a catastrophic event.

The following sections in the paper summarize the proposed methodology, a case study, conclusions and future work.

2. METHODOLOGY

The seismic fragility and resilience assessment of an infrastructural system in CIRAF consists of several steps including 1) definition of the system and hazards, 2) modelling of the infrastructural components, 3) creation of fragility database, 4) determining recovery and upgrade models, 5) understanding correlation between different components of the infrastructure, 6) estimation of losses, and 7) analysis of performance indicators as shown in Figure 1.

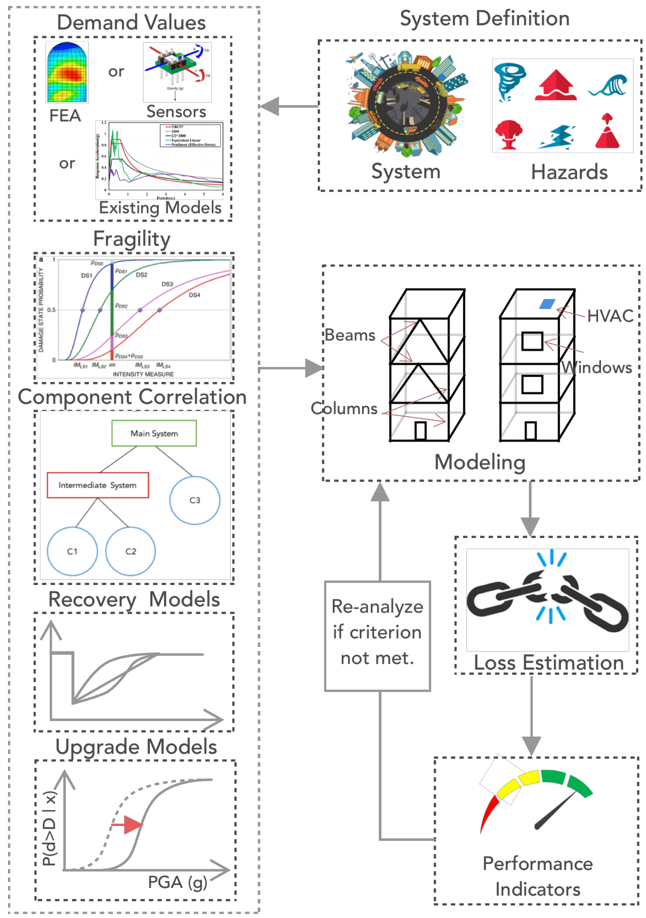

Figure 1 Workflow of Civil infrastructure Resilience Assessment Framework (CIRAF)

2.1. System & Hazard Definition

This involves modelling of the infrastructure system, and investigation of the potential hazards. A system can be spatially distributed also known as a system of systems or a single system comprising of multiple structural and non-structural components. A transportation network consisting of roads and bridges can be modelled as a system of systems while a bridge consisting of piers, abutments, etc. as components can be modelled as a single infrastructural system. Most systems consist of thousands of components, and only those components should be defined which are of extreme importance to the performance of the overall system. Potential hazards (e.g., earthquake, or floods) are dependent on various factors such as the location of the infrastructure, type of construction, etc.

2.2. Infrastructural Component Modelling

2.2.1. Fragility Database

Fragility curves defines the relationship between an intensity of hazard and probability of reaching a predefined limit states. Many literature, such as *Cimellaro et al*., 2010b and *Gehl et al*., 2016, among many others present seismic fragility functions. In this study a database of fragility functions are compiled based on available seismic fragility functions in *Cover et al.* (1983) and *HAZUS-MH 2.1* (2003).

2.2.2. Recovery Models

Bruneau et al. (2006) adopted recovery models in the form of linear, exponential, and cosine functions (Eq. (1) to (3)) to simulate recovery at the component level. But these functions could not represent the case where restoration does not always increase linearly or exponentially with time. For example, in the transportation system, damages to the roads may result in complete loss of traffic flow (*Kilanitis et al.,* 2018) and could only be functional once they have fully recovered. To account for this case, step recovery function ($f_{rec(E,C,S,L)}$) was included as shown in Eq. (4).

$$f_{recL}(t) = \left(1 - \frac{t - t_{0E}}{T_{RE}}\right) \quad (1)$$

$$f_{recE}(t) = exp\left[-(t - t_{0E}) * \frac{ln200}{T_{RE}}\right] \quad (2)$$

$$f_{recC}(t) = 0.5 * \left\{1 + cos\left[\frac{\pi(t - t_{0E})}{T_{RE}}\right]\right\} \quad (3)$$

$$f_{recS}(t) = \begin{cases} 0, & t_{0E} \leq t < T_{RE} \\ 1, & t \geq T_{RE} \end{cases} \quad (4)$$

where, T_{RE} is the repair time, and t_{0E} is the time at which extreme event occurs.

