Given a collection of damaged networks (made up of a set of damaged nodal components and a set of damaged line components), we can subdivide each network into different recovery zones. We can then write the zonal-scale optimization problem as the minimization of a set of objective function(s) (e.g., resilience metrics or cost) obtained by considering different priorities of the recovery zones.

The zonal-scale optimization problem is subject to physical and logical scheduling constraints for the recovery activities within each zone and service recovery constraints. Each set of these constrains entails a nested optimization. To schedule the recovery activities within each zone, we formulate a local-scale optimization problem whose objective is to minimize the recovery duration within the zone, while complying with physical and logical constraints to implement the recovery schedule. The objective of the service recovery optimization is to minimize a measure of discrepancy between the loss function estimates of the demand and supply measures through the recovery, while complying with the network-specific constraints, such as power balance equations for the power flow network (Glover et al. 2012). Further details about the recovery optimization can be found in Sharma et al. (2019b).

3.7.4.5 Resilience-Informed Infrastructure Recovery Example. The definition of an optimal recovery strategy is illustrated by modeling the performance of the electric power infrastructure in Shelby County, Tennessee. Shelby County has an approximately 1,000,000 population, and the region is subject to seismic hazards originating from New Madrid Seismic Zone (NMSZ). In this example, we consider a historical scenario earthquake with a moment magnitude of 7.7 and the epicenter at 35.93°N and 89.92°W. We model the spatial variation of the earthquake intensity measures by using a three-dimensional physics-based model to capture near-field effects [Guidotti, R., S. Tian, and P. Gardoni, "Simulation of seismic wave propagation in the Metro Memphis Statistical Area (MMSA)," in preparation] and ground motion prediction equations for far-field regions (Steelman et al. 2007).

The electrical power infrastructure in Shelby County is managed by the Memphis Light, Gas, and Water (MLGW) Division. The balancing authority of the region is the Tennessee Valley Authority (TVA) who also owns and operates the generators and transmission lines providing power to MLGW. The model for the power flow analysis is provided by Sharma et al. (2019a), building on the information provided in Shinozuka et al. (1998) and Birchfield et al. (2017). Figure 3-21 shows the topology of the developed model for Shelby County (b) and Tennessee (a).

To model the physical recovery, we estimate the damage to the vulnerable components and develop a detailed recovery schedule for the

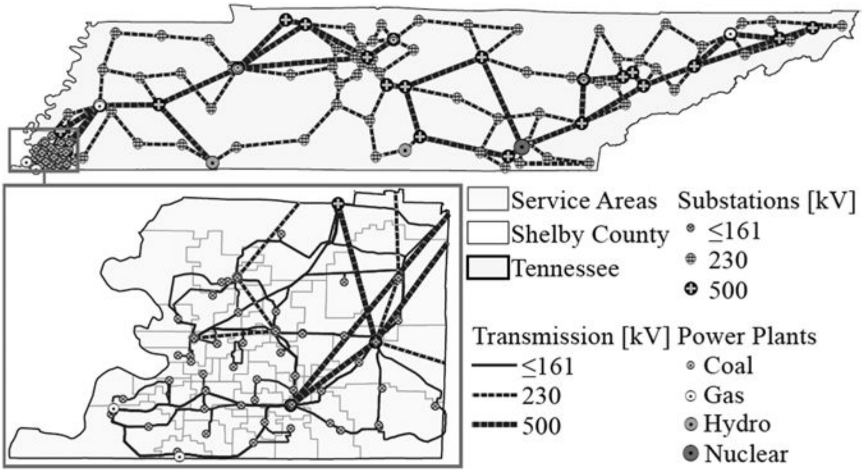

Figure 3-21. Electric power infrastructure in (a) Tennessee, and (b) Shelby County.
Source: Adapted from Sharma et al. (2019a).

repair or replacement of damaged components. Transformers, circuit breakers, and disconnect switches are vulnerable components to seismic excitations, which are all located in electric power substations. To develop the recovery schedule, we consider each substation and the corresponding service area as a single recovery zone. Given that two different agencies manage the electric power infrastructure inside and outside Shelby County, we define four different recovery projects as follows: (1) MLGW critical repairs, for nonfunctional substations in Shelby County; (2) MLGW noncritical repairs, for functional but damaged substations in Shelby County; (3) TVA critical repairs, for nonfunctional substations in Tennessee; and (4) TVA noncritical repairs, for functional but damaged substations in Tennessee. Further details of the recovery schedule can be found in Sharma et al. (2019a).

