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Inspection and Restoration Scheduling of Roadway and Other Lifeline Systems for Improved Post-disaster Infrastructure Systems Recovery

February 13, 2022

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LARSON TRANSPORTATION INSTITUTE

Technical Report Documentation Page

1. Report No.	**2. Government Accession No.**	**3. Recipient's Catalog No.**
CIAM-COR-R03		

4. Title and Subtitle

Inspection and Restoration Scheduling of Roadway and Other Lifeline Systems for Improved Post-disaster Infrastructure Systems Recovery

5. Report Date

February 13, 2022

6. Performing Organization Code

7. Author(s)

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8. Performing Organization Report No.

9. Performing Organization Name and Address

George Mason University
4400 University Drive
Fairfax, VA 22030

10. Work Unit No. (TRAIS)

11. Contract or Grant No.

69A3551847103

12. Sponsoring Agency Name and Address

U.S. Department of Transportation
Research and Innovative Technology Administration
3rd Fl, East Bldg E33-461
1200 New Jersey Ave, SE
Washington, DC 20590

13. Type of Report and Period Covered

Final Report 01-19-2020 – 07-31-2021

14. Sponsoring Agency Code

15. Supplementary Notes

Work funded through The Pennsylvania State University through the University Transportation Center Grant Agreement, Grant No. 69A3551847103.

16. Abstract

Natural hazards, such as hurricanes, cyclones, typhoons, earthquakes, and wind and ice events pose significant issues for the performance of critical lifelines, including roadways, railways, airways, waterways, gas lines, power systems, water supply systems, and wastewater networks. Post-disaster performance of roadway networks, in particular, is crucial, as the roadways are key links used in providing humanitarian relief aid, giving access for emergency response, and completing infrastructure repairs, such as to power (electricity and gas) and water and wastewater lines. It can also be critical in cleanup efforts, directly impacting human health. The main objective of this project was to develop a solution methodology for jointly devising post-disaster inspection and restoration activity schedules to minimize roadway downtime and maximize opportunities for timely completion of repairs to other lifelines over the recovery period. A second objective was to complete numerical experiments to show the benefits of coordinating actions over multiple lifelines in bringing back services to a community impacted by a disaster event.This project created a multi-stage stochastic programming formulation for jointly devising post-disaster inspection and restoration activity schedules to minimize roadway downtime and maximize opportunities for timely completion of repairs to other lifelines over the recovery period. Each lifeline is presumed to have dedicated inspection and repair crews, but no crew can access its lifeline element if no pathway to them exists. The formulation presumes the occurrence of a randomly arising disaster event whose impact may damage roadway links or other critical lifeline components, and its effects are only revealed at the time of inspection. That is, the status of the infrastructure links and nodes is known only with uncertainty and implemented and restoration cannot take place until inspection is complete. Results from an illustrative application show the benefits of coordinating actions over multiple lifelines in bringing back services to a community impacted by a disaster event.

17. Key Words

Infrastructure inspection, restoration, natural disaster, lifeline system, roadway connectivity

18. Distribution Statement

No restrictions. This document is available from the National Technical Information Service, Springfield, VA 22161

19. Security Classif. (of this report)	**20. Security Classif. (of this page)**	**21. No. of Pages**	**22. Price**
Unclassified	Unclassified	55	

Form DOT F 1700.7 **(8-72) Reproduction of completed page authorized**

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CHAPTER 1

Introduction

BACKGROUND

Natural hazards, such as hurricanes, cyclones, typhoons, earthquakes, and wind and ice events pose significant issues for the performance of critical lifelines, including roadways, railways, airways, waterways, gas lines, power systems, water supply systems, and wastewater networks. Post-disaster performance of roadway networks, in particular, is crucial, as the roadways are key links used in providing humanitarian relief aid, giving access for emergency response, and completing infrastructure repairs, such as to power (electricity and gas) and water and wastewater lines. It can also be critical in cleanup efforts, directly impacting human health.

The performance of the roadways depends on an ability to quickly assess roadway facility conditions, as roadways may be blocked with debris, inundated with water, or damaged. Information on the roadway elements, as well as on other infrastructure components, can be obtained from real-time condition monitoring or surveillance systems and supplemental inspection. While the use of remote sensing and Unmanned Aerial Vehicles (UAVs), such as drones, has increased in recent years and has been an excellent source of information on infrastructure condition in disaster areas (Fu et al., 2021), it is not a panacea and cannot totally replace the need for on-site inspection. UAVs can malfunction, have limited flight time, have obstructed views, and view only a surface. Their ability to fly is affected by weather. Some of these limitations are noted in (Ciampa, 2019). On-site, in-depth inspection is needed to confirm or deny sensed conditions and provide needed details of repair requirements. These inspection activities across infrastructure lifelines rely on access via the same roadway and bridge system that is under examination. Thus, some restoration activities to the roadway elements may need to be completed before inspections of other roadway network elements or elements of other infrastructure lifelines can even begin. The order in which these inspection and restoration activities take place can greatly affect the time until services from critical lifelines are restored, and the simultaneous consideration of the restoration needs of multiple lifelines given their reliance on the roadway network facilitates faster overall recovery of the communities they serve.

This project created a multi-stage stochastic programming formulation for jointly devising post-disaster inspection and restoration activity schedules to minimize roadway downtime and maximize opportunities for timely completion of repairs to other lifelines over the recovery period. Each lifeline is presumed to have dedicated inspection and repair crews, but no crew can access its lifeline element if no pathway to them exists. The formulation presumes the occurrence of a randomly arising disaster event whose impact may damage roadway links or other critical lifeline components, and its effects are only revealed at the time of inspection. That is, the status of the infrastructure links and nodes is known only with uncertainty. The status of the links and nodes is revealed only after an inspection decision is taken and implemented and restoration cannot take place until inspection is complete. The inspection and restoration crews are assumed to be stationed at a depot. If damaged, a roadway link is presumed to be impassable, powerline to be nonfunctioning, and water or gas pipeline to be broken, and an element at a node, such as a substation in a power distribution system or pump in a water supply system, to be nonfunctional.

When an inspection decision is taken, the inspection crew is sent from the depot to the inspection site. Inspectors, though, may not be able to access the site to complete repairs until a path is opened through roadway restoration actions. Thus, a cyclic relationship exists between inspection and restoration. Figure 1 illustrates this cyclic relationship between inspection and restoration on a toy network involving transportation and power networks with a single inspection-repair crew located pre-event at node 0. In Figure 1, links 1 and 3 are damaged during the disaster event. If the crew wishes to inspect the power substation located at node 4, a path from the depot to node 4 must be open. Yet some links that prevent access are down and cannot be repaired without first being inspected themselves. The figure shows the order in which inspection and restoration actions may be taken to account for the needed extra inspection-repair actions on the roadway network, where priority is given to the power network.

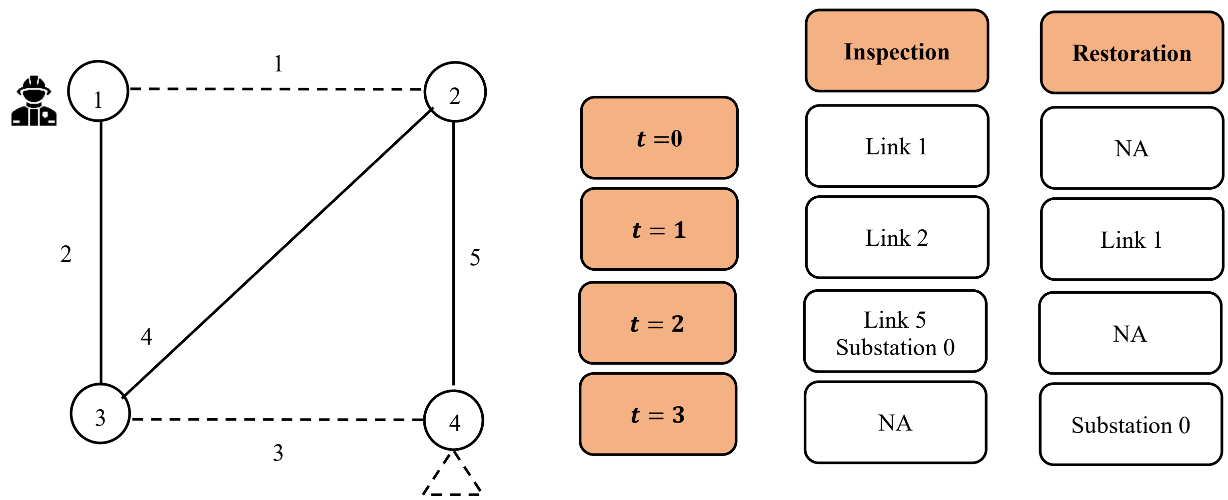


Figure 1. Cyclic relationship between inspection and repair across networks.

