Modification of FTOT to Incorporate Resilience Assessment

Supply chain, as a complex process spatially distributed over a large geographic area, is always exposed to multiple risks, such as extreme hazards (e.g., earthquake, floods, hurricane, etc.), and operation events (e.g., bankruptcies, major equipment breakdowns, etc.). Therefore, understanding multiple risk factors related to system operation and incorporating their effects on supply chain optimization design are necessary. Resilience can be defined as a performance indicator to quantify the supply chain capacity in response to multiple risk factors along with its service life. Since we develop a framework to assess the supply chain resilience exposed to a wide range of uncertain events and conditions, this modification of FTOT document is aimed to illustrate the proposed resilience framework based on the quick scenario 2 in FTOT.

1. Risk factors

Three types of risk factors are considered in resilience assessment framework, which are: extreme hazard (seismic event), cumulative negative event (dry climate due to climate change), and opportunity (technology development of processors). The effects of three risk factors on supply chain performance are listed in Table 1.

Table 1. Risk factors and their effect

Risk Factors	Effects
Seismic event	Damage of facilities and transport links
Dry climate due to climate change	Decrease of raw material amount
Technology development	Increase of processor conversion rate

2. Assumptions

- Total number of scenarios: N = 10
- Total planning horizon: 20 years
- Dry climate due to climate change with occurrence rate is 0.5, which causes a continuous decrease in the feedstock amount with the assumed rate of -1% per year
- Technology development in processor with occurrence rate is 0.5, which leads to an increase in the conversion rate at processor nodes with the assumed rate to be +1.5% per year occurs from fifth year.
- The occurrence of seismic events is modeled by Poisson process with the annual mean rate of occurrence of 0.05/year.
- Maximum earthquake frequency is assumed to be 1/year, because the probability for occurrence of multiple seismic events in one year is too rare to ignore this condition.

- The performance of supply chain system is measured on a yearly basis during normal operation. Following a hazard event, system performance is measured on a daily basis until it achieves the full functionality (i.e., UDR becomes 0)
- The location of occurrence of an earthquake event and the impacted area are not generated using probabilistic seismic hazard analysis for the illustration purpose. In other words, it is assumed that all the links and facilities in the supply chain system may be affected by a given earthquake, and their capacities are randomly sampled from a uniform distribution in [0,1]. Thus, the current set of scenarios will overestimate the risk of seismic events.
- Only consider the road transport mode in the case study.
- Five damage states for both facilities and transportation system are assumed based on their definitions in HAZUS-MH technical manual (FEMA, 2011), which include slight (DS1), moderate (DS2), extensive (DS3), and completive (DS4) damage states in addition to no damage (DS0).
- Based on the facility capacity, we can assign the damage state for each facility by using the relationship between damage state and available capacity (represented by damage ratios), and subsequently simulate the time-varying capacity by considering restoration activities.

Table 2. Relationship between available capacity, damage state and restoration time for facilities (Adapted from Table 15.10 in HAZUS-MH technical manual)

Capacity Range	Damage State	Median Restoration Time in days (RMP)	Median Restoration Time in days (Pro/Des)
[0,0.5)	DS4	120	360
[0.5,0.75)	DS3	60	240
[0.75,0.95)	DS2	20	90
[0.95,1]	DS1	2	10

Note: (a) "RMP" means raw material production; "Pro" is processor; "Des" is ultimate destination; (b) restoration functions are modeled as lognormal distribution with assumed std to be 0.15.

- In order to identify all the bridges located within each edge, the relationship between highway bridge (obtained from HAZUS) and FTOT road system is developed. This process is necessary because the fragility function of each type of bridge available in HAZUS-MH should be included in the FTOT framework to assess the earthquake-induced physical damage of bridges and the associated edge capacity reduction.
- For transport edges, we first sample random numbers from U (0,1) to assign bridge damage index (BDI). Then, calculate link damage index (LDI) in order to generate the link available capacity following an earthquake event. Finally, obtain the bridge damage state based on

the relationship between BDI and damage state (Shiraki et al., 2007), for subsequent simulation about time-varying capacity during post-disaster recovery process.