To model service recovery, we develop a structural network, $G^{[1]}$, and a power flow network, $G^{[2]}$. The structural capacity and demand measures are in terms of the hazard intensity measure, whereas the flow capacity and demand measures are in terms of the apparent power. The capacity of the flow network is dependent on the structural network. We account for this dependency in the modified flow capacity estimates and accordingly obtain the modified flow supply estimates by running power flow analyses. To summarize the overall service recovery, we define the aggregate performance measure $Q'^{[\text{agg}]}(\tau) = \sum_{\text{cell}=1}^{n_{\text{cell}}} w_{\text{cell}} Q'^{[2]}_{\text{cell}}(\tau)$, where cell is the service area of each substation; w_{cell} is a weight for the recovery cell that is proportional to the power demand in the recovery cell; and $Q'^{[2]}_{\text{cell}}(\tau)$ is the fraction of the power demand that is supplied in the recovery *cell*.

The scenario earthquake is estimated to cause damage to components in 17 of the 36 zones managed by MLGW, which require critical repairs. In this example, we use ρ_Q as the sole objective function in recovery optimization. To solve the optimization problem, we use a genetic algorithm (Goldberg 1989), whereas other algorithms could be used as well. Figure 3-22 shows the results for the service recovery in terms of $Q'^{[2]}_{\text{cell}}(\tau)$, which is a binary-value quantity (dark gray is nonfunctional, and light gray is functional). Figure 3-22(a) shows the results according to the current recovery practice as defined in MLGW (2017), and Figure 3-22(b) shows the results according to the optimized recovery schedule. In Figure 3-22(a), we observe that $Q'^{[2]}_{\text{cell}}(\tau)$ for some recovery cells fluctuates over time. This is because as the recovery advances, redistribution of loads on operating buses can result in voltage collapse. The optimized recovery results in $\rho_Q = 18.1$ h, compared with $\rho_Q = 26.5$ h for the current recovery practice (i.e., a 30.2% improvement). We can also observe that the improvement in $Q'^{[2]}_{\text{cell}}(\tau)$ is not uniform across the region because some areas experience slower recovery than the others. This is because the focus of ρ_Q, as the recovery objective, is on the recovery duration, thus not capturing the temporal and spatial variabilities in the recovery. Instead, one can use the formulation in Section 3.9.4 to define a multiobjective optimization problem that captures all desired resilience objectives in developing the recovery schedule.

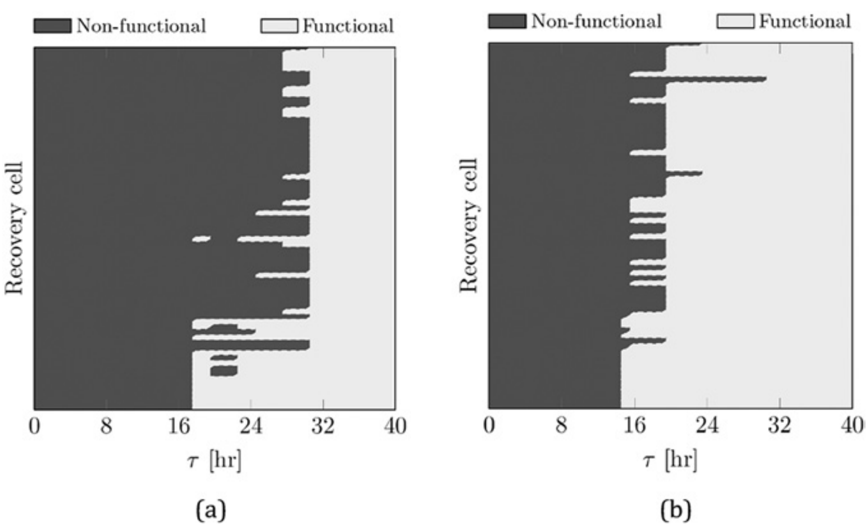

Figure 3-22. Predicted performance of the electric power infrastructure under (a) current recovery practice, and (b) optimized recovery schedule.