2.2.3. Upgrade Models

To compare different configurations of the system, retrofitting/upgrade models are defined characterized by two parameters namely, *Upgrade Factor (UF),* and *Upgrade Cost Ratio (UCR)*. UCR is defined as the ratio of the additional investment made on the component to the original cost of the component. UF reflects the decrease of probability of failure after the component is upgraded. Thus, UF has an effect of shifting fragility curves towards the right (*Bruneau et al.*, 2006) as shown in Figure 2.

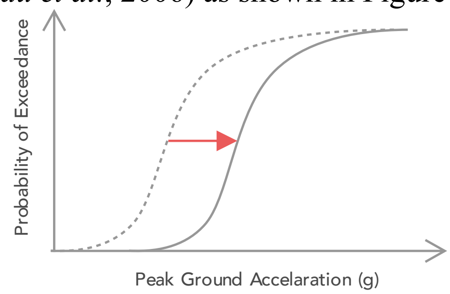

Figure 2 Shift in fragility curve after upgrade

2.2.4. Components Fragility Correlation

In recent years, there has been extensive research done to correlate fragilities of multiple components within an infrastructural system. Some of these techniques are system specific (*Tokgoz et al.*, 2013), and their applicability to a system of systems is very limited. Methods like typical Fault Tree/Event Tree analysis, Matrix-based System Reliability (MSR) methods (*Chang et al*., 2007), Bayesian Methods *(Gehl et al.*, 2016) are getting popular as they provide a generic framework to relate different components in an infrastructural system. For example, large infrastructural system consisting of roads, hospitals, power plants can be easily modelled using Bayesian networks *(Gehl et al*., 2016).

This study leverages the Bayesian network as the underlying framework to model the probabilistic dependence of components and sub-systems in a system. A system is defined as the collection of components or other systems (also known as sub-systems), each having multiple states. The fragility curve determines the state probabilities of each damage state of the component whereas states (failure modes) of the sub-system or system are defined by the experts/analysts performing the analysis, and the state probabilities are calculated using the Bayesian network. For example, consider a pumping system consisting of a pump, pipe, and voltage gear (VG). Possible failure modes that can be defined for the pumping system are *Failure Mode(FM)* 1 (System with 100% flow capacity), *Failure Mode* 2 (System with reduced flow capacity), and *Failure Mode* 3 (System with no flow capacity). Table 1 gives an example of Conditional Probability Table (CPT) that associates different damage states of the pump, pipe, voltage gear, and the failure modes of the pumping system. In this example, every component in this example is assumed to have two damage states each represented by 0 and 1, where 0 mean no damage(intact) and 1 means complete damage.

In the implementation in CIRAF, the system consists of component nodes, sub-system nodes, and system nodes in the Bayesian networks. To allow the capability of combining multiple Bayesian networks, there is an additional type of node, known as the transferred node. This is helpful in splitting the complex network in smaller sub-networks in order to ease the computational and memory requirement.

Table 1 CPT for Pumping System

Pump	Pipe	VG	FM 1	FM 2	FM 3
0	0	0	1	0	0
0	0	1	0	0	1
0	1	0	0	1	0
0	1	1	0	0	1
1	0	0	0	0	1
1	0	1	0	0	1
1	1	0	0	0	1
1	1	1	0	0	1

2.3. Loss Estimation

Losses incurred after the disaster are uncertain and vastly depend on the type of infrastructural system. Therefore, only losses arising from the physical damage were considered in this study at the component level and were calculated using Eq. (5) (*Cimellaro et al*., 2010):

$$L_i = \sum_{j=0}^{m} P_{i,j} * D_{i,j} \quad (5)$$

where, L_i loss factor for the component i; $P_{i,j}$ probability of failure for the component i in damage state j; $D_{i,j}$ damage ratio of the component i in damage state j; m number of damage states of the component i.

After the component has experienced some damage or losses, it is assumed to start recovering immediately defined by one of the equations in Eq. (1) to (4). Using the recovered functionality at the later time step, new failure probabilities of a component are back-calculated using the fragility curves of the component. These failure probabilities are necessary to calculate losses and functionality at the system and sub-system level at the later time step using Bayesian network. Figure 3 shows the procedure to evaluate losses at $t > t_0$.

