# UILLIS: Urban Infrastructure and Lifelines Interactions of Systems

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**SUMMARY:**
The study develops a rigorous multi-hazard methodology for the evaluation of the reliability associated with multistate damage of infrastructure systems subjected to various hazards. The hazards can be considered as statistically dependent, independent or mutually exclusive. By simulating multi-hazard effects as common cause failure (CCF) groups, an efficient, multistate, two-terminal, reliability method is developed for multi-hazard reliability analysis of an infrastructure network. The study then proposes a novel methodology for interdependency analysis among the complex systems incorporated into a new software package, UILLIS (Urban Infrastructure and Lifelines Interactions of Systems). A case study of a hypothetical infrastructure is performed to illustrate the advantages of the package in multi-hazard, interdependent reliability evaluation of a real-life system with multistate components.

*Keywords: Multi-hazard reliability, system interdependent reliability, lifeline infrastructures*

## 1. INTRODUCTION

Recently, reliability analysis of lifeline components and networks against natural and technological hazards has been increasingly reviewed for their capacity to address multi-hazard vulnerability and robustness under a wide variety of technological and natural hazards, including earthquake, wind, flood, freezing, landslide, power outage, fire and hazardous material release. In the past decades, tremendous research efforts have been expended in assessing reliability and performance of infrastructure networks generally under a single catastrophic event, but there are only minor researches presenting a multi-hazard model at this time. A multi-hazard approach represents a convenient way to address system reliability of an infrastructure system.

The hazard-resilience of a community depends crucially on the post-disaster of urban infrastructure networks. Today's networks are becoming increasingly dependent on one another. Diverse infrastructures such as water supply, transportation, and telecommunication and energy supply systems are coupled together. Damage to public infrastructure such as transportations, telecommunications, and power networks may also disrupt private supply chains and limit production and exports, as well as hindering production in other countries. Supply chain systems may be quite interdependent, as demonstrated after the 2011 Tohoku Earthquake and tsunami in Japan, which disrupted production lines across several countries. Fig. 1 illustrates the effects of this disaster on supply chain disruption (ChainLink Research & ImpactFactor, 2011).

In this study, we first propose a multi-hazard methodology capable of evaluating the reliability associated with multistate damage of infrastructure systems subject to various hazards. Then, we develop a new probabilistic method for interdependency analysis among the complex infrastructure networks. Finally, we present a recently developed computer package (UILLIS - Urban Infrastructure and Lifeline Interactions of Systems) that can integrate the analysis.