REFERENCES

AAR (Association of American Railroads). 2010. *Class I railroad statistics*. Washington, DC: AAR. Accessed July 10, 2019. http://www.aar.org.

AAR. 2018. *140,000-Mile private rail network delivers for America's economy*. Washington, DC: AAR. Accessed July 10, 2019. http://archive.freightrailworks.org/network/class-i/.

Agusdinata, B. 2008. *Exploratory modeling and analysis*. Delft, Netherlands: TU Delft (Delft University of Technology).

Alderson, D., G. Brown, and W. Carlyle. 2015. "Operational models of infrastructure resilience, risk analysis." *Risk Anal.* 35 (4): 562–586.

Almufti, I., and M. Willford. 2014. "The REDi™ rating system: A framework to implement resilience-based earthquake design for new buildings." In *Proc., 10th U.S. National Conf. on Earthquake Engineering*, Earthquake Engineering Research Institute, Anchorage, Alaska. Accessed March 14, 2020. https://datacenterhub.org/resources/12400/download/10NCEE-001055.pdf.

Ayyub, B. M. 2014a. "Systems resilience for multi-hazard environments: Definition, metrics and valuation for decision making." *Risk Anal.* 34 (2): 340–355.

Ayyub, B. M. 2014b. *Risk analysis in engineering and economics*. 2nd ed. Boca Raton, FL: Chapman & Hall/CRC.

Ayyub, B. 2015. "Practical resilience metrics for planning, design and decision making." *J. Risk Uncertainty Eng. Syst. Part A: Civ. Eng.* 1 (3): 04015008.

Bankes, S. 1993. "Exploratory modeling for policy analysis." *Oper. Res.* 41 (3): 435–449.

Batouli, M., and A. Mostafavi. 2014. "A hybrid simulation framework for integrated management of infrastructure networks." In *Proc., Winter Simulation Conf.*

Batouli, M., and A. Mostafavi. 2016. "Assessment of sea-level rise adaptations in coastal infrastructure systems: Robust decision making under uncertainty." In *Proc., Construction Research Congress*. 2016, San Juan, Puerto Rico, May 31–June 2, 2016, 1455-1464. https://ascelibrary.org/doi/book/10.1061/9780784479827

Batouli, M., and A. Mostafavi. 2018. "Multiagent simulation for complex adaptive modeling of road infrastructure resilience to sea-level rise." *Comput.-Aided Civ. Infrastruct. Eng.* 33 (5): 393–410.

Bhamidipati, S., T. van der Lei, and T. Herder. 2016. "A layered approach to model interconnected infrastructure and its significance for asset management." *Eur. J. Transp. Infrastruct. Res.* 16 (1): 254–272.

Birchfield, A. B., K. M. Gegner, T. Xu, K. S. Shetye, and T. J. Overbye. 2017. "Statistical considerations in the creation of realistic synthetic power grids for geomagnetic disturbance studies." *IEEE Trans. Power Syst.* 32 (2): 1502–1510.

Biringer, B., E. D. Vugrin, and D. Warren. 2013. *Critical infrastructure system security and resilience*. Boca Raton, FL: CRC Press.

Boardman, J., and B. Sauser. 2006. "System of systems—The meaning of OF." In *Proc., IEEE/SMC Int. Conf. on System of Systems Engineering.*, Los Angeles, 118–123. doi:10.1109/SYSOSE.2006.1652284 New York: IEEE.

Bruneau, M., S. E. Chang, R. T. Eguchi, G. C. Lee, T. D. O'Rourke, A. M. Reinhorn, et al. 2003. "A framework to quantitatively assess and enhance the seismic resilience of communities." *Earthquake Spectra* 19 (4): 733–752.

Bruneau, M., and A. Reinhorn. 2007. "Exploring the concept of seismic resilience for acute care facilities." *Earthquake Spectra* 23 (1): 41–62.

Chang, S. E., and M. Shinozuka. 2004. "Measuring improvements in the disaster resilience of communities." *Earthquake Spectra* 20 (3): 739–755.

