The World Health Organization (WHO) stated that healthcare systems "must be physically resilient and able to remain operational and continue providing vital health services" after disasters (WHO 2007). Thus, healthcare systems need to be resilient enough to cope with earthquakes and to provide timely medical treatment. Strong earthquakes can destroy infrastructure systems and cause injuries and/or fatalities. Therefore, it is important to investigate the seismic performance of interdependent healthcare – bridge network systems to guarantee immediate medical treatment after earthquakes. In this chapter, the seismic performance assessment of a healthcare system located near a bridge network is investigated considering both component and system performance levels and considering the correlation effects. After a destructive earthquake, the functionality of a highway network can be affected significantly; this, in turn, may hinder the emergency management. Additional travel time would result because of damaged bridges and links; consequently, injured persons may not receive treatment on time. Thus, it is important to account for the effects of damaged condition associated with a highway bridge network on the healthcare system performance (Dong and Frangopol 2017a). The flowchart used to compute the performance of an interdependent healthcare-bridge network is shown in Figure 3-6 (Dong and Frangopol 2017a). Overall, to achieve a resilient system, networks should be considered in the overall planning and operation before and after a disaster. The simulation framework for the interdependent infrastructure should be conducted to assess the correlation among these networks. Then based on the assessment, the

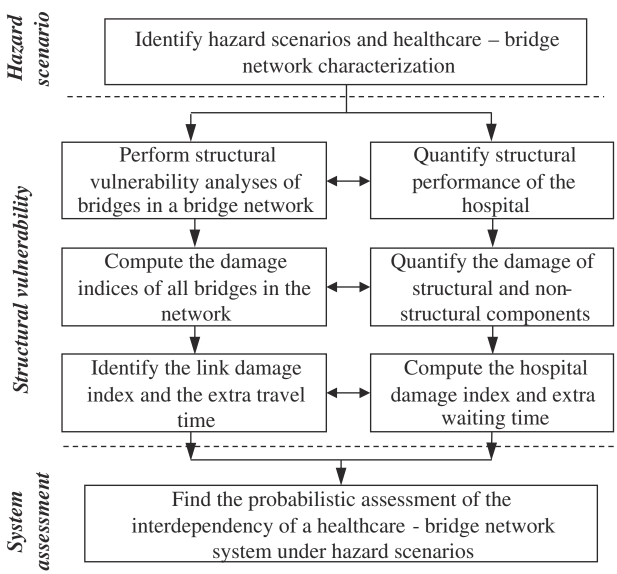

Figure 3-6. Performance assessment of the interdependent healthcare – bridge network system.
Source: Adapted from Dong and Frangopol (2017a).

optimization maintenance and mitigation plans for the infrastructure network considering these interdependencies can be formulated. The performance of other interdependent networks was also investigated in other studies. For instance, Eusgeld et al. (2011) presented an example of the coupling between the electric power system and the gas transportation network using a "system-of-systems" approach. Wu et al. (2016) captured the interdependencies among infrastructure systems when terrorist attacks occur considering not only the properties of topology and function of the infrastructure systems, but also the physical interdependencies and geographical interdependencies among these critical systems. Nan and Sansavini (2017) proposed an integrated metric for the quantitation of the coupling strength associated with interdependent networks and was applied to a system composed of three subsystems. Overall, it is of vital importance to understand the system resilience and to identify ways to enhance it, especially for interdependent networks.

3.5 LIFE-CYCLE ASSESSMENT

The life-cycle assessment and management approach has been widely adopted within the performance assessment of bridge networks (Bocchini et al. 2011; Bocchini and Frangopol 2011b; Dong et al. 2014b, 2015; Biondini and Frangopol 2016a, b; Frangopol et al. 2017). The life-cycle assessment could also be adopted within the assessment of other networks, for instance, to assess the performance of energy networks. Life-cycle assessment can improve our understanding of the life-cycle energy, GHG and air pollution emissions, and water-use implications of different power systems, including the activities related to raw materials acquisition, manufacturing, transportation, installation, operation, maintenance, and demolishing procedures. Overall, the life-cycle assessment can provide a comprehensive framework for assessing the performance of different networks and allowing for more sustainable and robust decisions.

To predict the performance of structural systems during their life cycle, deterioration mechanisms for the investigated systems must be carefully considered. Aggressive environmental conditions and aging processes facilitate a gradual reduction in the performance (e.g., system reliability) of existing networks. Alternatively, extreme events (blasts, fires, earthquakes, hurricanes, and terrorist attacks) can cause an abrupt reduction of the functionality of structures. During their life-cycle, these networks can be subjected to multiple hazards. Thus, it is necessary to consider the performance under structural deteriorations and hazard effects in a life-cycle context.