Since inspection decisions are outcomes of the mathematical model and inspection actions reveal the state of the links and nodes, uncertainty in this problem context is decision-dependent or endogenous. Goel and Grossmann (2006) divide stochastic programs with endogenous uncertainty into two types: Type 1, where decisions impact the probability of the random variable realizations, and Type 2, where decisions impact the timing of their realization. The problem studied in this project is of Type 2, in which inspection and repair decisions impact the timing of link and substation status realization. The vast majority of stochastic programs presented in the literature assume that the realization of the random variables occurs despite any decisions that are or are not taken. They are automatically realized at the end of a time stage. Consider a problem arising in retail, where customers decide whether or not to make a purchase. The retailer learns the demand for its product only at the end of the stage, and this demand is realized at this point regardless of any decisions made to this point. In this inspection-restoration problem, using the same logic, inspection outcomes would be realized whether or not decisions to inspect are made. To correct this, it is critical to allow the realization of random variables to be dependent on the decisions that are taken.

OBJECTIVES

The main objective of this project was to develop a solution methodology for jointly devising post-disaster inspection and restoration activity schedules to minimize roadway downtime and maximize opportunities for timely completion of repairs to other lifelines over the recovery period. A second objective was to complete numerical experiments to show the benefits of coordinating actions over multiple lifelines in bringing back services to a community impacted by a disaster event.

DATA AND DATA STRUCTURES

Data on the test network, including roadways, , and transmission lines of Arlington, Virginia were extracted from (County Board, 2010) and are described in Chapter 3.

CHAPTER 2

Literature Review

Numerous works in the literature propose optimization-based methods for scheduling post-disaster restoration actions for the purpose of restoring roadway connectivity. Table 1 synthesizes this literature. These works aim to optimize the scheduling of restoration activities with varying objectives, including, for example, maximizing network resilience, minimizing time to create a particular connection or to restore the entire network, minimizing cost for repairing damaged roadways, minimizing latency (time it takes for repair crew to access a node), maximizing earliness in restoration completion, and more. While most of these works consider a single repair crew, a few seek schedules for multiple, identical crews (Ajam et al. 2021; Akbari and Salman, 2017 a,b; Akbari et al., 2021a,b).

The vast majority of prior relevant works presume perfect information about the state of all network components by the time decisions on restoration scheduling are to be made. Two works recognize uncertainty in restoration times: Akbari et al. (2021a) and Caunhye et al. (2020). Akbari et al. (2021a) exploit updated information on condition state of the roadway elements in scheduling restoration actions. Specifically, they proposed a mixed-integer program (MIP) to allow updated information for repair decisions as actions are completed and realized restoration times are revealed. Their work differs, though, in that it does not seek to optimize the information flow as is included herein through inspection decisions. Caunhye et al. (2020) proposed a robust optimization model to optimize repair action schedules given uncertainty in restoration times. Such a robust approach helps simplify the problem mathematically but can result in overly conservative and, therefore, expensive restoration schedules that may not prove useful under other, more likely realizations.

Inspection activities are optimized in only a few prior works: Kallioras et al., 2014; Lagaros and Karlaftis, 2011; Jha et al., 2011. Most of these works optimize the routing of drones to increase situational awareness in post-disaster settings (e.g., Zhang et al., 2021; Ribeiro et al., 2021;

Adsanver et al., 2021). These works do not consider how this information will be utilized in making restoration scheduling decisions.

Zhang and Wei (2021) considered the problem of inspecting and restoring bridges post disaster. They proposed a MIP to model the joint inspection-restoration problem and an iterative procedure with an embedded genetic algorithm for its solution. They require that any link to be restored must first be fully inspected, and until the link is inspected, and restored if needed, that link cannot be used for a single inspection and repair crew to reach other locations for any purpose. The inspection actions are scheduled to support restoration schedule optimization. Inspection reveals the state of the bridge and effort required for its repair if such action is needed. When the state of a bridge is revealed through inspection, the problem is re-solved with the updated, deterministically known information.

Of relevance in terms of methodology is work by Macias et al. (2020), who proposed a multi-stage stochastic program with endogenous uncertainty that integrates roadway inspection and relief distribution decisions for a humanitarian aid application. The model seeks optimal routes to use in the delivery of aid given knowledge of the roadway elements' states based on results of inspection decisions taken, which are completed by drones. No repair or cleanup activities are included, however. There are numerous additional works that model roadway debris cleanup to enable humanitarian aid logistics. See, for example: Aksu and Ozdamer, 2014; Lorca et al., 2015; Sayarshad et al., 2020; Çelik et al., 2015; Berktas et al., 2016. Generally, the goal of these works is to find an optimal scheduling plan for debris clearing of roadways to enable transfer of relief goods to demand locations. These humanitarian works are numerous, have been reviewed (Caunhye et al., 2012), and are not directly related to the goals of this project. Thus, they are omitted from Table 1.

Herein, in addition to integrating inspection and restoration decisions, two (or more) infrastructure lifelines are considered, where roadway connectivity or restoration of the full roadway can be secondary to restoration of a second or third infrastructure lifeline. Works that consider both roadways and a second lifeline with relevance to network restoration are listed in Table 1. The goals of these works have been to quantify and/or maximize resilience of a system operating interdependently with other systems, minimize restoration costs, maximize performance, minimize travel time, and minimize inaccessibility. Restoration, sometimes scheduled, is incorporated in these assessments, but is not the main focus. Moreover, these works presume full information; inspection is not required.

The contribution of this work arises from an investigation of coordination in inspection and restoration actions across multiple lifelines that explicitly accounts for the inherent uncertainties in post-disaster environments. It recognizes the decision dependence of information realization from optimally scheduled inspections in the state of the lifeline elements, capturing the key elements of this endogeneity in uncertainty through added model constraints. This work illustrates the special relationship that roadways have in post-disaster restoration with other lifelines that these other lifelines rarely reciprocate. That is, repair of the roadway elements facilitates repair to other lifelines, while their repair typically does not enable roadway functionality. One exception might be where power restoration enables better functioning at roadway intersections (Fotouhi and Miller-Hooks, 2017) or renewing fuel supplies at, or power to, fueling stations facilitates the movement of restoration teams.

Table 1. Literature review.

	Citation	Stochasticity	Infrastructure	Objective Function
Inspection	Adsanver et al., 2021	N	Single	maximize total priority scores of power grids visited by drones
Inspection	Chowdhury et al., 2021	N	Single	minimize post-disaster inspection cost
Inspection	Jha et al., 2011	N	Single	maximize revenue and minimize travel time
Inspection	Kallioras and Lagaros, 2017	N	Single	minimize the distance traveled by inspection crew
Inspection	Kallioras et al., 2014	N	Single	minimize the distance traveled by inspection crew
Inspection	Nedjati et al., 2016	N	Single	minimize inspection time
Inspection	Oruç Ağlar, 2019	N	Single	maximize total importance of elements inspected
Inspection	Oruc and Kara, 2018	N	Single	maximize total importance of elements inspected
Inspection	Redi et al., 2021	N	Single	minimize operating time
Inspection	Reyes-Rubiano et al., 2021	N	Single	minimize route length required by Unmanned Aerial Vehicles (UAVs) to assess links for accessibility to locations of victims
Inspection	Ribeiro et al., 2021	N	Single	minimize cost of UAVs
Inspection	Singgih et al., 2018	N	Single	minimize inspection time
Inspection	Zhang et al., 2021	N	Single	maximize profit collected by visiting elements
Repair	Ajam et al., 2019	N	Single	minimize latency (time for repair crew to reach node)
Repair	Ajam et al., 2021	N	Single	minimize latency
Repair	Akbari and Salman, 2014	N	Single	minimize maximum cost of a crew’s route
Repair	Akbari and Salman, 2017a	N	Single	minimize maximum cost of a crew’s route
Repair	Akbari and Salman, 2017b	N	Single	maximize prize collected by connecting components to the depot
Repair	Akbari et al., 2021a	N	Single	minimize total unblocking and traversal times
Repair	Akbari et al., 2021b	N	Single	minimize total unblocking and traversal times

