Procedure for Resilience Assessment

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The primary purpose of this document is to describe how HAZUS-MH data can be utilized in resilience assessment of a supply chain. This procedure mainly simulates time-varying system performance following a hazard event by modeling the restorative activities of individual damaged components (i.e., facilities and bridges) and aggregating them until the system achieves its full functionality.

1. Input Data

Supply chain resilience assessment requires two types of input data as follows:

- Physical damage estimation: Damage states of facilities and edges induced by a specific hazard event are the outputs from risk assessment. Please refer to the document titled "Procedure for Estimating Capacity Reduction".
- Restoration function and cost (HAZUS-MH data): Restoration function and costs are used in resilience assessment to estimate the recovery process of damaged facilities and edges and the associated restoration costs.

2. Example 1: Seismic Hazards

Based on the damage states of facilities and edges immediately following a scenario seismic event, post-earthquake recovery processes of individual components can be simulated. The recovery processes include (a) delay time and (b) repair time.

Step 1: *Estimate the delay time for damaged facilities and bridges*

<u>Facility delay time estimation</u>

The time to initiate repair activities of a damaged facility is not immediately after the time of occurrence of an event but may be delayed due to several impeding factors, including post-disaster inspection, engineering mobilization and review/re-design, financing, contractor mobilization and bid process, permitting, etc. Each impeding factor is considered as a random variable and assumed to follow a lognormal distribution with the median and COV values reported in Table 1 (Almufti and Willford, 2013). Figure 1 describes three delay sequences of a damaged facility due to these impeding factors as introduced in the REDi™ framework. Each sequence has different combinations of impeding factors and provides the associated expected delay time as follows:

$$T_{delay,1} = T_{inspection} + T_{financing} \tag{1a}$$

$$T_{delay,2} = T_{inspection} + T_{engineering} + T_{permitting} \tag{1b}$$

$$T_{delay,2} = T_{inspection} + T_{mobilization} \tag{1c}$$

The longest delay sequence controls the overall delay time. Thus, the total expected delay time of a damaged facility is (Zhao et al., 2020):

$$T_{delay} = \max\left(T_{delay,i}\right), i = 1,2,3 \tag{2}$$

Table 1. Lognormal distribution parameters of impeding factors (adapted from Almufti and Willford, 2013)

Impeding Factor	Building Conditions	Median (unit: weeks)	COV
Inspection	DS_0, DS_1	0	0
	DS_2, DS_3, DS_4	5	0.54
Engineering Mobilization and Review/Redesign	DS_0	0	0
	DS_1	6	0.40
	DS_2, DS_3	12	0.40
	DS_4	50	0.32
Financing	Insurance	6	1.11
	Government Assistance	48	0.57
Contractor Mobilization	DS_0	0	0
	DS_1, DS_2	11	0.43
	DS_3, DS_4	23	0.41
Permitting	DS_0	0	0
	DS_1, DS_2	1	0.86
	DS_3, DS_4	8	0.32

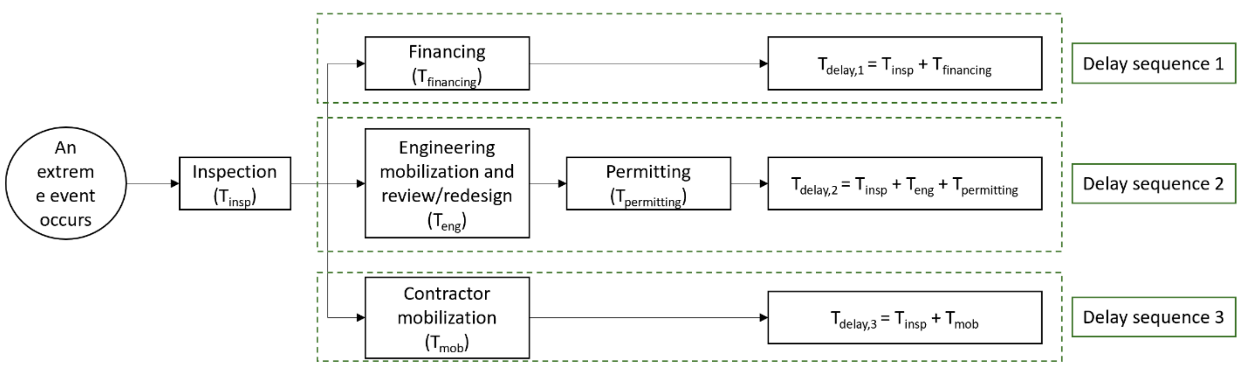

Figure 1. Three delay sequences of a damaged facility (adapted from Zhao et al., 2020)

Bridge delay time estimation

For a damaged bridge, the total delay time can be directly obtained from Hashemi et al. (2019), which is presented in Table 2.