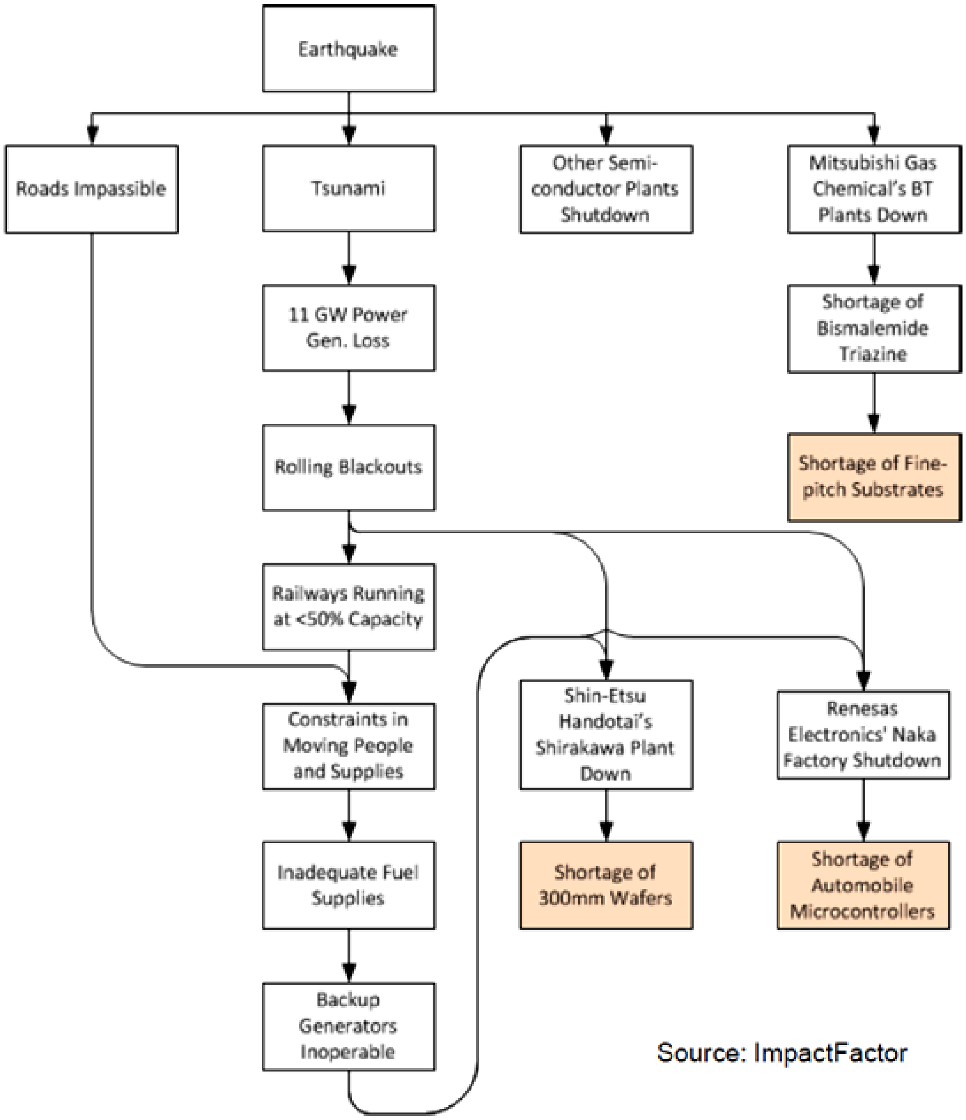


**Figure 1.** Effects of infrastructure failures on supply chain disruptions (ChainLink Research & ImpactFactor, 2011)

## 2. MULTISTATE CAPACITATED RELIABILITY MODEL

The reliability model proposed in this study is an extension of the multistate minimal path method for two-terminal reliability of networks previously developed by the authors (Javanbarg et al. 2009a). Multistate two-terminal reliability at a certain demand level can be defined as the probability that the system capacity generated by multistate components is greater than or equal to a specified certain demand. The proposed model takes into account the multistate nature of both the network and its components. For a network consists of *n* nodes with known source node *s*, demand node *t*, and flow level *j* from *s* to *t*, the capacitated two-terminal reliability can be computed as in the following steps:

- Step 1: For the demand (terminal) node *t*, obtain the node incident links and its respective capacity vectors and the capacity combination vectors at demand level *j*.
- Step 2: Enumerate each combination of node incident capacity vectors obtained in step 1 from 1 to *n*. Each combination yields a new network with new requirements to be fulfilled. If $n=0$, then reliability at level *j*, $R(j)=0$. Demand at level *j* cannot be fulfilled.

- Step 3: For each combination create a new network updating the terminal node. For every *n* repeat the step 1.
- Step 4: Repeat the algorithm from terminal to source.

## 3. MULTI-HAZARD RELIABILITY MODEL

The multi-hazard reliability model used in this paper is based on a common cause failure model previously proposed by the authors (Javanbarg et al. 2009b). Common cause failures are frequently associated with natural and technical disasters such as earthquake, wind, flood, freezing, landslide, power outage, fire and hazardous material release. Such an event can cause simultaneous failures of the network components. The components of a network may have statistically independent (*s*-independent) failure but which are also subject to common cause failures from both technical and natural hazards.