	Citation	Stochasticity	Infrastructure	Objective Function
Repair	Aksu and Ozdamer, 2014	N	Single	maximize earliness of path repair compared to schedule
Repair	Alkhaleel et al., 2022	N	Multiple	maximize resilience
Repair	Almoghathawi et al., 2019	N	Multiple	maximize resilience
Repair	Atsiz et al., 2021	N	Multiple	minimize sum of recovery times for all network components
Repair	Baidya and Sun, 2017	N	Multiple	maximize total load pickup
Repair	Barkerring et al., 2018	N	Multiple	maximize resilience and minimize total cost
Repair	Caunhye et al., 2020	Y	Single	minimize needed time to restore a network
Repair	Cavdaroglu et al., 2013	N	Multiple	minimize cost (flow cost, cost for unsatisfied demand, installation, and assignment)
Repair	Duque and Sörensen, 2011	N	Single	minimize weighted sum of time to travel from each node to closest regional center
Repair	Duque et al., 2016	N	Single	minimize time a node becomes accessible
Repair	El-Anwar et al., 2016	N	Single	minimize cost
Repair	Fang and Sansavini, 2019	N	Multiple	minimize performance loss
Repair	Fotouhi et al., 2017	Y	Multiple	maximize resilience and minimize total travel time
Repair	García-Alviz et al., 2021	N	Single	minimize the time to finish trips
Repair	Ghannad and Lee, 2020	N	Single	minimize deviation from socioeconomic optimal solution, minimize the reconstruction cost and time
Repair	Ghannad et al., 2020	N	Single	minimize deviation from socioeconomic optimal solution, minimize the reconstruction cost and time
Repair	Gokalp et al., 2021	N	Single	minimize total travel delay
Repair	Gonzalez et al., 2016	N	Multiple	minimize total cost
Repair	Ho and Sumalee, 2014	N	Single	minimize travel cost
Repair	Iloglu and Albert, 2020	N	Single	maximize multiple coverage of emergency demand over time horizon

	Citation	Stochasticity	Infrastructure	Objective Function
Repair	Karakoc et al., 2019	N	Multiple	maximize resilience and minimize cost
Repair	Karalftis et al., 2007	N	Single	maximize total improvements made
Repair	Kasaei and Salman, 2016	N	Single	minimize unblocking and traversal times
Repair	Kaviani et al., 2020	N	Single	maximize resilience
Repair	Kim et al., 2017	N	Single	minimize sum of total damages caused by isolation
Repair	Kim et al., 2018	N	Single	minimize the total damages in isolation and minimize time to complete restoration
Repair	Kong et al., 2019	N	Multiple	minimize time to bring infrastructure resilience back to basic level
Repair	Kong et al., 2021	N	Multiple	maximize resilience
Repair	Lertworawanich, 2012	N	Single	minimize demand loss and network travel time
Repair	Li and Teo, 2019	N	Single	maximize accessibility, minimize time, maximize satisfaction
Repair	Liu et al., 2020	N	Single	maximize resilience
Repair	Liu et al., 2021	N	Single	minimize project duration time
Repair	Lu et al., 2016	N	Single	minimize road network travel cost and restoration of damaged links
Repair	Luo and Yang, 2021	N	Single	minimize the time cost
Repair	Mao et al., 2021	N	Single	maximize resilience in terms of performance loss and recovery rapidity
Repair	Merschman et al., 2020	N	Single	maximize network performance
Repair	Mhatre et al., 2019	N	Single	maximize total number of people at demand nodes who can reach each resource node over time horizon
Repair	Moghtadernejad et al., 2020	N	Single	minimize weighted sum of direct and indirect costs
Repair	Moreno et al., 2019	N	Single	minimize time that demand nodes cannot be accessed from a depot
Repair	Morshedlou et al., 2018	N	Single	maximize resilience
Repair	Mredul et al., 2021	N	Single	minimize post-disaster loss in life and wealth

	Citation	Stochasticity	Infrastructure	Objective Function
Repair	Najafi et al., 2020	N	Multiple	minimize inaccessibility and minimize cost
Repair	Niyazi and Behnamian, 2021	N	Single	minimize time for repair and relief distribution activities
Repair	Orabi et al., 2009	N	Single	minimize network performance loss and costs
Repair	Sharkey et al., 2015	N	Multiple	maximize performance of interdependent infrastructure networks
Repair	Shen, 2013	N	Multiple	minimize cost
Repair	Somy et al., 2021	N	Single	minimize total recovery time and skew of recovery trajectory
Repair	Ulusan, 2019	N	Multiple	maximize benefits of meeting demand over time
Repair	Vodák et al., 2018	N	Single	minimize repair time
Repair	Wang et al., 2021	Y	Multiple	minimize cost of system performance loss
Repair	Wu et al., 2021	N	Single	minimize travel time
Repair	Xu et al., 2019	N	Multiple	minimize resilience loss
Repair	Zhang and Miller-Hooks, 2015	Y	Single	maximize the total throughput
Repair	Zhang et al., 2018	N	Multiple	maximize resilience
Repair	Zhang et al., 2021	N	Single	maximize benefits gained from inspection
Repair	Zhao et al., 2020	N	Single	minimize both skew of recovery trajectory and economic loss
Repair	Zou and Chen, 2019	N	Single	maximize resilience
Repair	Zou and Chen, 2021	N	Multiple	maximize resilience
Both	Zhang and Wei, 2021	N	Single	maximize resilience
Both	Our work	Y	Multiple	maximize number of nodes and links repaired over planning horizon

CHAPTER 3

Methodology

The multi-stage, stochastic, integer formulation of the problem of determining an optimal inspection-repair schedule of elements of infrastructure lifelines damaged in a disaster event is proposed in this section. The formulation accounts for endogenous uncertainty arising from inspection decisions. Decisions are taken at the beginning of each time interval within a discretized time horizon. Without loss of generality, it is presented in terms of only two infrastructure lifelines: roadway and power networks. The roadway network is represented by a set of links connected at nodes representing their intersections. While a focus of earlier work by Zhang and Wei (2021), travel times along the open links here are presumed to be trivial in comparison to inspection and repair activities, and thus, are not modeled. Likewise, the specific routing of the inspection and repair crews is not a focus herein. The power network consists of substations located at the nodes of the roadway network and transmission lines given by their own set of links. Access to components of the power network requires open roadways from a depot. Power and roadway crews are modeled separately, but for simplicity only are assumed to position at a single depot. Each lifeline has two crews, one for inspection and one for repair, both of which are presumed to take one time interval. Roadway and power elements requiring repair are not functional until completion of the repair activity. Power requires a functioning transmission line and a transmission line can only be functional if a connected substation is functional. Demand for power is implicitly presumed to be uniformly distributed across the study area.

Before proceeding to the formulation, notation used in the model is defined.

Sets and parameters:

N	Set of nodes, $n \in N = \{1,2, \dots, \lvert N \rvert\}$, representing the intersections between roadway links
A	Set of roadway links $a \in A = \{1,2, \dots, \lvert A \rvert\}$
A_k	Set of roadway links on path k
L	Set of substations $l \in L = \{1,2, \dots, \lvert L \rvert\}$

S	Set of scenarios $s \in S = \{1,2, \ldots, \lvert S \rvert\}$
H	Set of transmission lines h$\in H = \{1,2, \ldots, \lvert H \rvert\}$
T	Set of time increments $t \in T = \{1,2, \ldots, \lvert T \rvert\}$
B	Available budget
w, w'	Weights on objective components, $w + w' = 1$
ω_a	Criticality index of roadway link a
ω_l	Criticality index of substation l
ω_h	Criticality index of roadway link h
b_a	Cost of inspecting link *a*
b'_a	Cost of repairing link *a*
b_l	Cost of inspecting substation *l*
b'_l	Cost of repairing substation *l*
b_h	Cost of inspecting transmission line h
b'_h	Cost of repairing transmission line h
I_{an}	If link *a* is incident on node *n*
I'_{hl}	If transmission line *h* is powered by substation *l*

Variables:

β_{at}(s)	=1 if roadway inspection crew inspects damaged link *a* at time *t* under scenario s, =0 otherwise
$\delta_{at}(s)$	=1 if roadway repair crew repairs damaged link *a* at time *t* under scenario s, =0 otherwise
$\lambda_{lt}(s)$	=1 if power inspection crew inspects damaged substation *l* at time *t* under scenario s, 0 otherwise
$\sigma_{lt}(s)$	=1 if power repair crew repairs damaged substation *l* at time *t* under scenario s, =0 otherwise
$\theta_{ht}(s)$	=1 if power inspection crew inspects transmission line *h* at time *t* under scenario s, =0 otherwise
$\vartheta_{ht}(s)$	=1 if power repair crew repairs damaged transmission line *h* at time *t* under scenario s, =0 otherwise