Table 2. Bridge damage state and the associated delay time (adapted from Hashemi et al., 2019)

Damage State	**Delay time (days)**
DS_1	20
DS_2	60
DS_3	60
DS_4	100

Step 2: *Estimate the recovery time for damaged facilities and bridges*

Each damaged facility or bridge has its own restoration functions, which can be obtained from HAZUS-MH technical manual. There are two types of restoration functions in HAZUS-MH technical manual: discrete and continuous restoration functions. Moreover, recovery process can be modeled as either one-step or multi-step procedure.

One-step recovery process

One-step recovery process assumes that the functionality of a damaged facility/bridge is recovered only after all the repair activities are completed. As shown in Figure 2, its functionality remains constant during the delay and whole recovery time, and upon the completion of its recovery process, it is fully recovered. The recovery time of a damaged facility/bridge can be obtained from its continuous restoration function, while the delay time can be obtained from the previous step. For example, the post-earthquake recovery time of a highway bridge depends on its damage state and is modeled as a normal random variable (see the parameters of normal distributions in Table 3). Since the damage state of each bridge has already been realized from risk assessment, based on Table 3, its recovery time can be calculated using Monte-Carlo Simulation (MCS) method.

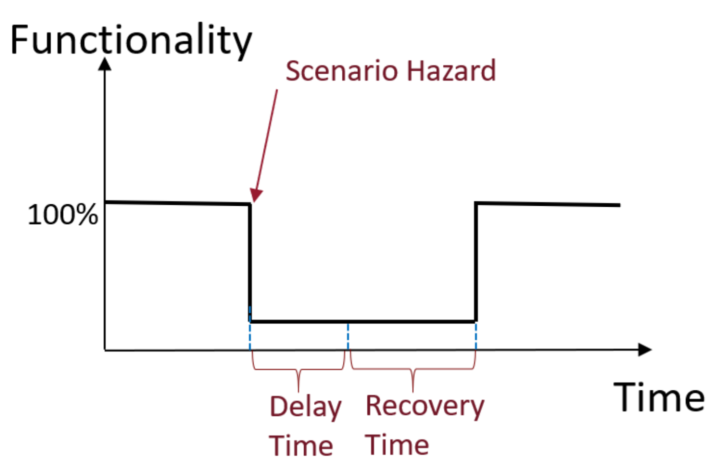

Figure 2. One-step recovery process of a damaged facility/bridge

Table 3. Continuous restoration functions for highway bridge (adapted from Table 7-3 in HAZUS-MH earthquake technical manual)

Damage State	Mean (days)	Std. (days)
DS_1	0.6	0.6
DS_2	2.5	2.7
DS_3	75	42
DS_4	230	110

Multi-step recovery process

Multi-step recovery process assumes stepwise increases in the functionality of a damaged facility or bridge as presented in Figure 3. For example, unlike one-step recovery process, its functionality increases step-by-step based on discrete restoration function until it achieves the full functionality. Table 4 shows the discrete restoration function of a highway bridge which describes the changes in functional percentages at different points in time given the damage state.

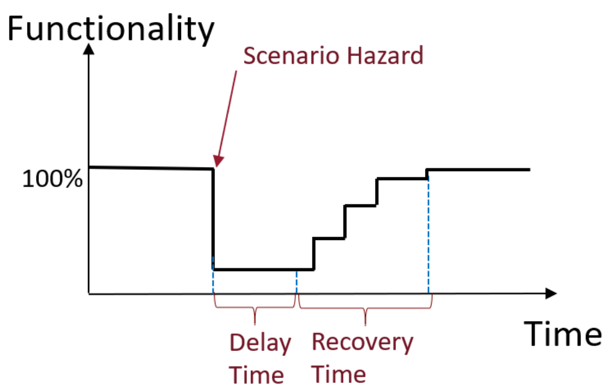

Figure 3. Multi-step recovery process of a damaged facility/bridge

Table 4. Discrete restoration functions for highway bridge (adapted from Table 7-4 in HAZUS-MH earthquake technical manual)

Damage State	Functional Percentage				
	1 day	3 days	7 days	30 days	90 days
DS_1	70	100	100	100	100
DS_2	30	60	95	100	100
DS_3	2	5	6	15	65
DS_4	0	2	2	10	10

It should be noted that, in both processes, the functionalities of bridges (i.e. bridge damage index) need to be converted into the remaining capacities of the associated edges at each time step as described in to the document titled "Procedure for Estimating Capacity Reduction".