Cimellaro, G. P., A. M. Reinhorn, and M. Bruneau. 2010. "Framework for analytical quantification of disaster resilience." *Eng. Struct.* 32 (11): 3639–3649.

Decò, A., P. Bocchini, and D. M. Frangopol. 2013. "A probabilistic approach for the prediction of seismic resilience of bridges." *Earthquake Eng. Struct. Dyn.* 42 (10): 1469–1487.

Dehghani, M. S., G. Flintsch, and S. McNeil. 2014. "Impact of road conditions and disruption uncertainties on network vulnerability." *J. Infrastruct. Syst.* 20 (3): 04014015.

DeLaurentis, D. 2005. "Understanding transportation as a system-of-systems design problem." In *Proc., 43rd AIAA Aerospace Sciences Meeting and Exhibit*. Reston, VA: American Institute of Aeronautics and Astronautics.

DeLaurentis, D., and R. K. C. Callaway. 2004. "A system-of-systems perspective for public policy decisions." *Rev. Policy Res.* 21 (6): 829–837.

Field, C., R. Look, and T. Lindsay. 2016. "Resilience insight: 12 cities assessment. BuroHappold Engineering, BRE and Worshipful Company of Constructors." Accessed May 21, 2020. https://www.burohappold.com/wp-content/uploads/2016/06/2016-Royal-Charter-International-Research-Award-BuroHappold-Resilience-Insight-12-Cities-Assessment-v2.pdf.

Field, C., R. Look, and T. Lindsay. 2017. "A comprehensive approach to city & building resilience." In *Proc., AEI Annual Convention*. Accessed March 14, 2020. https://www.researchgate.net/publication/315850846_A_Comprehensive_Approach_to_City_and_Building_Resilience.

Fisher, R., and M. Norman. 2010. "Developing measurement indices to enhance protection and resilience of critical infrastructures and key resources." *J. Bus. Continuity*, 4(3), 191–206.

Floyd, R. W. 1962. "Algorithm 97: Shortest path." *Commun. ACM* 5 (6): 345–345.

Gao, J., B. Barzel, and A.-L. Barabási. 2016. "Universal resilience patterns in complex networks." *Nature* 530 (7590): 307.

Gardoni, P., ed. 2019. *Handbook of sustainable and resilient infrastructure*. Abington, UK: Routledge.

Gardoni, P., A. Der Kiureghian, and K. M. Mosalam. 2002. "Probabilistic capacity models and fragility estimates for reinforced concrete columns based on experimental observations." *J. Eng. Mech.* 128 (10): 1024–1038.

Gardoni, P., K. M. Mosalam, and A. Der Kiureghian. 2003. "Probabilistic seismic demand models and fragility estimates for RC bridges." *J. Earthquake Eng.* 7 (spec01): 79–106.

Gardoni, P., and C. Murphy. 2018. "Society-based design: promoting societal well-being by designing sustainable and resilient infrastructure." *Sustainable Resilient Infrastruct*. 5(1-2), https://doi.org/10.1080/23789689.2018.1448667

Gilbert, S., and B. M. Ayyub. 2016. "Models for the economics of resilience." *J. Risk Uncertainty Eng. Syst. Part A: Civ. Eng.* 2 (4): 04016003.

Glover, J. D., M. S. Sarma, and T. Overbye. 2012. *Power system analysis and design*. Boston: Cengage Learning.

Goldberg, D. E. 1989. *Genetic algorithms in search, optimization, and machine learning*. Reading, MA: Addison-Wesley.

Guidotti, R., P. Gardoni, and Y. Chen. 2017. "Network reliability analysis with link and nodal weights and auxiliary nodes." *Struct. Saf.* 65: 12–26.

Hassan, E., and H. Mahmoud. 2019. "Full functionality and recovery assessment framework for a hospital subjected to a scenario earthquake event." *Eng. Struct.* 188: 165–177.

Henry, D., and J. E. Ramirez-Marquez. 2012. "Generic metrics and quantitative approaches for system resilience as a function of time." *Reliab. Eng. Syst. Saf.* 99: 114–122.