Table 3. Relationship between bridge damage state and BDI (Adapted from Table 1 of Shiraki et al., 2007 and Table 7.4 in HAZUS-MH technical manual)

BDI Range	Damage State	Restoration time in days (mean of normal dist.)	Restoration time in days (Std of normal dist.)
[0,0.1)	DS1	0.6	0.6
[0.1,0.3)	DS2	2.5	2.7
[0.3,0.75)	DS3	75	42
[0.75,1]	DS4	230	110

- Repair cost of each facility/bridge for five damage states (DS0-4) is assumed as [0,2000,5000,10000,50000] with unit to be dollar ($).

3. Resilience assessment method

The study defines supply chain resilience as its combined ability to resist and recover from hazard events, adapt to changing conditions, and capitalize on opportunities. In this case, a new resilience index is proposed with consisting of three components, including non-hazard-induced cumulative loss of functionality (CLF), hazard-induced CLF, and opportunity-induced cumulative gain of functionality (CGF). These resilience components ($R_{1,n}$, $R_{2,n}$, and $R_{3,n}$) are computed as follows:

$$R_{1,n} = \sum_k \int_{t_{c,k}} cost_n\left(t_{c,k}\right) dt_{c,k} \tag{1a}$$

$$R_{2,n} = \sum_i \int_{t_{h,i}} cost_n\left(t_{h,i}\right) dt_{h,i} \tag{1b}$$

$$R_{3,n} = \sum_j \int_{t_{p,j}} cost_n\left(t_{p,j}\right) dt_{p,j} \tag{1c}$$

where $R_{m,n}$ = the m^{th} resilience component during scenario n; k = the number of non-hazard risk factors over T during scenario n; $t_{c,k}$ = the periods during which $+UDR$ is induced by cumulative negative impacts caused by the k^{th} non-hazard event/condition; i = the number of hazard events over T during scenario n; $t_{h,i}$ = the periods during which +UDR is induced by the i^{th} hazard; j = the number of positive events over T during scenario n; and $t_{p,j}$ = the periods during which $-UDR$ is induced by the j^{th} event. The total costs associated with each resilience component consist of five parts as following:

$$cost_{\,n}(t) = Transpotation + Contruction + UDP + Restoration + Operation \tag{2}$$

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

$$R_n = -\,w_{1,n}R_{1,n} - w_{2,n}R_{2,n} + w_{3,n}R_{3,n} \tag{3}$$

where $w_{m,n}$ = the weighting factor for the m^{th} component under the n^{th} scenario reflecting the importance of each component. Those factors are assumed to be 1 in this example. Finally, since $R_n$varies among scenarios, the overall resilience of the supply chain system can be expressed by its expected value or its PDF.

4. Optimizer objective

The objective function in this modified version is adjusted to incorporate the weighted resilience cost as another component, expressed as:

$$min_{n,t}\ (I_C(daily/yearly) + w * I_{R,n,t}) \tag{4}$$

where I_C is the daily/yearly initial cost; $I_{R,n,t}$ is the increased/reduced daily/yearly resilience cost for scenario n and time t; *w* represents decision-makers' preference towards supply chain resilience design (assumed to be 1 in this case). In this case study, I_C can be obtained by directly applying supply chain optimization without consider any risk factors.

5. Newly developed Python files and outputs

In order to assess the effect of three risk factors on supply chain performance, several Python files are newly developed to obtain their consequences. For example, seismic event can cause damages and associated capacity reductions of bridges, links, and facilities in the affected area, and subsequently play a negative effect on supply chain operation. Table 4 shows four newly developed Python files and their major outputs.