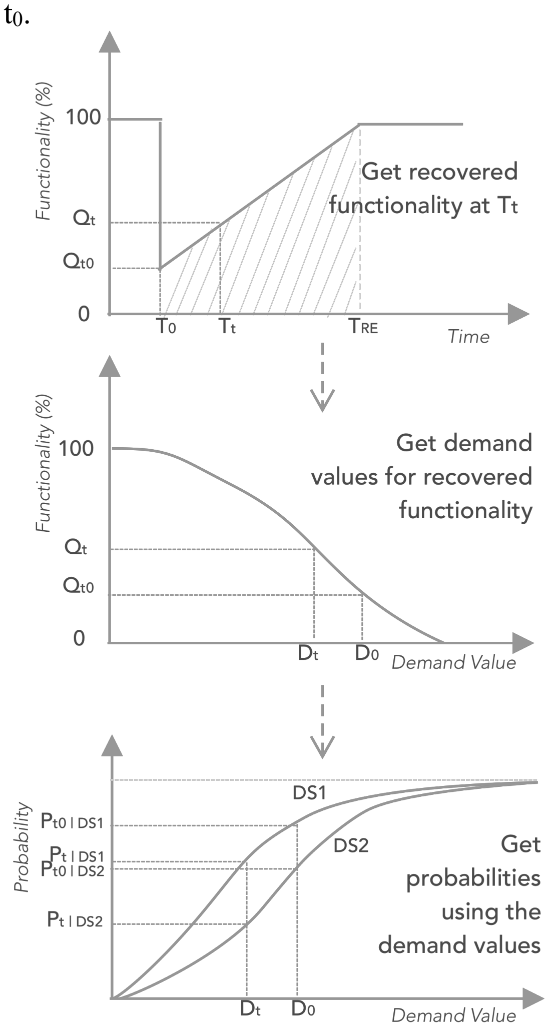

Figure 3 Flow for calculating losses at the component level for $t > t_0$

Evaluation of losses at the component level is straightforward but at the system level, the evaluation of losses is complicated due to the complex arrangement of components within a system. Consider an example of a system consisting of two components having m_{c1} and m_{c2} damage states. Two failure modes have been defined for this system whose conditional probabilities for different combination of damage states are established using a conditional probability table (CPT). For this system, loss function for the k^{th} failure mode can be expressed through the following equation:

$$L_{sys,k} = \sum_{i=0}^{m_{c1}} \sum_{j=0}^{m_{c2}} CP_{k\mid c1i,c2j} \,.\, P_{c1,i} P_{c2,j} (w_{c1} DR_{c1,i} + w_{c2} DR_{c2,j}) \tag{6}$$

where, $L_{sys,k}$ is the loss function of the k^{th} failure mode of the system comprising of components c1 and c2; $CP_{k\mid c1i,c2j}$ is the conditional probability of failure mode k when c1 and c2 are in damage states i and j respectively; $P_{cx,a}$ is the probability of component cx to be in damage state a; $DR_{cx,a}$ is the damage ratio of the component cx associated with damage state a; w_{cx} is the weight factor of the component cx calculated by taking average of the replacement cost of all the components that comprises the system with the component cx. The probability of two damage states of two different components occurring at the same time is assumed to be an independent event given the fact that the demand values for those components are determined independently through finite element analysis or by a user. Once the probabilities (P_k, where $k = [1,2]$) for each of the two failure modes are evaluated using Bayesian inference, then the final loss value for the system can be calculated as follows:

$$L_{sys} = \sum_{k=1}^{2} L_{sys,k} \,.\, P_k \tag{7}$$

Equations (6) to (7) describe the loss function for only a two-component system, but in reality, a system would be consisting of more than 2 components. To generalize the loss function (**$\mathbf{L_{sys}}$**) at the system level, a matrix formulation has been defined. (*Singhal*, 2018).