Consider the following general assumptions: 1) The components of a network can be subjected to a set of $m$ elementary common cause events $E = \{E_1, E_2, ..., E_m\}$ ; 2). Different common cause $E$ may occur *s*-independently, mutually exclusively, or *s*-dependently. The $m$ common cause $E$ divides networks into the following $2^m$ disjoint sub-networks $CCE$ , in which mutually exclusive events can occur in the network, $CCE_1 = \overline{E}_1 \cap \overline{E}_2 \cap ... \cap \overline{E}_m$ , $CCE_2 = E_1 \cap \overline{E}_2 \cap ... \cap \overline{E}_m$ , $CCE_{2^m} = E_1 \cap E_2 \cap ... \cap E_m$ . Therefore, a common cause set $\Omega_{CCE} = \{CCE_1, CCE_2, ..., CCE_m\}$ can be constructed. If the occurrence probability of each $CCE_j$ is denoted as $\Pr(CCE_j)$ , then we have $\sum_{j=1}^{2^m} \Pr(CCE_j) = 1$ and $CCE_i \cap CCE_j = \phi$ for any $i \neq j$ . In general lifeline networks are distributed over a wide geographical area. Therefore the order of magnitude for external hazard $E$ may not be the same for all parts of the system, and various components will in general experience different intensities of hazard. Considering the common cause set $\Omega_{CCE}$ and the Total Probability Theorem, the probability of failure of network $P_F$ , can be obtained:

$$P_F = \sum_{i=1}^{2^m} \left[ \Pr(F | CCE_i) \bullet \Pr(CCE_i) \right] \tag{3.1}$$

where $\Pr(CCE_j)$ is the occurrence probability of each common cause event $CCE_i$ , and $\Pr(F | CCE_i)$ is the conditional probability that the network fails conditioned on the occurrence of $CCE_i$ . Constructing the reduced network related to each $CCE_i$ (e.g. network components of set $E_i$ have been deleted from the network); the conditional probability $\Pr(F | CCE_i)$ can be considered as unconditional probability that the reduced network functions. The network reliability for each of the reduced networks can be evaluated by available reliability methods. Once the overall probability of failure $P_F$ is calculated, the reliability of network could be evaluated as $R_N = 1 - P_F$ .

## 4. INTERDEPENDENT RELIABILITY MODEL

For evaluation of the interdependent reliability of a system, we have applied the same model for multi-hazard reliability analysis based on CCF and the Total Probability Theorem proposed in the previous section. The only difference is that in case of multi-hazard reliability, the external causes can be either technical or natural hazard, meanwhile, for interdependent reliability; the external cause could be failure effects of other interconnected systems triggering cascading failure in one system.

It may be helpful to explain the interdependency model by applying it to interdependent reliability analysis of a hypothetical network. A model with three interconnected networks is presented in Fig. 2. The figure exemplifies a situation in which an earthquake (common cause failure) may cause simultaneous failures of several components in each network. Initial failure of each component in one network may lead to an iterative cascade of failures that cause the three networks to become fragmented.

We are interested in evaluating the multistate capacitated reliability of a transportation network conditioned on seismic failure effects in both power and communication networks. For the sake of simplicity, suppose that the failure in power and communication networks is *s*-independent. Also assume that we have calculated the reliability of power and communication networks under seismic condition. This is to say, we have the probability of failure of power and communication networks as $P_p = 0.5117$ and $P_c = 0.0989$, respectively. Considering failure effects of power and communication networks as the external common cause failure, a set including four common cause events $\Omega_{CCE} = (CCE_1, CCE_2, CCE_3, CCE_4)$ can be constructed and the transportation network can be divided into four reduced network as presented in Fig. 3. In network $N_1$, the components of the transportation network are only subject to independent failure caused by the earthquake. This would be the $CCE_1$. In network $N_2$, nodes $t_3$ and $t_7$ are additionally subject to power failure ($CCE_2$). Failure effect of communication may also cause links 8 and 9, and node $t_7$ fail in network $N_3$ ($CCE_3$). The, network $N_4$ includes the effects of both power and communication failures ($CCE_4$). Using model discussed in section 2, we can easily evaluate multistate capacitated reliability of networks $N_1$ through $N_4$. Having reliability of node $t_9$, conditional probability $\Pr(F|CCE_i)$ which the network fails conditioned on the occurrence of each $CCE_i$ can be evaluated. Table 4.1 presents the reliability of node $t_9$ for different demand level *j* in each reduced transportation network.