Jenelius, E., and L.-G. Mattsson. 2015. "Road network vulnerability analysis: Conceptualization, implementation and application." *Comput. Environ. Urban Syst.* 49 (1): 136–147.

Jenelius, E., T. Petersen, and L.-G. Mattsson. 2006. "Importance and exposure in road network vulnerability analysis." *Transp. Res. Part A Policy Pract.* 40 (7): 537–560.

Jones, D. A., L. K. Nozick, M. A. Turnquist, M. W. Hollingsworth, C. R. Lawton, M. A. Ehlen, et al. 2003. *Impact analysis of potential disruptions to major railroad bridges in the U.S.—Phase I Report*. Albuquerque, NM: National Infrastructure Simulation and Analysis Center, Sandia National Laboratories.

Kaplan, S., and B. J. Garrick. 1981. "On the quantitative definition of risk." *Risk Anal.* 1: 11–27.

Koetse, M. J., and P. Rietveld. 2009. "The impact of climate change and weather on transport: An overview of empirical findings." *Transp. Res. Part D Transp. Environ.* 14 (3): 205–221.

Kwakkel, J. H., and E. Pruyt. 2013. "Exploratory modeling and analysis, an approach for model-based foresight under deep uncertainty." *Technol. Forecasting Social Change* 80 (3): 419–431.

Lambert, J. H., Y.-J. Wu, H. You, A. Clarens, and B. Smith. 2013. "Climate change influence on priority setting for transportation infrastructure assets." *J. Infrastruct. Syst.* 19 (1): 36–46.

Latora, V., and M. Marchiori. 2001. "Efficient behavior of small-world networks." *Phys. Rev. Lett.* 87 (19): 4.

Lempert, R., N. Nakicenovic, D. Sarewitz, and M. Schlesinger. 2004. "Characterizing climate-change uncertainties for decision-makers. An editorial essay." *Clim. Change* 65 (1–2): 1–9.

Maier, M. W. 1998. "Architecting principles for systems-of-systems." *Syst. Eng.* 1 (4): 267–284.

MLGW (Memphis Light, Gas and Water). 2017. "How MLGW restores power." Press release. Accessed July 10, 2019. http://www.mlgw.com/news/how-mlgw-restores-power-5-2017.

Mori, Y., and B. R. Ellingwood. 1993. "Time-dependent system reliability analysis by adaptive importance sampling." *Struct. Saf.* 12 (1): 59–73.

Mostafavi, A., D. Abraham, and D. DeLaurentis. 2014. "Ex-ante policy analysis in civil infrastructure systems." *J. Comput. Civil Eng.* 28 (5): A4014006.

Mostafavi, A., D. M. Abraham, D. DeLaurentis, and J. Sinfield. 2011. "Exploring the dimensions of systems of innovation analysis: A system of systems framework." *IEEE Syst. J.* 5 (2): 256–265.

Mostafavi, A., D. Abraham, D. DeLaurentis, J. Sinfield, A. Kandil, and C. Queiroz. 2016. "Agent-based simulation model for assessment of financing scenarios in highway transportation infrastructure systems." *J. Comput. Civil Eng.* 30 (2): 04015012.

Mostafavi, A., D. M. Abraham, and J. Lee. 2012. "System-of-systems approach for assessment of financial innovations in infrastructure." *Built Environ. Project Asset Manage.* 2 (2): 250–265.

Mostafavi, A., and N. E. Ganapati. 2019. "Toward convergence disaster research: Building integrative theories using simulation." *Risk Anal.* https://doi.org/10.1111/risa.13303

NEI (Nuclear Energy Institute). 2016. *Diverse and flexible coping strategies (FLEX) implementation guide*. NEI 12-06, Revision 4. Washington, DC: NEI. Accessed March 18, 2020. https://www.nrc.gov/docs/ML1635/ML16354B421.pdf.

NEII (Nuclear Energy Institute Infographic). 2012. "Making safe nuclear energy safer after Fukushima." Accessed March 18, 2020. http://assets.safetyfirst.nei.org.s3.amazonaws.com/wordpress/wp-content/uploads/2012/03/NEI_Infographic.jpg.

Newman, M. E. J. 2010. *Mathematics of networks. Networks, an introduction*, 99–166. New York: Oxford University Press.