$d_a(s)$	=1 if link *a* is up under scenario s or =0 if it is down
$d_l(s)$	=1 if substation *l* is up under scenario s or =0 if it is down
$d_h(s)$	=1 if transmission line *h* is up under scenario s or =0 if it is down
$x_{at}(s)$	=1 if status of link *a* at end of time *t* under scenario s is up or =0 if down
$y_{lt}(s)$	=1 if status of substation *l* at end of time *t* under scenario s is up or =0 if down
$v_{ht}(s)$	=1 if status of transmission line *h* at end of time *t* under scenario s is up or =0 if down
$p_{nkt}(s)$	If all links on path *k* to node *n* are up at time *t* under scenario *s*
m_k	Number of constituent links in path *k*

$$Max\ Z = \sum_{s}(P(s) \cdot (w \cdot \sum_{a}\sum_{t}\omega_a \cdot x_{at}(s) + w' \cdot (\sum_{l}\sum_{t}\omega_l \cdot y_{lt}(s) + \sum_{h}\sum_{t}\omega_h \cdot v_{ht}(s))) \quad (1)$$

$$\sum_{a}\sum_{t}\sum_{s} b_a.\beta_{at}(s) + \sum_{a}\sum_{t}\sum_{s} b'_a,\delta_{at}(s) + \sum_{l}\sum_{t}\sum_{s} b_l.\lambda_{lt}(s) + \sum_{l}\sum_{t}\sum_{s} b'_l.\sigma_{lt}(s) + \sum_{h}\sum_{t}\sum_{s} b_h.\theta_{ht}(s) + \sum_{h}\sum_{t}\sum_{s} b'_h.\vartheta_{ht}(s) \le B \quad (2)$$

$$\sum_{a}\beta_{at}(s) \le 1, \forall s, t \quad (3)$$

$$\sum_{a}\delta_{at}(s) \le 1, \forall s, t \quad (4)$$

$$\sum_{l}\lambda_{lt}(s) \le 1, \forall s, t \quad (5)$$

$$\sum_{l} \sigma_{lt}(s) \leq 1, \forall s, t \tag{6}$$

$$\sum_{h} \theta_{ht}(s) \leq 1, \forall s, t \tag{7}$$

$$\sum_{h} \vartheta_{ht}(s) \leq 1, \forall s, t \tag{8}$$

$$\sum_{t} \beta_{at}(s) \leq 1, \forall s, a \tag{9}$$

$$\sum_{t} \delta_{at}(s) \leq 1, \forall s, a \tag{10}$$

$$\sum_{t} \lambda_{lt}(s) \leq 1, \forall s, l \tag{11}$$

$$\sum_{t} \sigma_{lt}(s) \leq 1, \forall s, l \tag{12}$$

$$\sum_{t} \theta_{ht}(s) \leq 1, \forall s, h \tag{13}$$

$$\sum_{t} \vartheta_{ht}(s) \leq 1, \forall s, h \tag{14}$$

$$\vartheta_{ht}(s) \leq \sum_{l} I'_{hl}. y_{lt}(s), \forall h, s, t \tag{15}$$

$$x_{at}(s) = d_a(s) + \sum_{t'=0}^{t-1} \delta_{at}(s), \forall a, s, t \tag{16}$$

$$y_{lt}(s) = d_l(s) + \sum_{t'=0}^{t-1} \sigma_{lt}(s), \forall l, s, t \tag{17}$$

$$v_{ht}(s) \leq d_h(s) + \sum_{t'=0}^{t-1} \vartheta_{lt}(s), \forall l, s, t \tag{18}$$

$$d_a(s) + \sum_{t} \delta_{at}(s) \leq 1, \forall a, s \tag{19}$$

$$d_l(s) + \sum_{t} \sigma_{lt}(s) \leq 1, \forall l, s \tag{20}$$

$$d_h(s) + \sum_{t} \vartheta_{ht}(s) \leq 1, \forall h, s \tag{21}$$

$$\delta_{at}(s) \leq \sum_{t'=0}^{t-1} \beta_{at'}(s), \forall a, s \tag{22}$$

$$\sigma_{at}(s) \leq \sum_{t'=0}^{t-1} \lambda_{at'}(s), \forall a, s \tag{23}$$

$$\vartheta_{ht}(s) \leq \sum_{t'=0}^{t-1} \theta_{at'}(s), \forall h, s \tag{24}$$

$$\beta_{at}(s) \leq \sum_{k} I_{an}.\, p_{nkt}(s)\, , \forall a, t, s \tag{25}$$

$$\lambda_{lt}(s) \leq \sum_{k} I'_{ln}.\, p_{nkt}(s), \forall l, t, s \tag{26}$$

$$\theta_{ht}(s) \leq \sum_{k} I''_{hn}.\, p_{nkt}(s), \forall h, t, s \tag{27}$$

$$\frac{\sum_{a' \in A_k} x_{a't}(s)}{|m_k|} \geq p_{nkt}(s), \forall t, s, n, k \tag{28}$$

$$p_{0kt}(s) \leq 1, \forall k, t, s \tag{29}$$

$$\beta_{a0}(s) = \beta_{a0}(s'), \forall (s, s') \in S, a \tag{30}$$

$$\lambda_{l0}(s) = \lambda_{l0}(s'), \forall (s, s') \in S, l \tag{31}$$

$$\theta_{h0}(s) = \theta_{h0}(s'), \forall (s, s') \in S, h \tag{32}$$

$$\beta_{at}(s) - \beta_{at}(s') \leq \sum_{t'<t} \sum_{a' \in \Phi(s,s')} \beta_{a't'}(s) + \sum_{t'<t} \sum_{a \in \Phi(s,s')} \beta_{a't'}(s'), \forall (s, s') \in S \quad (33)$$

$$\beta_{at}(s') - \beta_{at}(s) \leq \sum_{t'<t} \sum_{a' \in \Phi(s,s')} \beta_{a't'}(s) + \sum_{t'<t} \sum_{a' \in \Phi(s,s')} \beta_{a't'}(s'), \forall (s, s') \in S \quad (34)$$

$$\lambda_{lt}(s) - \lambda_{lt}(s') \leq \sum_{t'<t} \sum_{l' \in \Phi(s,s')} \lambda_{l't'}(s) + \sum_{t'<t} \sum_{l' \in \Phi(s,s')} \lambda_{l't'}(s'), \forall (s, s') \in S \quad (35)$$

$$\lambda_{lt}(s') - \lambda_{lt}(s) \leq \sum_{t'<t} \sum_{l' \in \Phi(s,s')} \lambda_{l't'}(s) + \sum_{t'<t} \sum_{l' \in \Phi(s,s')} \lambda_{l't'}(s'), \forall (s, s') \in S \quad (36)$$

$$\theta_{ht}(s) - \theta_{ht}(s') \leq \sum_{t'<t} \sum_{h' \in \Phi(s,s')} \theta_{h't'}(s) + \sum_{t'<t} \sum_{h' \in \Phi(s,s')} \theta_{h't'}(s'), \forall (s, s') \in S \quad (37)$$

$$\theta_{ht}(s') - \theta_{ht}(s) \leq \sum_{t'<t} \sum_{h' \in \Phi(s,s')} \theta_{h't'}(s) + \sum_{t'<t} \sum_{h' \in \Phi(s,s')} \theta_{h't'}(s'), \forall (s, s') \in S \quad (38)$$

$$\beta_{at}(\mathrm{s}), \delta_{at}(s), \lambda_{lt}(\mathrm{s}), \sigma_{lt}(\mathrm{s}), \theta_{ht}(\mathrm{s}), \vartheta_{ht}(\mathrm{s}) \in \{0,1\} \quad (39)$$

Objective function (1) seeks to maximize the expected number of time intervals for which roadway and power elements function over a short-term, post-disaster time horizon. The power network is restored by repairing any damaged substations and transmission lines supported by access along the roadway network. The relative value given to either network is managed by the application of weights applied to the terms of the objective function. Roughly speaking, to bring both networks back simultaneously, equal weights can be applied. If the focus is on only one of the networks, the full weight can be given to that network in the objective. Additionally, with appropriate values for ω_{at}, ω_{lt}, and ω_{ht}, more critical roadway links, e.g., those that carry more traffic, and power network components can be given more weight in inspection and restoration decisions.