2.4. Performance Indicators

2.4.1. Resilience

Resilience (R) was defined at the component and system level in terms of the functionality (Q). The mathematical formulation was adopted from *Cimellaro et al*., (2010) as shown in Equations (8) to (9). It is defined as a function of recovery model ($frec_i$), and loss function (L_i) calculated using Equations (1) to (6). Thereafter, Resilience (R) can be calculated using Eq. (9). After the extreme event, functionality is assumed to drop suddenly at time (t_o) having a value ranging from 0 to 100%, where 100 means no reduction in performance of the infrastructure after the disaster and 0 means complete loss of performance.

$$Q_i(t) = \{1 - L_i\,[H(t - t_o) - H(t - (t_o + Tre_i))]\} \cdot frec_i \tag{8}$$

$$R_i = \frac{1}{T_{LC}} \int_{t_0}^{t_0 + Tre_i} Q_i(t) \cdot dt \tag{9}$$

2.4.2. Repair Time

Repair time (Tre_i) for an individual component (i) can be calculated using the Eq. (10).

$$Tre_i = \sum_{j=0}^{m} P_{i,j} * Tre_{i,j} \tag{10}$$

where $P_{i,j}$ probability of failure of component i in damage state j; $Tre_{i,j}$ repair time of component i in damage state j. Repair time at the system level is defined as the maximum recovery time of components as shown in Eq. (11).

$$Tre_{sys} = \max(Tre_1, Tre_2, Tre_3 \ldots\ldots Tre_n) \tag{11}$$

2.4.3. Repair Cost

Repair Cost(RC_i) are calculated by multiplying loss function(L_i) with the replacement cost(I_i) of the component. At the sub-system and system level, Repair Cost(RC_{sys}) is calculated as shown by the Eq. (12):

$$RC_{sys} = L_{sys} \sum_{i=1}^{n} I_i \tag{12}$$

2.4.4. Upgrade Benefit Index (UBI)

Upgrade Benefit Index reflects the benefit of upgrading a component on the overall system. Mathematically, UBI can be defined by the Eq. (13) (*Wang et al*., 2010). Its value ranges from 0 to 1, where 0 signifies no prominent effect on the functionality of the system upon upgrading the component.

$$UBI_i = \frac{Q_{upgraded\ Ci} - Q_{sys}}{1 - Q_{sys}} \quad (13)$$

where, $Q_{upgraded\ Ci}$ is the changed functionality of system after upgrading Component i, Q_{sys} is the functionality of the system before upgrading the Component i.

2.4.5. Damage Consequence Index (DCI)

Damage Consequence index reflects the consequence on the overall system when a specific component gets fully damaged or loses its complete functionality. This metric has been adopted from *Wang et al*. (2010) and is represented by Eq. (14). DCI also ranges from 0 to 1 where 0 mean no effect of full damage on the functionality of the overall system and 1 means severe consequences on upon complete failure of that component.

$$DCI_i = \frac{Q_{sys} - Q_{sys\,|\,Ci\ has\ failed}}{Q_{sys}} \quad (14)$$

where, DCI_i is the Damage Consequence Index of component i, Q_{sys} is the functionality of the system before assuming complete failure of component i , $Q_{sys\,|\,Ci\ has\ failed}$ is the functionality of system after assuming complete failure of component i.

3. CASE STUDY

In this section, a simplified hypothetical pumping system was used to illustrate the mathematical basis of the framework.

3.1. Component Details

The layout of the components (pump, pipe and two-story 3-dimensional portal frame) are shown in Figure 4.

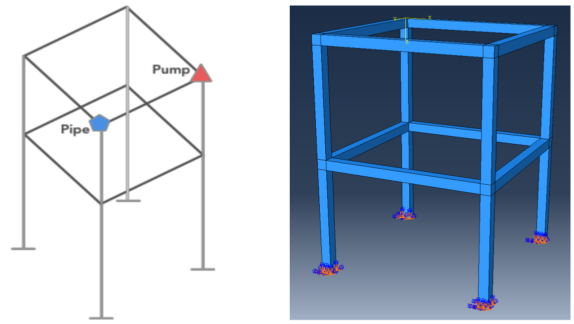

Figure 4 Structural layout of pumping system

The north-south (NS) component of the El-Centro earthquake was considered as the hazard for the assessment. The portal frame was assumed to be made of eight columns and eight beams and does not have any other complex geometrical properties. The density, Young's Modulus, and Poisson's Ratio are assumed to be 8,050 kg/m^3, 200 GPa and 0.3 respectively. The structural characteristics of the pump and the pipe (shown as point object) are not explicitly defined as they were treated as non-structural component and hence, were not considered in the finite element analysis.

The analysis results consisting of nodal values of acceleration, velocities, and displacements were imported to CIRAF from ABAQUS. The demand values for the pump and the pipe were arbitrary assumed to be 1.5 g and 1.2 g respectively. Drift ratio was evaluated for all the steps, and the one with the maximum absolute value was used as the demand value for the two-story frame. The estimated value of drift ratio is 0.026 rad. Readers can refer to *Singhal* (2018) for more detailed calculations.