Table 4. Newly developed Python files and their outputs

Python Files	Outputs	Descriptions
FacilityCapacity.py	earthquake_scenario	Earthauake occurrence condition for each scenario and time period (1 means earthquake occurs, otherwise 0)
	facility_cap	Remaining percentage of facility capacity following three risk factors for each facility, scenario and time period
	facility_cap_noEarthquake	Remaining percentage of facility capacity without considering the effect of seismic event for each facility, scenario and time period
	facility_DS	facility Damage State (0-4) following seismic event for each facility, scenario and time period
BridgeDamage.py	bridge_damage	Bridge damage index following seismic event for each bridge, scenario and time period

	bridge_DS	facility Damage State (0-4) following seismic event for each bridge, scenario and time period
EdgeCapacity.py	edge_cap	Remaining percentage of facility capacity following seismic event for each edge, scenario and time period
RepairCost.py & RepairCost_2.py	repair_time_bridge	Restoration time for each bridge, scenario and time period
	repair_time_facility	Restoration time for each facility, scenario and time period
	total_repair_time	Total Restoration time of supply chain for each scenario and time period
	repair_costs	Restoration costs for each scenario and time period

6. Overall framework for modification of FTOT

The major modifications to incorporate the resilience assessment framework occur in optimization steps (o1 and o2 steps) as shown in Figure 1. After earthquake occurrence, a daily-based simulation is applied to reflect the post-disaster recovery process.