Constraint (2) sets a bound on total restoration and inspection costs for cases where restoration budgets are limited. This constraint can be split into two, one for the transportation system and another for the power network, if disaster response resources come from separate sources. That at each point in time only one link can be inspected or repaired given the presence of only one crew per activity and lifeline is guaranteed in constraints (3) - (4) for the roadway links (5) - (6) for the substations, and (7) - (8) for the transmission lines. Constraints (9) - (10), (11) - (12), and (13) - (14) similarly restrict each link, substation and transmission line, respectively, to be inspected or repaired at most once. It is presumed that a transmission line can supply power only if it is connected to a substation that is functioning. Constraint (15) requires that a transmission line be connected to a functioning substation to be functional itself. Constraints (16) – (18) determine a link or substation or transmission line's status given its condition under a chosen scenario and whether it was repaired in a previous time stage. Constraints (19) – (21) restrict restoration actions to only those links or substations or transmission lines, respectively, that are currently "down." That restoration actions can only be applied if the links or substations or transmission lines were previously inspected is guaranteed through constraints (22) – (24).

Required for completing inspection or repairs, a link or substation must be accessible along a path from the inspection or repair crew's current location. This is implemented through constraints (25) – (27), assuming that all crews are initially located at a single depot, but can be generalized. That a path is "up" only if all its constituent links are up is ensured by Constraint (28). Constraint (29) sets the depot to be node 0. First-stage non-anticaptivity constraints (NACs) wherein all scenarios are indistinguishable are set in Constraints (30) - (32). These constraints are applied across all pairs of scenarios. Constraints (33) - (38) enforce conditional NACs at later stages. These constraints are conditioned on prior realizations of link and/or substation damage states as a function of the disaster's impact. Finally, Constraint (39) guarantees non-negativity and integrality as required.

Conditional NACs: The formulation relies on the mathematical modeling of conditional NACs (Constraints (33) – (38)), which requires a concept of indistinguishable and distinguishable scenarios. Two scenarios are indistinguishable at a stage t if and only if they have the same realizations for of all revealed random variables up to that stage (Apap and Grossman, 2017). In the example shown in Figure 2, scenarios 1 and 2 differ in link 1's status. Thus, as long as link 1 is not inspected, these two scenarios remain indistinguishable and the same decision should be enforced for both of these scenarios. When link 1 is inspected and its status is revealed, these two scenarios become distinguishable and, therefore, the same decision need not be applied in both.

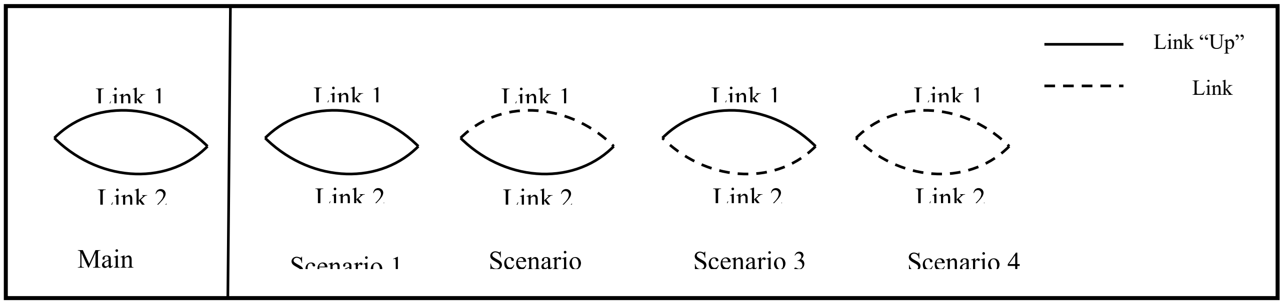


Figure 2. Scenarios.

Timing of knowledge of the outcome of random variables of link, substation, and transmission line statuses is dependent on inspection decisions. Once inspected, the element's status is known with certainty. Thus, the conditional NACs need only be applied in relation to inspection decisions and not restoration actions. For additional details on conditional NACs, see: Apap and Grossmann (2017) or Hooshmand, Khaligh, and Mirhassani (2015).

To develop Constraints (33) - (38) for the example in Figure 2, consider equation (38), where $\Phi(s,s')$ is the set of links with different realizations in scenarios s and s'. At each stage, if this set of links was not previously inspected, inspection decisions must be the same for the two scenarios. Since $\Phi(1,2)=\{1\}$, a conditional NAC constraint is required for only link 1. This is specified in equation (39) for this example.

$$if \sum_{t'<t}\sum_{a'\in\{1\}} \beta_{a't}(1) + \sum_{t'<t}\sum_{a'\in\{1\}} \beta_{a't}(2) = 0, \text{ then } \beta_{at}(1) = \beta_{at}(2), \forall (s,s') \in S\,, t \tag{40}$$

Equation (40) requires that at each stage, if roadway link 1 is not inspected at prior stages for scenarios 1 and 2 ($\sum_{t'<t}\beta_{1t}(1) + \sum_{t'<t}\beta_{1t}(2) = 0$), then the same decisions must be enforced for all roadway links at each stage for scenarios 1 and 2 ($\beta_{at}(1) = \beta_{at}(2)$). Equation (40) is generalized for larger applications as in (41).

$$if \sum_{t'<t} \sum_{a' \in \Phi(s,s')} \beta_{a't}(s) + \sum_{t'<t} \sum_{a' \in \Phi(s,s')} \beta_{a't}(s') = 0 \text{ then } \beta_{at}(s) = \beta_{at}(s'), \forall (s,s') \in S, t \tag{41}$$

Equations (33) - (34) give a linear-equivalent representation of Equation (41). A similar linearization approach was applied to obtain linearly equivalent equations (35) - (38) for the power network.

CHAPTER 4

Application and Findings

APPLICATION AND EXPERIMENTAL DESIGN

The proposed stochastic optimization was implemented on a representation of a portion of the roadway and power networks designed on Arlington, Virginia. Immediately across the Potomac River from the heart of the federal government in Washington, D.C., and home to a variety of additional agencies, Arlington is an important location for the region. For this application, a network including roadways, substations and transmission lines of Arlington was extracted from (County Board, 2010) as shown in Figure 3. A single network representation of the coupled system is constructed using 11 links and 9 nodes. The links include nine roadway sections and two transmission lines. The nodes act as connections between the roadway links. Three substations are positioned at three of the nodes. Six randomly generated scenarios were created as depicted in the figure.

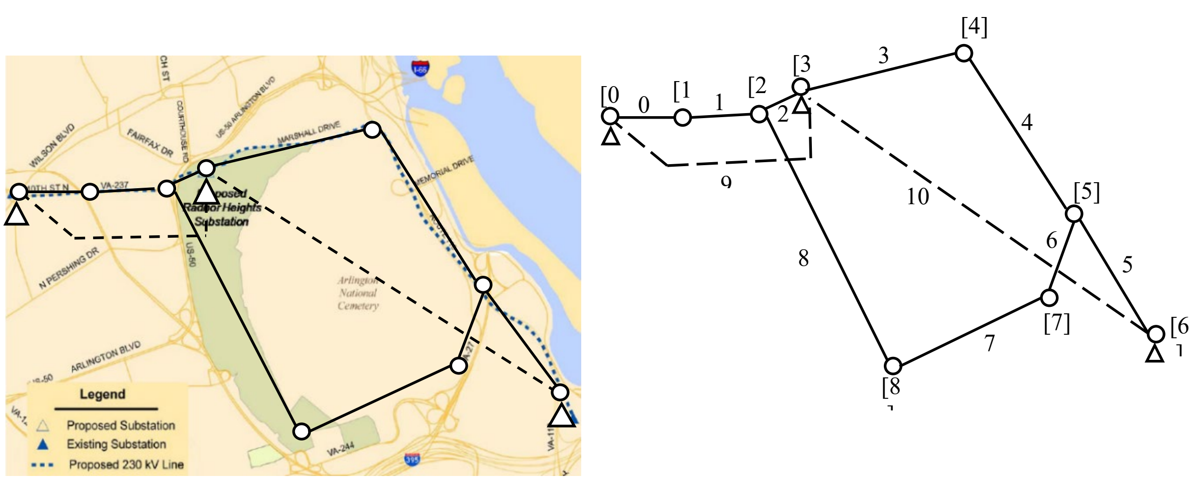


Figure 3. Roadway-power network representation overlaid on roadway-power map, with legend for link and node numbering (adapted from map published by Virginia Places, 2022).