Ortiz-García, J. J., S. B. Costello, and M. S. Snaith. 2006. "Derivation of transition probability matrices for pavement deterioration modeling." *J. Transp. Eng.* 132 (2): 141–161.

Pahl-Wostl, C. 2002. "Towards sustainability in the water sector—The importance of human actors and processes of social learning." *Aquat. Sci.* 64 (4): 394–411.

Paul, S. K. 2014. "Vulnerability concepts and its application in various fields: A review on geographical perspective." *J. Life Earth Sci.* 8: 63–81.

Petit, T. J., J. Fiksel, and K. L. Croxton. 2010. "Ensuring supply chain resilience: Development of a conceptual framework." *J. Bus. Logist.* 31: 1–21.

Powell, M., J. Taylor, and S. Baier. 2013. "Developing the FLEX Plan, 2013." NS Energy. Accessed March 14, 2020. https://www.nsenergybusiness.com/features/featuredeveloping-the-flex-plan/.

PPD (Presidential Policy Directive). 2011. "Presidential policy directive 8 and the national preparedness system: Background and issues for congress." Accessed August 13, 2019. https://fas.org/sgp/crs/homesec/R42073.pdf.

PPD. 2013. "Critical infrastructure security and resilience." PPD-21. Accessed May 12, 2019. https://obamawhitehouse.archives.gov/the-press-office/2013/02/12/presidential-policy-directive-critical-infrastructure-security-and-resil.

Rashedi, R., and T. Hegazy. 2016. "Holistic analysis of infrastructure deterioration and rehabilitation using system dynamics." *J. Infrastruct. Syst.* 22 (1): 04015016.

Rasoulkhani, K., B. Logasa, M. Presa Reyes, and A. Mostafavi. 2018. "Understanding fundamental phenomena affecting the water conservation technology adoption of residential consumers using agent-based modeling." *Water* 10 (8): 993.

Rasoulkhani, K., and A. Mostafavi. 2018. "Resilience as an emergent property of human-infrastructure dynamics: A multi-agent simulation model for characterizing regime shifts and tipping point behaviors in infrastructure systems." *PLoS One* 13 (11): e0207674.

Rasoulkhani, K., A. Mostafavi, J. Cole, and S. Sharvelle. 2019. "Resilience-based infrastructure planning and asset management: Study of dual and singular water distribution infrastructure performance using a simulation approach." *Sustainable Cities Soc.* 48: 101577.

Rechtin, E. 1991. *Systems architecting: Creating and building complex systems*. Englewood Cliffs, NJ: Prentice Hall.

Reed, D. A., K. C. Kapur, and R. D. Christie. 2009. "Methodology for assessing the resilience of networked infrastructure." *IEEE Syst. J.* 3 (2): 174–180.

Reed, D. A., S. Wang, K. C. Kapur, and C. Zheng. 2015. "Systems-based approach to interdependent electric power delivery and telecommunications infrastructure resilience subject to weather-related hazards." *J. Struct. Eng.* 142 (8): C4015011.

Rehan, R., M. A. Knight, C. T. Haas, and A. J. A. Unger. 2011. "Application of system dynamics for developing financially self-sustaining management policies for water and wastewater systems." *Water Res.* 45 (16): 4737–4750.

Rose, A. 2007. "Economic resilience to natural and man-made disasters: Multidisciplinary origins and contextual dimensions." *Environ. Hazards* 7: 383–398.

Saadat, Y., B. M. Ayyub, Y. J. Zhang, D. M. Zhang, and H. W. Huang. 2019. "Resilience of metrorail networks: Quantification with Washington D.C. as a case study." *ASCE-ASME J. Risk Uncertainty Eng. Syst. Part B: Mech. Eng.* 5 (4): 041011.

Saadat, Y., B. M. Ayyub, Y. Zhang, D. Zhang, and H. Huang. 2020. "Resilience-based strategies for topology enhancement and recovery of metrorail transit networks." *ASCE-ASME J. Risk Uncertainty Eng. Syst. Part A: Civ. Eng.* 6 (2): 04020017.

Sanford Bernhardt, K. L., and S. McNeil. 2008. "Agent-based modeling: Approach for improving infrastructure management." *J. Infrastruct. Syst.* 14 (3): 253–261.