Furthermore, the effects of maintenance, repair, and rehabilitation on structural life-cycle performance should be well understood. The influence of maintenance and repairs on structural performance can be incorporated in a generalized framework for multi-criteria optimization of the life-cycle management of infrastructure networks (Frangopol 2011; Frangopol and Soliman 2016;

Frangopol et al. 2017). One of the most important life-cycle performance measures in the evaluation of a network is life-cycle cost. The total cost during the lifetime of a network can be expressed as (Frangopol et al. 1997a)

$$C_{ET} = C_T + C_{PM} + C_{INS} + C_{REP} + C_F \tag{3-12}$$

where
C_T = Initial cost,
C_{PM} = Expected cost of routine maintenance cost,
C_{INS} = Expected cost of inspections,
C_{REP} = Expected cost of repair, and
C_F = Expected failure cost.

The total cost of maintenance actions for an entire network during a time horizon can be expressed as (Liu and Frangopol 2006b)

$$C_{\mathrm{PM}} = \sum_{i=1}^{k} \sum_{j=1}^{N_i^{\mathrm{PM}}} \frac{C_{ij}^{\mathrm{PM}}(t_{ij})}{(1+\gamma)^{t_{ij}}} \tag{3-13}$$

where
k = Number of components within a network,
N_i^{PM} = Number of maintenance actions for component i during the investigated time span,
C_{ij}^{Ret} = Maintenance cost associated with action j on component i,
t_{ij} = Application time of the maintenance, and
γ = Monetary discount rate.

The failure cost associated with an extreme event (e.g., earthquake and flood) should also be incorporated within the evaluation process. Given the occurrence of the hazard as a Poisson process, the total life-cycle failure loss of a component during the time interval $[0, t_{int}]$ can be computed as (Dong and Frangopol 2016a, b)

$$C_F(t_{\mathrm{int}}) = \sum_{i=1}^{N(t_{\mathrm{int}})} l(t_k) \cdot e^{-\gamma t_k} \tag{3-14}$$

where
t_{int} = Investigated time interval,
$N(t_{int})$ = Number of hazard events that occur during the time interval, and
$l(t_k)$ = Expected annual hazard loss at time t_k given the occurrence of the hazard.

Given the Poisson model with mean rate equal to λ_f, the total expected failure loss under hazard effects can be computed as

$$E[C_F(t_{\mathrm{int}})] = \frac{\lambda_f \cdot E(l)}{\gamma} \cdot (1 - e^{-\gamma \cdot t_{\mathrm{int}}}) \tag{3-15}$$

where $E(l)$ is the expected value of annual loss l of a component (e.g., bridge, building) given a hazard event, respectively.

The network can be regarded as a group of components. The losses associated with the components within a network are correlated. The variance of loss of a network depends not only on the expected value of total loss but also on the variance and the correlation among the losses. Considering the correlation effects, the variance of the annual loss of a network under an extreme event is expressed as (Dong and Frangopol 2017b)

$$\mathrm{Var}(RL) = \sum_{i=i}^{n_{bu}} \mathrm{Var}(l_i) + 2 \cdot \sum_{i=1,i<j}^{n_{bu}} \sum_{j}^{n_{bu}} \rho(l_i,l_j) \cdot \sqrt{\mathrm{Var}(l_i) \cdot \mathrm{Var}(l_j)} \quad (3\text{-}16)$$

where
$\rho(l_i, l_j)$ is the correlation coefficient between the annual flood loss of component i and component j under the given extreme event, and
$\mathrm{Var}(l_i)$ and $\mathrm{Var}(l_j)$ are the variances of the annual loss of the components i and j, respectively.

Considering the uncertainties within the life-cycle cost analysis, the probability of exceedance of life-cycle cost during a certain time interval can be estimated. This information can aid the decision-making process with respect to the hazard mitigation strategy.

3.6 LIFE-CYCLE OPTIMAL MANAGEMENT

3.6.1 Cost–Benefit Analysis

Cost–benefit analysis is a commonly used method to compare the cost and benefit of different maintenance and mitigation strategies over an investigated time interval (Dong and Frangopol 2017b). Herein, cost–benefit analysis can be adopted to support the performance improvement procedure of a network with correlated components in a life-cycle context. Quantifying the relationship between the retrofit actions and the retrofit cost can help the decision regarding the management process. For instance, the flowchart of the cost-benefit analysis of hazard mitigation strategy of a structural component is indicated in Figure 3-7 (Dong and Frangopol 2017b). The investigated hazard scenarios, time interval, and structural performance under retrofit actions are considered within the cost–benefit analysis process. The probabilistic benefit-cost ratio is introduced to directly compare the benefit and cost of a retrofit action and aid the decision making associated with hazard mitigation. The benefit-cost ratio can be calculated as