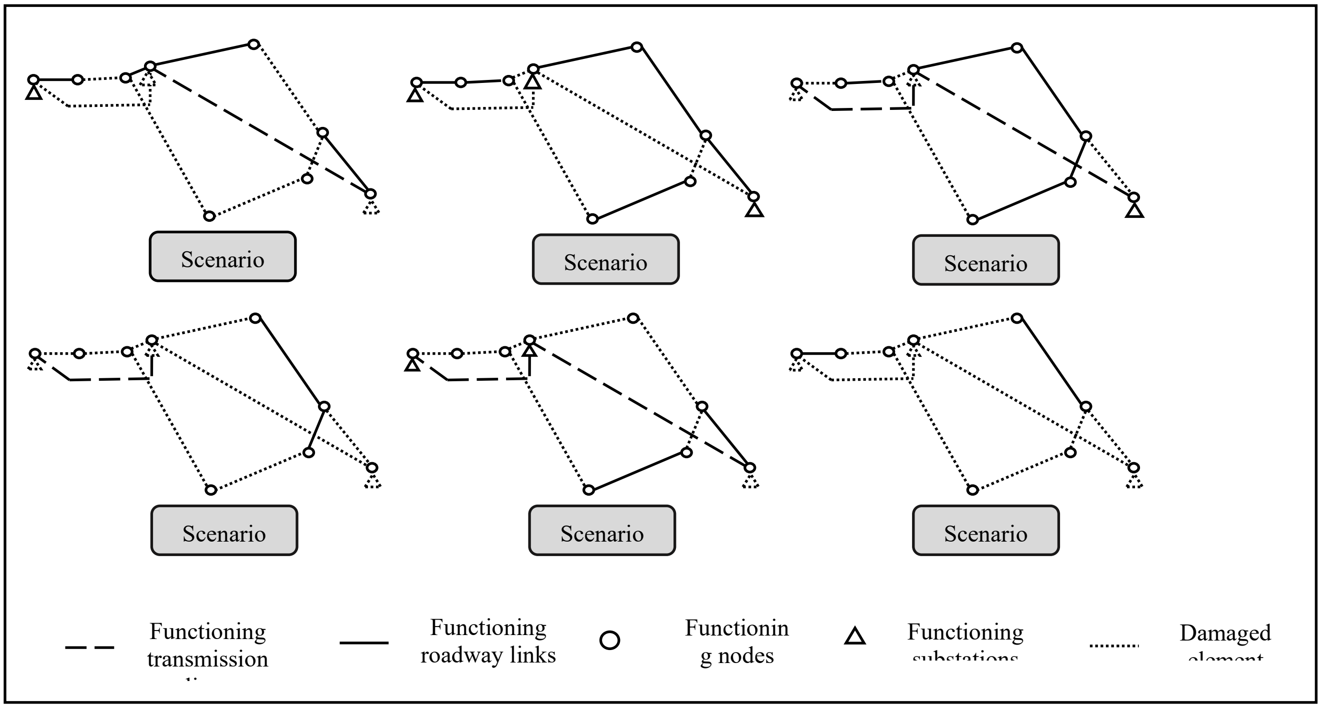


Figure 4. Considered scenarios.

RESULTS

Figure 5 shows the results over six tested scenarios when reaching the end of the planning horizon for three combinations of weights in the objective function, each combination of which aligns with changing emphases on the different infrastructure lifelines. Specific components of each network are presumed to be equal in criticality.

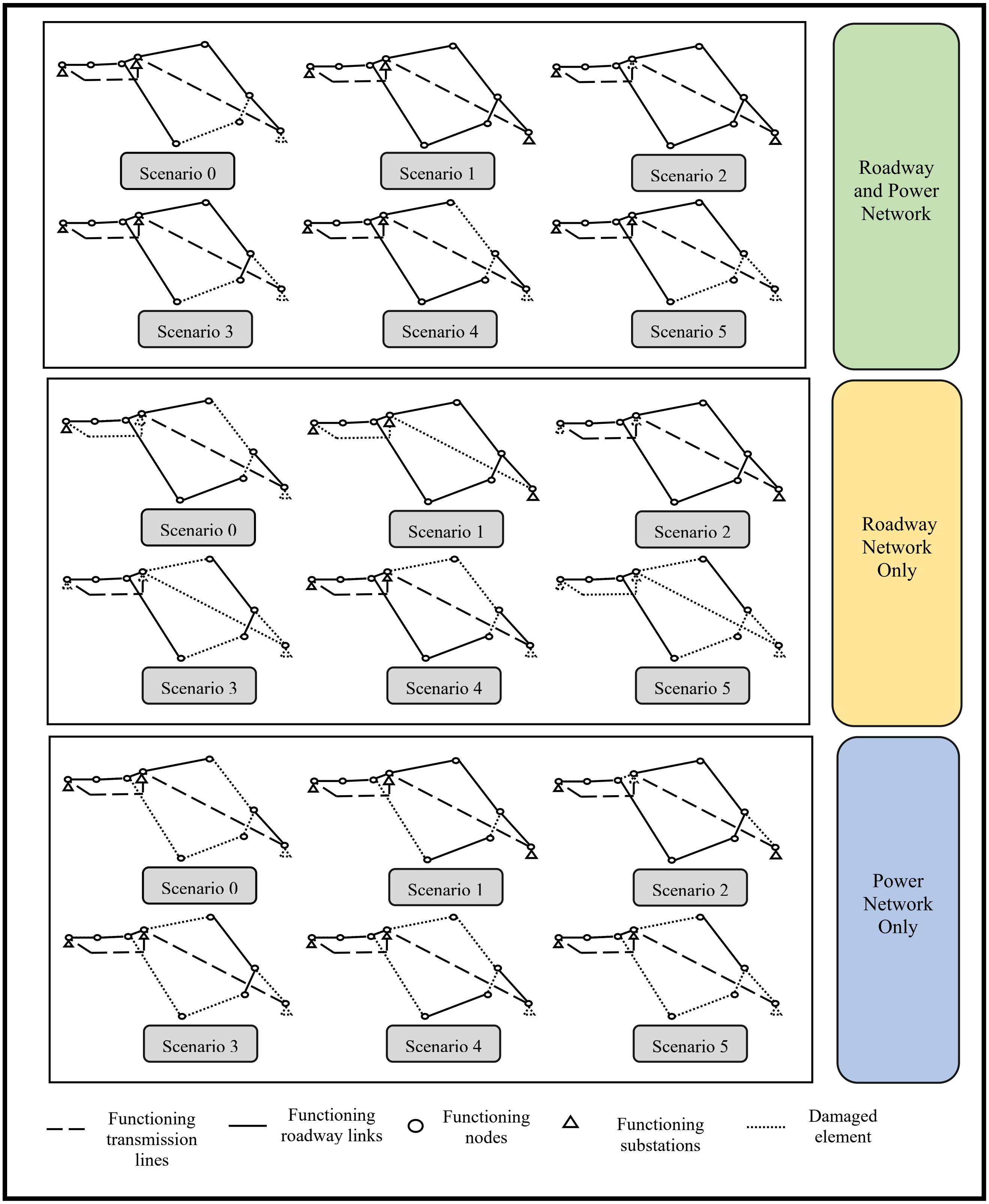
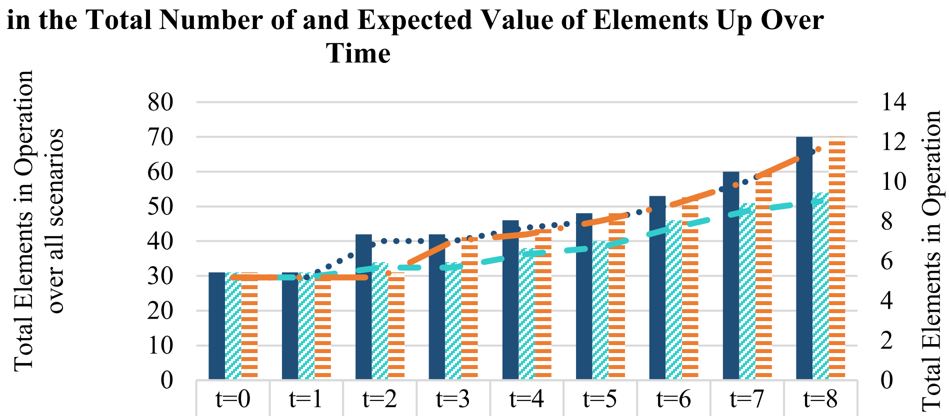


Fig. 5. Solution by scenario at the end of the planning horizon.



	t=0	t=1	t=2	t=3	t=4	t=5	t=6	t=7	t=8
Total number of functioning elements in roadway and power networks	31	31	42	42	46	48	53	60	70
Total number of functioning elements in roadway network only	31	31	34	34	38	40	46	51	54
Total number of functioning elements in power network only	31	31	31	42	44	48	53	60	70
Expected number of functioning elements in roadway and power networks	5.2	5.2	7.0	7.0	7.7	8.0	8.9	10.0	11.7
Expected number of functioning elements in roadway network only	5.2	5.2	5.7	5.7	6.3	6.7	7.7	8.5	9.0
Expected number of functioning elements in power network only	5.2	5.2	5.2	7.0	7.3	8.0	8.9	10.0	11.7

Fig. 6. Changes in the total number and expected value of number of functioning elements (roadway links, substations, and transmission lines) over time.