Assuming that power and communication systems fail statistically independent, the probability of occurrence of each $CCE_i$ can be calculated as follows:

- $\Pr(CCE_1) = (1 - P_p)(1 - P_c) = 0.440$
- $\Pr(CCE_2) = P_p(1 - P_c) = 0.461$
- $\Pr(CCE_3) = (1 - P_p)P_c = 0.482$
- $\Pr(CCE_4) = P_p P_c$

Therefore, the overall probability of failure $P_F$ for transportation network is calculated using Eqn. 4.1. Finally, the interdependent reliability of transportation network for different demand level could be evaluated. Fig. 4 illustrates both the system reliability and interdependent system reliability of node $t_9$ for different demand level.

## 5. UILLIS

Based on the methods developed in this study, we have prepared a computer package, UILLIS, with a graphical user interface (GUI) that can integrate the analysis. Fig. 5 depicts a snapshot of the main window of the package which is prepared for working with maps and graphs. Several tools for drawing nodes and links of a new network have been provided. Different type of data formats including spread sheets such as excel can be imported into window as the input for defining a reliability model. Four modules for performing different tasks related to system reliability evaluation have been implemented. First module can perform a connectivity analysis of network which can consider both unreliable nodes and links using minimal path method. Second module is able to perform a reliability evaluation of large-scale network using Monte Carlo technique. Third module is beneficial to multistate capacitated reliability of the network using a multistate minimal path method. Last module applies to both multi-hazard and interdependent reliability analyses.