3.2. Fragility Curves

The demand parameters used for the fragility functions are *Acceleration* and *Storey Drift Ratio* and their fragility definitions have been adopted from FEMA (2012). The portal frame and pipe have 5 defined damage states while the pump has 2 damage states. The first damage state for each of the component is *Intact* where no damage has been considered. The other set of damage states range from *slight* to *complete* damage.

3.3. Recovery & Upgrade Models

Exponential, linear, and cosine recovery functions were assumed for pump, pipe, and frame respectively. The upgrade factors are also summarized in Table 2.

Table 2 Summary of Recovery and Upgrade Models

Name	**Recovery Model**	**Upgrade Factor**	**Upgrade Cost Ratio**
Pump	Exponential	10	2.0
Pipe	Linear	10	3.0
Frame	Cosine	20	1.5

3.4. Component Fragility Correlation

The damage states of these components were correlated to form two other systems. The components pump and pipe were combined to form a sub-system node called *Intermediate System* (IS). The Intermediate System is again combined with the two-story frame structure to form a system node called *Main System* (MS). The layout consisting of all three component nodes and two system nodes is shown in Figure 5. The IS and MS have 2 and 3 failure modes respectively and their state dependency has been summarized in Table 3. The losses, functionality, etc. were calculated using a Bayesian network using Eqs. (7) to (11) and the results are summarized in the next section.

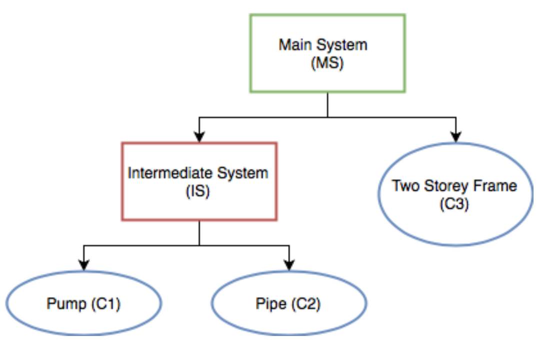

Figure 5 Layout Consisting of Three Component Nodes and Two System Nodes

Table 3 Failure Modes and State Dependency of IS and MS Nodes

States	**IS**	**MS**
Failure Mode 1 ($\boldsymbol{FM_1}$)	Intact State ($DS_{pump} = 1$ and $DS_{pipe} <= 3$)	Intact State ($DS_{IS} = 1$ and $DS_{frame} = 1$)
Failure Mode 2 ($\boldsymbol{FM_2}$)	Failure State ($DS_{pump} = 2$ and DS_{pipe} is any)	Partial State ($DS_{IS} = 1$ and $1 < DS_{frame} < 5$)
Failure Mode 3 ($\boldsymbol{FM_3}$)	-	Complete State ($DS_{IS} = 2$ and DS_{frame} is any)

3.5. Results

The pumping system was analyzed for two different configurations. (1) No components Upgraded (*As-built*), (2) With Upgraded Pump. These upgrades are assumed fictitious for the demonstration purposes but can be properly quantified when used in a real-life infrastructural system. Table 4 summarizes the Resilience(R) and Functionality(Q) for the 2 analysis cases mentioned above.

Table 4 Pumping System results comparison

Components	**As-Built Case**		**Upgrade Case I**	
	Q (%)	**R (%)**	**Q (%)**	**R (%)**
Pump	59.9	98.7	100.0	100.0
Pipe	76.3	98.9	76.3	98.9
Portal Frame	100.0	100.0	100.0	100.0
Intermediate System	80.8	96	96.9	99.8
Main System	96.8	99.9	99.7	99.9

4. CONCLUSIONS

This paper presents an open-ended framework and a state-of-the-art visualization and decision supporting a tool to assess seismic fragility and resilience of civil infrastructure. It can be used to quantify and analyze various performance indicators such as resilience, functionality, repair time, repair cost, upgrade benefit index, etc. and ultimately help decision makers to analyze the impact of future disruptive events. It would enable them to build better policies to mitigate the risk and improve the recovery process. Some of the main assumptions that were made: (1) Only physical structural damages were considered, (2) Recovery of systems and sub-systems are evaluated by taking in account the recovery of the components/sub-system comprising them and is considered to be a function of damage states of the fragility curves. As a part of future work, the methodology outlined here can be refined in many ways such as, (1) Ability to define and assess recovery of the component at the damage state level whereas in reality some damage states may have more or less recovery time than others, (2) Improving the computational efficiency of the Bayesian network by leveraging parallel processing, (3) Expanding the scope of loss estimation by considering flow-based, human loss, and other socio-economic losses.

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