$$CB_{BP} = (LCC_{BP,NR} - LCC_{BP,WR})/C_{r,BP} \quad (3\text{-}17)$$

$$C_{r,BP} = \sum_{i=0}^{n_{bu}} c_{r,bi} \quad (3\text{-}18)$$

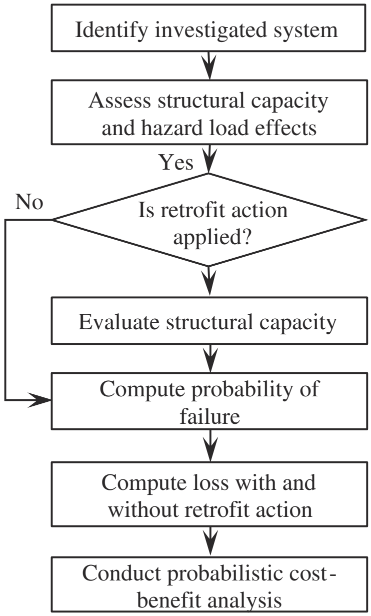

Figure 3-7. Cost–benefit analysis associated with retrofit actions.
Source: Adapted from Dong and Frangopol (2017b).

where
$LCC_{BP,NR}$ and $LCC_{BP,WR}$ = Life-cycle cost of a network under hazard effects without and with retrofit, respectively,
$C_{r,BP}$ = Total retrofit cost of the network, and
$c_{r,bi}$ = Retrofit cost associated with component i within the network.

The benefit-cost ratio essentially quantifies the effectiveness of a retrofit plan. Values less than 1 indicate that retrofit is not cost-effective, whereas values greater than 1 denote that it is beneficial to perform the retrofit. For a network under climate change effects, the cost–benefit analysis can be used to compare the cost and benefit of different structural adaptation strategies over an investigated time interval (Dong and Frangopol 2017c). The cost–benefit analysis involves determining the cost and benefit associated with structural adaptation. Quantification of the relationship between benefit and cost associated with structural adaptations can facilitate an effective decision-making process regarding the adaptation procedure.

3.6.2 Optimization

For the optimal adaptation management of a network, an optimal decision should be made regarding the types of adaptation actions on the components within the investigated network under limited resources (Dong et al. 2014a, b; Frangopol et al. 2017). Different objectives could be considered within the optimization process, such as the expected life-cycle loss and the total adaptation cost, which are used within an optimization procedure as the objective functions selected to be minimized. The optimization process associated with optimal retrofit planning of a transportation network is indicated in Figure 3-8 (Dong et al. 2014b). As shown, first the optimization process sends the candidates for the design variables (e.g., adaptation actions applied to each component within the investigated region) to the performance (i.e., Objective 1) and cost (i.e., Objective 2) modules, which compute the value of each objective function associated with life-cycle loss and total adaptation cost. The constraint on time span between consecutive actions can reflect the budget constraint. The outcome of the performance module is the expected total life-cycle loss during the investigated time interval, considering the hazard probability of occurrence, structural vulnerability, damage, and loss. Genetic algorithms (GAs) can be adopted with an adequate number of generations to obtain the set of Pareto optimum solutions associated with the multi-objective problem. The solutions from the optimization process can provide the information on the sequence of component retrofitting. Accordingly, the information regarding component importance can be obtained. After an adequate number of generations, the optimization module provides the Pareto optimum solutions for the timing of retrofit actions for each component. The effect of climate change on the Pareto optimal front is investigated. Pareto optimal fronts considering changing climates are shown in Figure 3-9 (Dong and Frangopol 2017c). As indicated, assuming the similar life-cycle loss, the case considering climate change effects will result in a larger value associated with total adaptation cost than that without considering climate change. Given the Pareto optimal solutions, the decision maker can choose one option based on his/her own need.