In Figure 6, also assuming all elements of both networks to be equally critical, the total and expected numbers of elements that are operational over the stages of the studied time horizon are shown. When equal weight was given to bringing back both networks, a 30% increase in total number of functioning elements by time 9 was noted over using an objective that focuses only on the power network. With 14 critical roadway and power elements and 6 scenarios, the percent of total elements (roadway and power, including both substations and transmission lines) that are functioning at the end of the planning horizon over all scenarios compared with immediately after disaster impact is 56% (67% of roadway and 36% of power elements) for roadway and power network, as well as roadway network only, and 43% (54% of roadway and 22% of power elements) for power network only. While the results at the end of time interval 8 are the same for roadway and power and roadway-only runs, the intermediate results differ. These results are achieved by setting an unlimited budget but are reached within a limited time frame.

Tables 2 and 3 illustrate the change in schedule of inspection and repairs when the focus of the objective function is on power alone, roadway alone, or both power and roadway networks.

The roadway link is indicated in these tables if it is repaired in one or more scenarios in that time interval. The results of the tables indicate that when actions are focused entirely on bringing the power network back up, roadway links not required to support inspection and/or repairs in the power network will not be repaired.

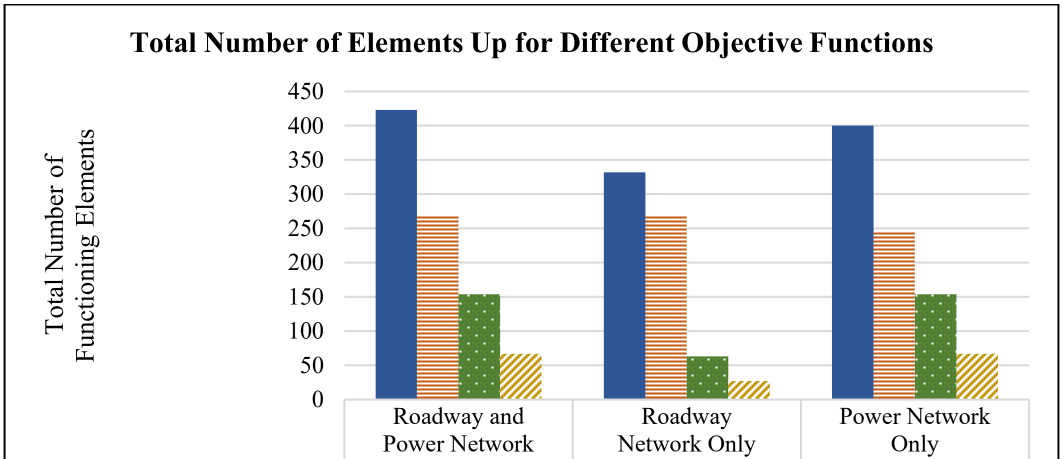
Table 2. Roadway link inspection schedule under differing weights in the objective function.

Network	$t = 0$	$t = 1$	$t = 2$	$t = 3$	$t = 4$	$t = 5$	$t = 6$	$t = 7$	$t = 8$
Roadway and Power Network	0	NA	1	2	2	4, 5, 6, 8	3, 8	NA	NA
Roadway Network Only	0	NA	1	2	2	5, 6, 8	3, 4	NA	NA
Power Network Only	0	NA	1	2	2, 8	NA	NA	NA	NA

Table 3. Roadway link repair schedule under differing weights in the objective function.

Network	$t = 0$	$t = 1$	$t = 2$	$t = 3$	$t = 4$	$t = 5$	$t = 6$	$t = 7$	$t = 8$
Roadway and Power Network	NA	0	NA	1	2	2	4, 5, 6, 8	3, 8	NA
Roadway Network Only	NA	0	NA	1	2	2	5, 6, 8	3, 4	NA
Power Network Only	NA	0	NA	1	2	2, 8	NA	NA	NA

By comparing the number of elements of each system to which there is a path from the depot established by each point in time in the study time horizon, it is possible to evaluate the impact of coordination between systems. Tables 4 and 5 provide aggregate information on these paths for the power and roadway network elements, respectively. Details of these results separated by scenario and element are given in Appendix A. Figure 7 gives the total number of elements over all scenarios and time intervals functioning over time.



	Roadway and Power Network	Roadway Network Only	Power Network Only
Total elements up	423	332	400
Roadway	269	269	246
Power elements	154	63	154
Powered transmission lines	67	27	67

Fig. 7. Total number of functioning elements (links, substations, and power lines) by objective.

Table 4 shows that the number of paths created from the depot to power network elements over time is increased by a coordinated or roadway-only lifeline strategy, and that more of these paths are open earlier. Moreover, as indicated in Figure 7, a coordinated strategy leads to the same number of functioning power elements as the strategy that focuses only on power, but has a greater total number of functioning elements in both networks. Together, Table 5 and Figure 7 reveal that a reduced number of roadway links, likely those required for accessing the substations and transmission lines, were chosen for repair when the objective focused only on the power network.

Table 4. Number of transmission lines and substations connected to depot by an open path by time t summed over scenarios.

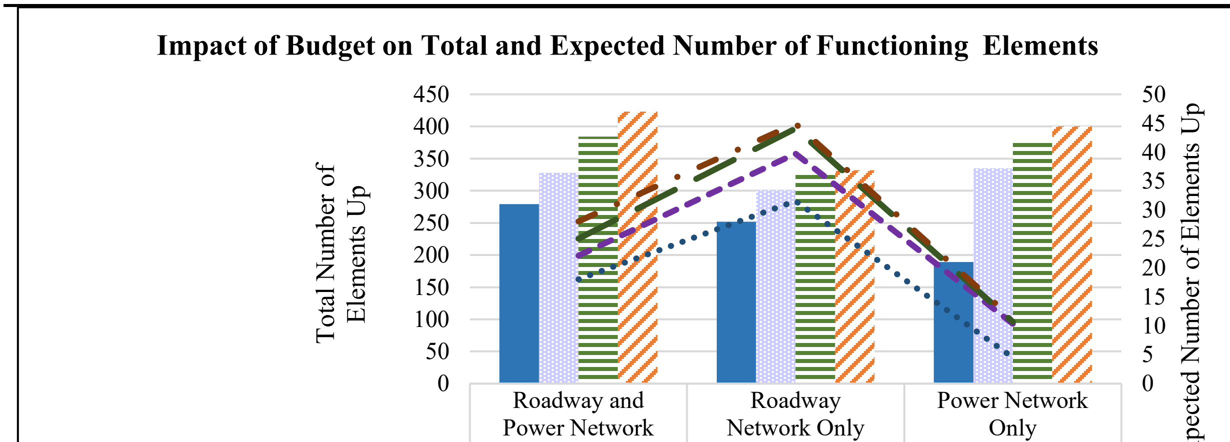
	Roadway and Power Network	Roadway Network Only	Power Network Only
t=0	12	12	12
t=1	12	12	12
t=2	12	12	12
t=3	12	12	12
t=4	14	14	14
t=5	19	19	14
t=6	25	19	25
t=7	27	25	25
t=8	27	27	25
Sum	160	152	151

Table 5. Number of nodes of roadway network connected to depot by an open path by time t summed over scenarios.