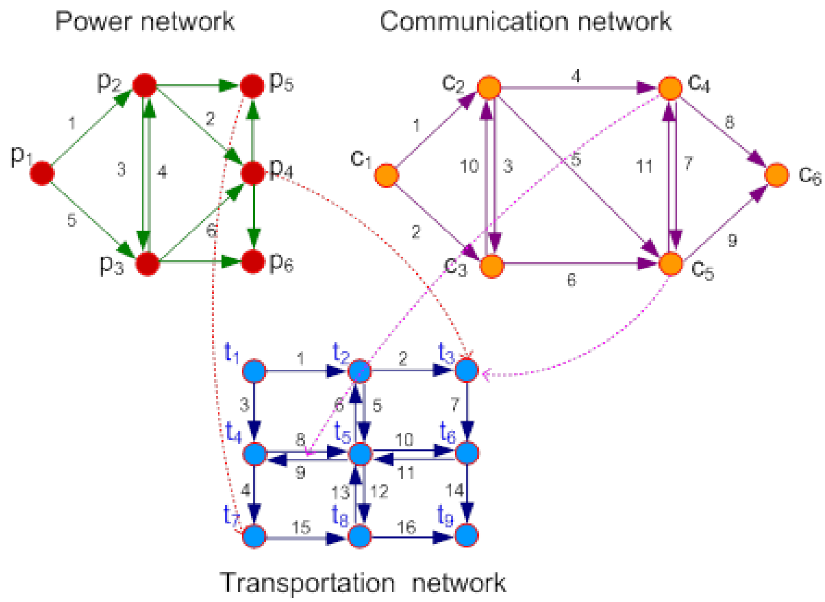


**Figure 2.** Interdependent networks

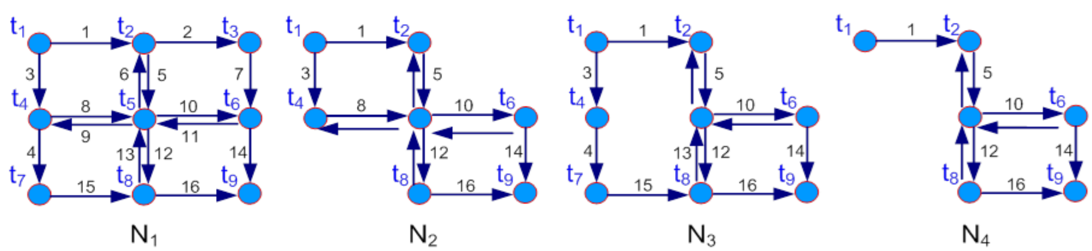


**Figure 3.** Reduced transportation networks resulting from failures in power and communication networks

**Table 4.1**. Multistate capacitated reliability of node $t_9$ reduced transportation networks

| Demand | Reliability ($R_{t9}$) – $N_1$ | Reliability ($R_{t9}$) – $N_2$ | Reliability ($R_{t9}$) – $N_3$ | Reliability ($Rt_9$) – $N_4$ |
|---|---|---|---|---|
| 0 | 1 | 1 | 1 | 1 |
| 1 | 0.9990 | 0.9807 | 0.9799 | 0.9700 |
| 2 | 0.9890 | 0.9314 | 0.9269 | 0.8512 |
| 3 | 0.9490 | 0.8158 | 0.8109 | 0.6589 |
| 4 | 0.8770 | 0.5429 | 0.6151 | 0.3521 |
| 5 | 0.7100 | 0.0 | 0.3743 | 0.0 |
| 6 | 0.5260 | 0.0 | 0.1702 | 0.0 |
| 7 | 0.2600 | 0.0 | 0.0365 | 0.0 |
| 8 | 0.0870 | 0.0 | 0.0017 | 0.0 |