Step 3: *Calculate the repair costs of damaged facilities*

Only the repair costs of damaged facilities are considered as part of the total supply chain cost. Based on the HAZUS-MH earthquake technical manual, each damage state is related to each damage ratio which is defined as the ratio of repair to replacement cost. Therefore, damage ratio can be used in estimating facility repair cost. For example, Table 5 presents the best estimate damage ratios for oil refineries in four damage states. By multiplying the facility replacement cost by its damage ratio, the total repair cost of the oil refinery conditioned on damage state can be calculated.

Table 5. Damage ratio for oil refineries (adapted from Table 11-17 in HAZUS-MH earthquake technical manual)

Damage State	Best Estimate Damage Ratio
DS_1	0.09
DS_2	0.23
DS_3	0.78
DS_4	1.00

Step 4: *Modify facility and edge property tables*

Following a scenario earthquake event, each facility/edge has its own damage state and recovery process, which can be used to generate its time-varying capacity, as described in Steps 1 and 2. To capture such time-varying capacities of facilities and edges and incorporate them in supply chain analysis, facility and edge property tables should be modified at every time step.

Step 5: *Modify the objective function of the FTOT optimization*

The objective function of the optimization is to minimize the total supply chain costs per product ($cost_n(t)$) and is mathematically expressed by:

$$cost_n(t) = \frac{cost_0 + w_R \cdot (cost_{R,n}(t) - reward_n(t))}{product_n(t)} \tag{3}$$

where $cost_0$ = the business-as-usual supply chain costs consisting of transportation cost and operation cost; $cost_{R,n}(t)$ = the resilience cost at time *t* under the n^{th} scenario; $reward_n(t)$ = the reward at time *t* under the n^{th} scenario; w_R = the weighting factor determined by a decision-maker based on the relative importance of the resilience cost/reward in total cost calculation; and $product_n(t)$ = the amount of the final product at time *t* under the n^{th} scenario. More specifically, $cost_{R,n}(t)$ comprises four cost components, including unmet demand penalty (c_{UDP}), facility restoration cost in the aftermath of hazard events ($c_{restoration}$), and changes (Δ) in transportation cost ($c_{transportation}$) and operations cost ($c_{operation}$) due to risk factors. $reward_n(t)$ is the reward for demand surplus to account for system redundancy. This term may not be an actual economic benefit that a supply chain system produces but a benefit obtained from meeting the minimum target demand under any uncertain scenarios in the form of redundancy or backup. The resilience cost and reward terms can be summarized in the following equations respectively:

$$cost_R(t) = c_{UDP}(t) + c_{restoration}(t) + \Delta(c_{transportation}(t) + c_{operation}(t)) \tag{4a}$$

$$reward(t) = -UDR(t) \cdot r_{product} \tag{4b}$$

where *UDR* = the unmet demand ratio that will be obtained from optimization; and $r_{product}$ = the reward rate per unit surplus (assumed to be the same as unmet demand penalty rate).

Step 6: *Run optimization simulation at each time step over planning horizon for each scenario*

Supply chain optimization simulation is mainly used to measure the performance of supply chain (cost, unmet demand ratio (UDR)) at each time step for each scenario. Immediately following a hazard event, structural damages (and the associated capacity reduction) to all supply chain components (nodes and transportation edges) are computed (as described in Steps 1 – 4), and their effects are incorporated into supply chain analysis to reoptimize transportation routes. After reoptimizing transportation routes immediately following the hazard event, the recovery processes of the nodes and edges are simulated at every time step t_h (where t_h is the time interval considered during the recovery process), and their structural capacities are updated in supply chain analysis. This process is repeated until supply chain performance achieves its pre-hazard-event functionality. As shown in Figure 4, the entire simulation process has an iterative structure and is repeated over the planning horizon (*T*). This simulation generates a single long-term supply chain performance scenario and should be repeated to generate a set of *N* scenarios. Due to uncertainties in risk factors, each scenario results in a distinctive long-term supply chain performance