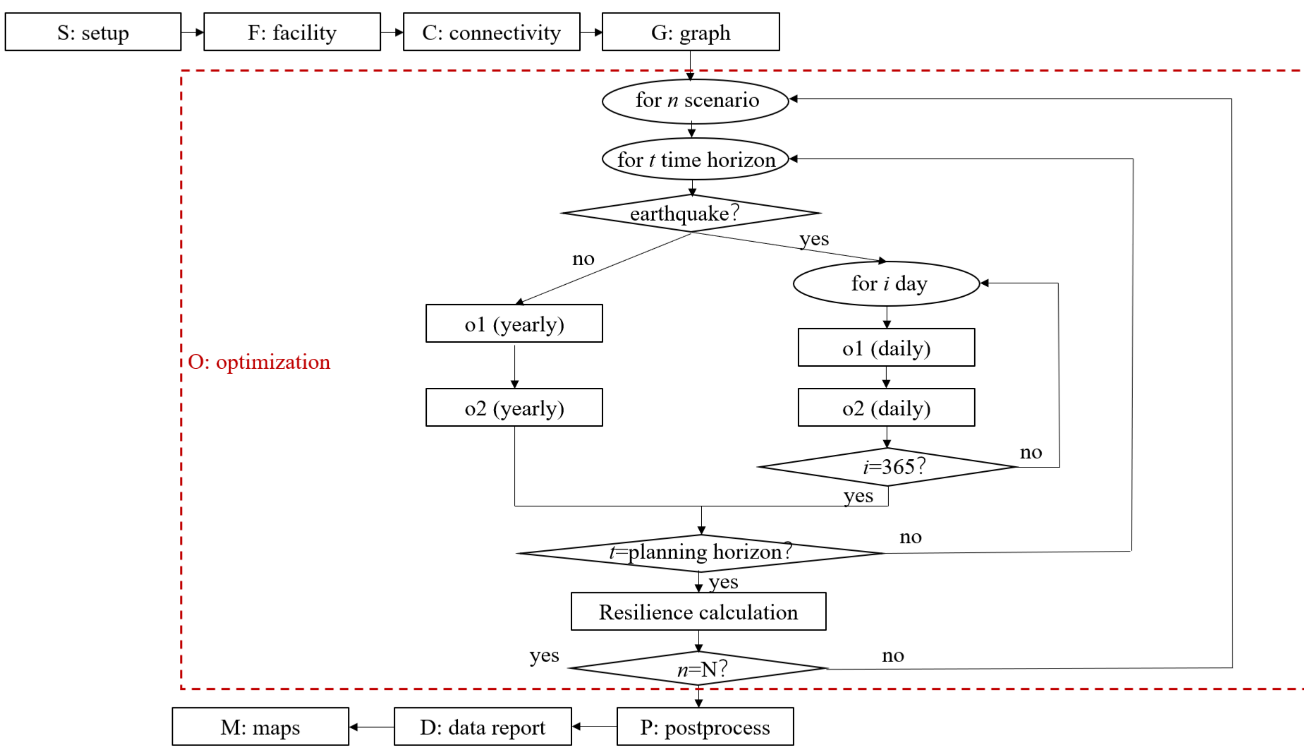

Figure 1. Overall framework and steps

7. Modification in FTOT Python file

- ftot.py
    - generate two loops (scenarios and time horizons) to run the FTOT optimization for each scenario and time step
    - add resilience calculation process based on the optimal outputs to obtain the resilience for each scenario
- ftot_pulp.py: instead of applying ftot_pulp.py, we develop two different Python files, in order to run the daily and yearly optimization step separately.
    - in ftot_pulp_daily.py, (a) multiply the facility "quantity" parameter by a capacity reduction index due to combined effects of three risk factors; (b) multiply the network "max_daily_capacity" parameter by a capacity reduction index due to earthquake effect; (c) add two new cost components, operation and restoration costs in objective function; (d) modify the range of unmet demand ratio to be $[-\infty, +\infty]$.
    - in ftot_pulp_yearly.py, (a) multiply the facility "quantity" parameter by a capacity reduction index due to combined effects of two risk factors; (b) add two new cost components, operation and restoration costs in objective function; (c) modify the range of unmet demand ratio to be $[-\infty, +\infty]$.
- input_data.csv: in order to show the effect of risk factors on supply chain resilience, the input and output quantity for processor are modified from 100 to 90.

8. Run the case study

The proposed framework is applied in Quick Scenario 2, in order to test the feasibility of these modifications of FTOT to incorporate the resilience assessment methodology. This case study also provides probability to users for applying the resilience as an additional objective in supply chain optimization.

Case study should run in C:\FTOT\scenarios\quick_start\qs2_rmp_proc_dest\Default folder. Prior to run this case, (a) replace the original Python code package (C:\FTOT\program folder) by the new one (Modified_FTOT\program folder), because some modifications are adopted in Python codes to apply resilience assessment; (b) replace the original QS2 (C:\FTOT\scenarios\quick_start\qs2_rmp_proc_dest folder) by the new one (Modified_FTOT\ qs2_rmp_proc_dest folder folder); (c) run the FacilityCapacity.py, BridgeDamage.py, EdgeCapacity.py, RepairCost.py, RepairCost_2.py in sequence in qs2_rmp_proc_dest\Default, in order to obtain the results from risk assessment; (d) execute run_v5_1.bat in qs2_rmp_proc_dest\Default to run the QS2 scenario.

The run should take about 4-5 days. This case study support both 32-bit and 64-bit simulation. If the ArcGIS 64-bit background geoprocessing is installed, users can run FTOT in 64-bit by using the batch script files called run_v5_ 1.bat. Otherwise, click run_v5_ 1_32bit.bat to run FTOT in 32-bit.

9. Further study

The purpose of this version of FTOT modification is to develop a framework to illustrate how to incorporate the resilience assessment into supply chain optimization. However, this version of modification is unrealistic, because many restrictive assumptions are utilized for integrated risk assessment part. Therefore, proposed framework would be applied to a realistic supply chain system (forest residuals-to-jet fuel supply chain in PNW region) for next study, and use Probabilistic Seismic Hazard Analysis (PHSA) for earthquake scenario generation. At the same time, some improvements in FTOT files can also be considered for further research: (a) define parameters in scenario XML file to provide more flexibilities to users, such as the weight factors, planning horizon, scenarios; (c) generate damage distribution maps due to extreme events as map outputs; (c) modify the code for report generation to show the supply chain resilience-related results.

Reference

Shiraki, N., Shinozuka, M., Moore, J., Chang, S., Kameda, H., and Tanaka, S. (2007). "System risk curves: Probabilistic performance scenarios for highway networks subject to earthquake damage." J. Infrastruct. Syst., 10.1061/(ASCE)1076-0342(2007)13:1(43), 43–54.