Sharma, N., and P. Gardoni. 2019. "Modeling the time-varying performance of electrical infrastructure during post disaster recovery using tensors." In *Handbook of sustainable and resilient infrastructure*, edited by P. Gardoni, 259–276. Abington, UK: Routledge.

Sharma, N., A. Tabandeh, and P. Gardoni. 2018. "Resilience analysis: A mathematical formulation to model resilience of engineering systems." *Sustainable Resilient Infrastruct.* 3 (2): 49–67.

Sharma, N., A. Tabandeh, and P. Gardoni. 2019a. "Regional resilience analysis: A multi-scale formulation to model the recovery of interdependent infrastructure." In *Handbook of sustainable and resilient infrastructure*, edited by P. Gardoni, 521–544. Abington, UK: Routledge.

Sharma, N., A. Tabandeh, and P. Gardoni. 2019b. "Recovery optimization of interdependent infrastructure: A multi-scale approach." In *Proc., 13th Int. Conf. on Applications of Statistics and Probability in Civil Engineering*.

Shinozuka, M., A. Rose, and R. T. Eguchi. 1998. *Engineering and socioeconomic impacts of earthquakes*. Monograph 98-MN02. Buffalo, NY:

Multidisciplinary Center for Earthquake Engineering Research (MCEER).

Steelman, J., J. Song, and F. Jerome. 2007. *Integrated data flow and risk aggregation for consequence-based risk management of seismic regional losses*. Technical Rep. Urbana, IL: Mid-America Earthquake Center, University of Illinois at Urbana-Champaign.

Tabandeh, A., P. Gardoni, C. Murphy, and N. Myers. 2019. "Societal risk and resilience analysis: Dynamic Bayesian network formulation of a capability approach." *ASCE-ASME J. Risk Uncertainty Eng. Syst. Part A: Civ. Eng.* 5 (1): 04018046.

Tierney, K., and M. Bruneau. 2007. "Conceptualized and measuring resilience." *TR News* 250: 14–17. Accessed April 8, 2015. http://onlinepubs.trb.org/onlinepubs/trnews/trnews250_p14-17.pdf.

Vugrin, E. D., M. J. Baca, M. D. Mitchell, and K. L. Stamber. 2014a. "Evaluating the effect of resource constraints on resilience of bulk power system with an electric power restoration model." *Int. J. Syst. Syst. Eng.* 5 (1): 68–91.

Vugrin, E. D., M. A. Turnquist, and N. J. K. Brown. 2010. *Optimal recovery sequencing for critical infrastructure resilience assessment*. Technical Rep. SAND2010-6237. Albuquerque, NM: Sandia National Laboratories.

Vugrin, E. D., M. A. Turnquist, and N. J. K. Brown. 2014b. "Optimal recovery sequencing for enhanced resilience and service restoration in transportation networks." *Int. J. Crit. Infrastruct.* 10 (3/4): 218–246.

Vugrin, E. D., S. J. Verzi, P. D. Finley, M. A. Turnquist, A. R. Griffin, K. A. Ricci, and T. Wyte-Lake. 2015. "Modeling evacuation of a hospital without electric power." *Prehospital Disaster Med.* 30 (3): 279–287.

Vugrin, E. D., D. E. Warren, and M. A. Ehlen. 2011. "A resilience assessment framework for infrastructure and economic systems: Quantitative and qualitative resilience analysis of petrochemical supply chains to a hurricane." *Process Saf. Prog.* 30 (3): 280–290.

Washington DC Metro Fiscal Year (FY) Budget. 2018. Accessed October 31, 2018. https://www.wmata.com/about/records/public_docs/upload/Metro_FY2018_Proposed_Budget_15Dec16_v4.pdf.

Zhu, J., and A. Mostafavi. 2014. "Towards a new paradigm for management of complex engineering projects: A system-of-systems framework." In *Proc., IEEE Int. Systems Conf*. 213–219, 2014. Ottawa, ON.

Zhu, J., and A. Mostafavi. 2018. "Performance assessment in complex engineering projects using a system-of-systems framework." *IEEE Syst. J.* 12 (1): 262–273.