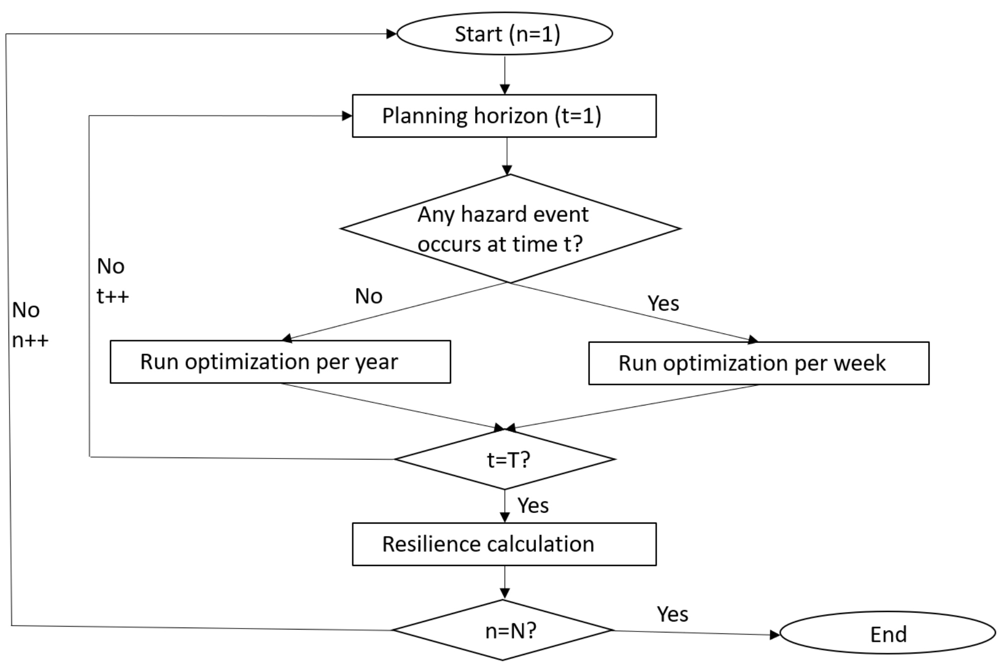

Figure 4. Simulation process for supply chain optimization

Step 7: *Calculate the supply chain resilience over planning horizon for each scenario*

The UDR is used as one of the performance measures of a supply chain system. Since facility/edge capacity may vary at each time step among *N* scenarios, the UDR is also a time-dependent parameter that can be obtained from FTOT optimization. For a specific scenario, resilience components ($R_{1,n}$, $R_{2,n}$, and $R_{3,n}$) can be identified based on *UDR*, and measured by cost/reward function, which can be computed as follows:

$$R_{1,n} = \sum_i \int_{t_{h,i}} cost_{R,n}(t_{h,i})dt_{h,i} \quad (5a)$$

$$R_{2,n} = \sum_j \int_{t_{o,j}} reward_n(t_{o,j})dt_{o,j} \quad (5b)$$

$$R_{3,n} = \int_{\overline{t_h}} cost_{R,n}(\overline{t_h})d\overline{t_h} \quad (5c)$$

where $R_{m,n}$ = the m^{th} resilience component under the n^{th} scenario; i = the number of hazard events over T under the n^{th} scenario; $t_{h,i}$ = the time period during which +*UDR* is induced by the i^{th} hazard; j = the number of time periods during which -*UDR* is induced by opportunities over T under the n^{th} scenario; $t_{o,j}$ = the j^{th} time period during which -*UDR* is induced by opportunities; and $\overline{t_h}$ = the time period during +*UDR* is induced by non-hazard events. More specifically, $R_{1,n}$ = hazard-induced CLF under the n^{th} scenario; $R_{2,n}$= opportunity-induced CGF under the n^{th} scenario; and $R_{3,n}$ = non-hazard-induced CLF under the n^{th} scenario.

By combining these three resilience components, the overall resilience of the supply chain system under the n^{th} scenario (R_n) can be expressed by:

$$R_n = w_{1,n}R_{1,n} + w_{2,n}R_{2,n} + w_{3,n}R_{3,n} \quad (6)$$

where $w_{m,n}$ = the weighting factor assigned to the m^{th} resilience component under the n^{th} scenario reflecting the relative importance of each component. These weighting factors can be determined by decision-makers to represent their preferences towards each resilience component. In this context, to better reflect the consequences of each risk factor to system performance, the following weighting factors are used for the purpose of illustration:

$$w_{1,n} \propto E_i\left[\frac{\int_{t_{h,i}} cost_{R,n}(t_{h,i})dt_{h,i}}{t_{h,i}}\right] \quad (7a)$$

$$w_{2,n} \propto E_j\left[\frac{\int_{t_{o,j}} reward_n(t_{o,j})dt_{o,j}}{t_{o,j}}\right] \quad (7b)$$

$$w_{3,n} \propto E_k\left[\frac{\int_{\overline{t_h}} cost_{R,n}(\overline{t_h})d\overline{t_h}}{\overline{t_h}}\right] \quad (7c)$$

Step 8: *Generate the simulation structure for resilience assessment*

The entire simulation process should be repeated to generate a set of long-term supply chain performance under *N* scenarios. Due to uncertainties in risk factors, each scenario results in a distinctive supply chain resilience value. Finally, the final form of the overall resilience index can be represented by probability density function (PDF) or cumulative distribution function (CDF).

Reference

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