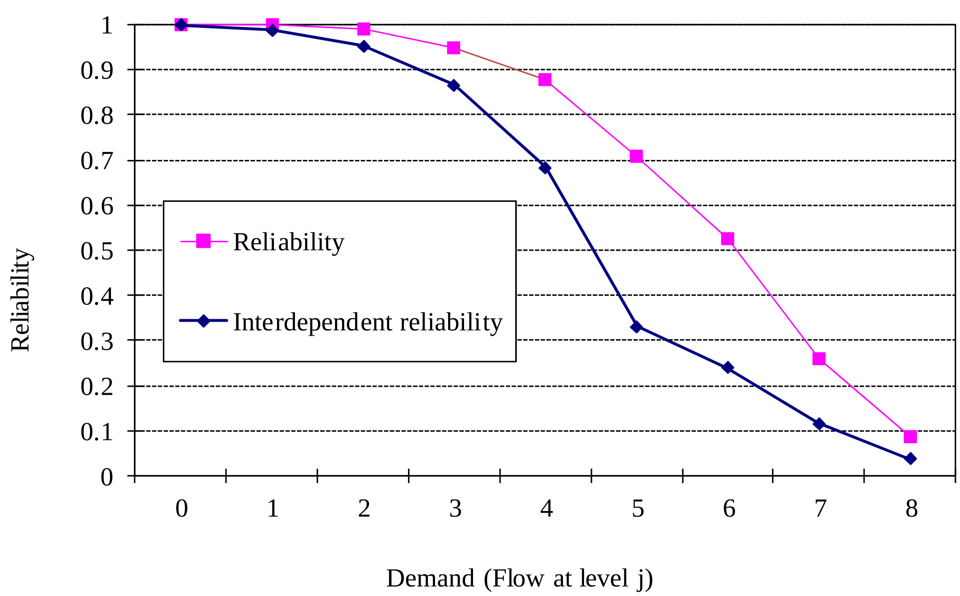


**Figure 4.** Interdependent reliability of the transportation network for different demand level

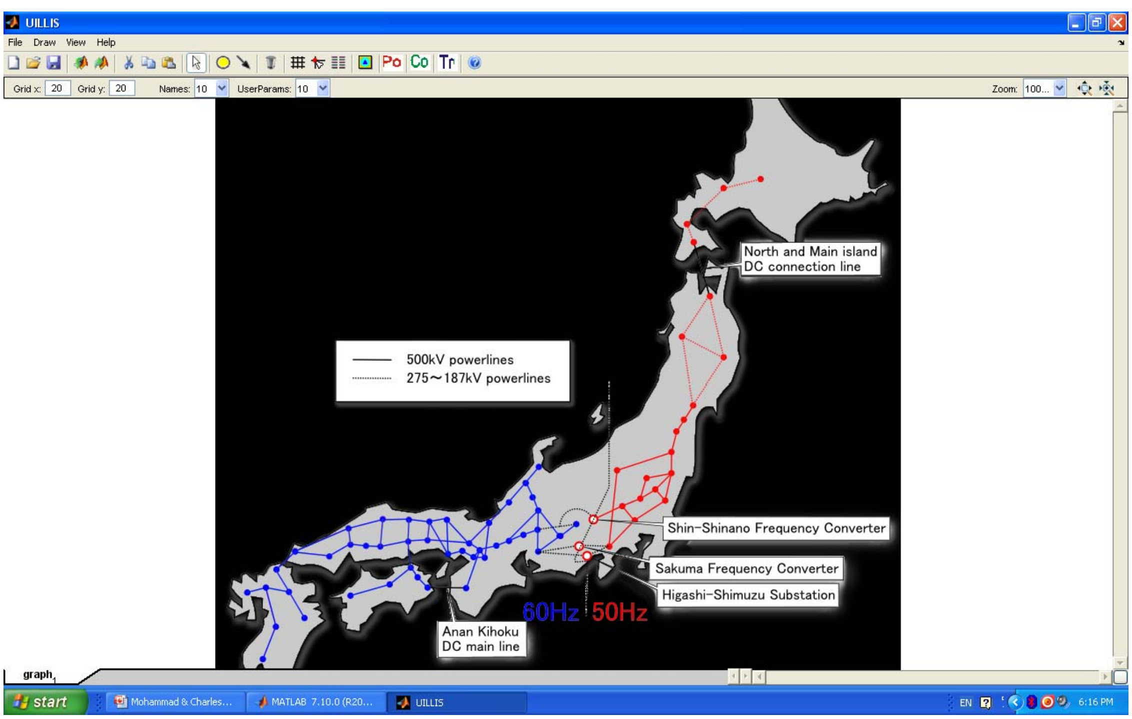


**Figure 5.** Graphical user interface for working with maps in UILLIS

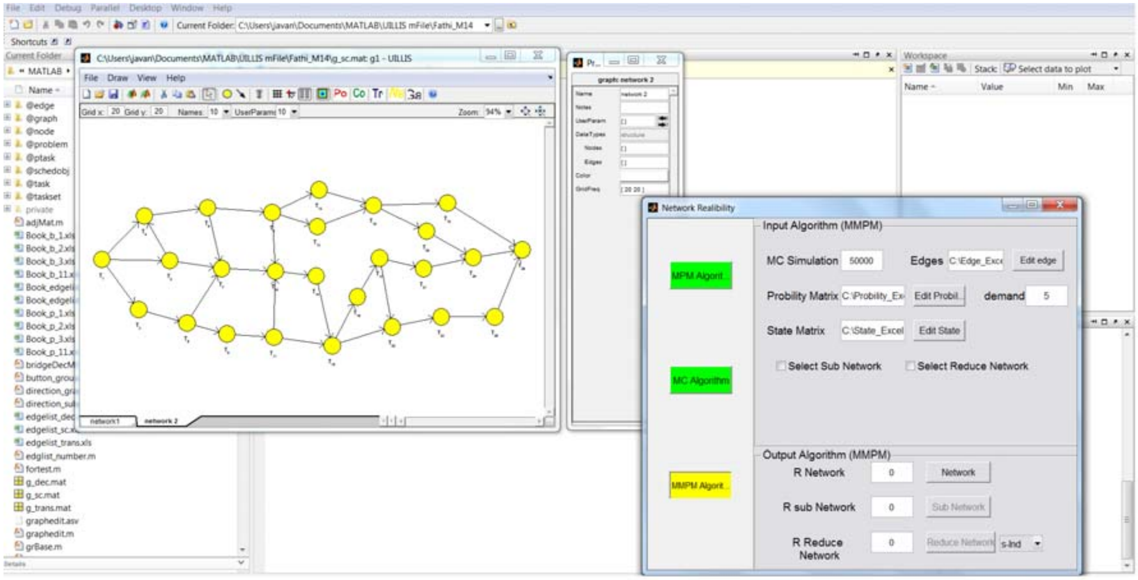


**Figure 6.** Different reliability modules in UILLIS

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