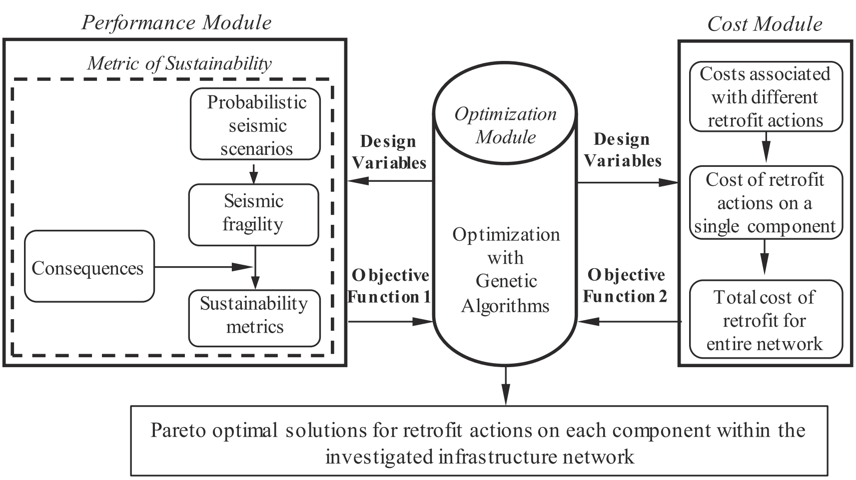

Figure 3-8. Optimization process for the retrofit plans of infrastructure networks.
Source: Adapted from Dong et al. (2014b).

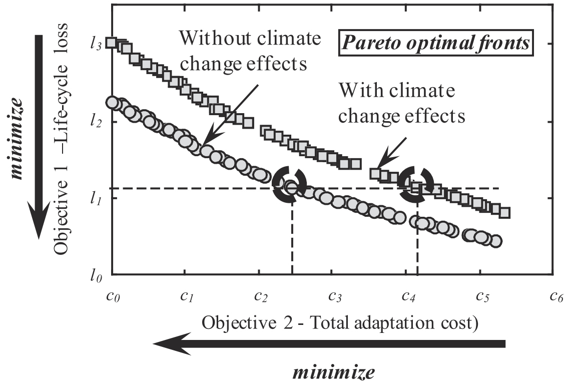

Figure 3-9. Pareto optimal solutions with and without considering climate change effects.
Source: Adapted from Dong and Frangopol (2017c).

The optimization process could be applied to different infrastructure networks, such as bridge networks and water distribution networks, to minimize the life-cycle cost and to maximize the performance as objectives. The relevant structural performance should be assessed in a life-cycle context. For instance, Jayaram and Srinivasan (2008) presented a performance-based optimal design and rehabilitation approach for water distribution networks considering the life-cycle performance. The life-cycle cost was considered to comprise the initial cost of pipes, cost of replacing the old pipes with new ones, cost of cleaning and lining existing pipes, the repair cost associated with pipe break, and the salvage value of the pipes that are replaced. The resilience indicator was incorporated within the optimization process. Then given the optimization techniques (e.g., GA), the Pareto optimal solutions associated with multiple objectives can be achieved. In addition, the recent increasing awareness of sustainability and climate change, especially global warming, has led to research in which GHG emissions are considered. The GHG emissions in a life-cycle context of different networks could also be incorporated within the optimization process to aid the development of a sustainable society. Wu et al. (2009) investigated the impact of minimizing the GHG emissions on the optimization of water distribution networks and found that the inclusion of GHG emission minimization as one of the objectives can result in significant trade-offs between the economic and environmental objectives.

The optimization could aid the hazard management process. In general, the disaster management program consists of three aspects: predisaster activities, emergency response activities, and postdisaster recovery activities. The predisaster activities conduct the risk assessment, risk mitigation, and planning to obtain the optimal actions before the occurrence of a disaster to reduce its consequences and enhance resilience. The emergency response activities include implementation of the repair activities with the available resources under the emergency condition. The postdisaster recovery activities involve the consideration of the long-term performance goal, such as restoration of the lifeline system to its original condition and functionality. The optimization technologies could be adopted to obtain optimal retrofit plans for infrastructure as a means of predisaster risk mitigation and optimal emergency response operations. For instance, after a power outage caused by a natural disaster, the most important task for system operators is to restore the power system as quickly as possible and minimize the economic loss to customers. The research on how to optimize the recovery program could potentially save a large amount of money, as well as increase the resilience of the program.

3.7 CONCLUSIONS

This chapter presents a brief overview of the assessment and management of networks incorporating risk, sustainability, and resilience measures in a life-cycle context. The framework covers predicting the component and system performance and scheduling the optimal interventions, including inspections, monitoring, maintenance, and/or repair actions to enhance the life-cycle performance and resilience. Various aspects of the life-cycle assessment and management framework are briefly explained with special attention given to the performance assessment and the life-cycle optimization processes. Structural deterioration, extreme events, and climate change are considered and incorporated within a probabilistic framework. Furthermore, this chapter presents available methodologies for quantifying the economic, social, and environmental metrics and resilience of networks. The presented framework supports the resilient and sustainable development of infrastructure networks and provides the optimal intervention decisions related to design, inspection, maintenance, monitoring, repair, and replacement of networks under multiple objectives and constraints. To aid the development of sustainable and resilient infrastructure networks in a life-cycle context, advanced modeling, computation, assessment, and optimization methods should be developed.

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