	Roadway and Power Network	Roadway Network Only	Power Network Only
t=0	10	10	10
t=1	14	10	10
t=2	14	14	14
t=3	14	20	14
t=4	20	20	20
t=5	29	29	24
t=6	34	36	28
t=7	42	40	28
t=8	42	41	28
Sum	219	220	176

The focus of the optimization was on restoring power. It was assumed that a transmission line could provide power if it itself is functioning and a substation that connects to it is also functioning. Thus, rather than evaluate performance in terms of number of elements in the power network that are functioning, the focus can be on the number of transmission lines that are functioning. This is shown in Figure 7. If this metric is used in place of the number of elements, the same general findings are observed.

Figure 8 shows the impact of a limited budget for action on the total and expected numbers of functioning elements over the planning horizon, again assuming equal criticality of elements of both networks. It is shown here that increasing the budget will help bring back 51% more elements when considering both roadway and power networks in the objective and 31% and 116% more elements when considering roadway and power networks individually, respectively.



	Roadway and Power Network	Roadway Network Only	Power Network Only
Low budget- total number of functioning elements	279	252	189
Medium budget- total number of functioning elements	328	301	335
High budget- total number of functioning elements	384	327	376
Unlimited budget- total number of functioning elements	423	332	400
Low budget- expected number of functioning elements	18.04	31.56	4.51
Medium budget- expected number of functioning elements	22.13	39.74	10.35
High budget- expected number of functioning elements	25.05	44.08	10.68
Unlimited budget- expected number of functioning elements	28.05	44.92	11.18

Fig. 8. Impact of budget on total and expected number of functioning éléments.

In an additional set of runs with unlimited budgets, roadway link 8 was presumed to be a critical link with a weight of 10 compared to other elements with criticality values of 1. In comparison to a run with equally critical element values across networks, when considering the criticality of link 8, inspection and repair actions were moved up a stage (from stage 3 to stage 2) under 1 scenario. To enable this, the path to link 8 was also opened one time stage earlier.

The gains that can be achieved through perfect knowledge of the future can be assessed through comparison of the optimal solution value of the stochastic program to that of the Expected Value of Perfect Information (EVPI). The EVPI is computed by assuming full knowledge of each scenario in advance. Actions are determined to achieve the best solution for each scenario with deterministic information, and the expected value over these solutions is computed. The EVPI provides an upper bound on performance, and this comparison provides an indication of the potential benefits of having improved predictive capabilities. In the case with equal emphasis given to both roadway and power networks, where all elements were considered to be equally critical, and an unlimited budget is provided, a potential gain of over 12% in the expected number of elements that can be returned to full functionality over the considered time period given perfect information of the future (79.16 vs. 70.5 in restored power and roadway links) was found. Thus, a sizeable improvement in returning the lifelines to pre-disaster conditions could be attained through more accurate information in this specific application.

CHAPTER 5

Recommendations

The problem of determining optimal inspection and repair decisions of infrastructure lifelines in the aftermath of a disaster event impacting a geographic area is modeled as a multi-stage, stochastic integer program with endogenous uncertainty capturing that inspection and repair decisions impact the timing of network element status realization. Inspections reveal which links of the networks are in need of repair or are otherwise functioning. Repair actions allow access to additional portions of the network, creating the possibility for additional inspection with the new information it brings, and restoration of more of the networks.

Results from an illustrative application show the benefits of coordinating actions over multiple lifelines in bringing back services to a community impacted by a disaster event. When the restoration's focus is on power, the repair activities of the secondary, supporting roadway infrastructure were scheduled in a way to support access to the primary power lifeline. In fact, repair actions on the roadways can be ordered to support faster return of power services with little loss for the roadway network.

The formulation is proposed in terms of only two lifelines. It can readily be extended to incorporate additional lifelines. In expanding to more infrastructure networks, it may be necessary to account for dependencies and interdependencies between network functions. These can be modeled through added state variables. See (Tariverdi et al., 2019) for details. Additionally, only the most basic elements of the power network were incorporated. The power network representation can be expanded to more accurately capture its components and their interactions. An alternative objective may be used to minimize unmet power demand as would be useful in an area with geographically dispersed consumers of power.

Study of the value of perfect information showed a more than 12% value added from improved situational awareness, which might be enabled through added sensing on network components and structures.

Finally, a comment on problem scale is warranted. The need to incorporate the NACs to appropriately model how information is revealed in this stochastic environment produces the need for a very large number of variables and constraints that grows polynomially with problem size. The stochastic modeling framework captures the complexity of decision-dependent uncertainty, but at the cost of computational efficiency. Moreover, laying out the model details for larger instances and/or instances including more infrastructure lifelines is cumbersome. Lagrangean decomposition, approximate dynamic programming, or heuristic methods may be warranted. Application of more scalable approaches can be embedded in a rolling horizon framework for real-time use not unlike the iterative process used by Zhang and Wei (2021). Alternatively, deep reinforcement learning may provide a plausible method for policy development in real-time environments, where updated data are readily available.

Appendix

Table A1. Path existence from depot by scenario and time (power elements)

Network			sub. 0	sub. 1	sub. 2	tr. 0	tr. 1
Rdwy & Pwr	t=0	s0	yes			yes	
Rdwy & Pwr	t=0	s1	yes			yes	
Rdwy & Pwr	t=0	s2	yes			yes	
Rdwy & Pwr	t=0	s3	yes			yes	
Rdwy & Pwr	t=0	s4	yes			yes	
Rdwy & Pwr	t=0	s5	yes			yes	
Rdwy & Pwr	t=1	s0	yes			yes	
Rdwy & Pwr	t=1	s1	yes			yes	
Rdwy & Pwr	t=1	s2	yes			yes	
Rdwy & Pwr	t=1	s3	yes			yes	
Rdwy & Pwr	t=1	s4	yes			yes	
Rdwy & Pwr	t=1	s5	yes			yes	
Rdwy & Pwr	t=2	s0	yes			yes	
Rdwy & Pwr	t=2	s1	yes			yes	
Rdwy & Pwr	t=2	s2	yes			yes	
Rdwy & Pwr	t=2	s3	yes			yes	
Rdwy & Pwr	t=2	s4	yes			yes	
Rdwy & Pwr	t=2	s5	yes			yes	
Rdwy & Pwr	t=3	s0	yes			yes	
Rdwy & Pwr	t=3	s1	yes			yes	
Rdwy & Pwr	t=3	s2	yes			yes	
Rdwy & Pwr	t=3	s3	yes			yes	
Rdwy & Pwr	t=3	s4	yes			yes	
Rdwy & Pwr	t=3	s5	yes			yes	
Rdwy & Pwr	t=4	s0	yes	yes		yes	yes
Rdwy & Pwr	t=4	s1	yes			yes	
Rdwy & Pwr	t=4	s2	yes			yes	
Rdwy & Pwr	t=4	s3	yes			yes	
Rdwy & Pwr	t=4	s4	yes			yes	
Rdwy & Pwr	t=4	s5	yes			yes	
Rdwy & Pwr	t=5	s0	yes	yes		yes	yes
Rdwy & Pwr	t=5	s1	yes	yes	yes	yes	yes
Rdwy & Pwr	t=5	s2	yes	yes		yes	yes
Rdwy & Pwr	t=5	s3	yes			yes	

Network			sub. 0	sub. 1	sub. 2	tr. 0	tr. 1
Rdwy & Pwr	t=5	s4	yes			yes	
Rdwy & Pwr	t=5	s5	yes			yes	
Rdwy & Pwr	t=6	s0	yes	yes		yes	yes
Rdwy & Pwr	t=6	s1	yes	yes	yes	yes	yes
Rdwy & Pwr	t=6	s2	yes	yes		yes	yes
Rdwy & Pwr	t=6	s3	yes	yes		yes	yes
Rdwy & Pwr	t=6	s4	yes	yes		yes	yes
Rdwy & Pwr	t=6	s5	yes	yes		yes	yes
Rdwy & Pwr	t=7	s0	yes	yes	yes	yes	yes
Rdwy & Pwr	t=7	s1	yes	yes	yes	yes	yes
Rdwy & Pwr	t=7	s2	yes	yes	yes	yes	yes
Rdwy & Pwr	t=7	s3	yes	yes		yes	yes
Rdwy & Pwr	t=7	s4	yes	yes		yes	yes
Rdwy & Pwr	t=7	s5	yes	yes		yes	yes
Rdwy & Pwr	t=8	s0	yes	yes	yes	yes	yes
Rdwy & Pwr	t=8	s1	yes	yes	yes	yes	yes
Rdwy & Pwr	t=8	s2	yes	yes	yes	yes	yes
Rdwy & Pwr	t=8	s3	yes	yes		yes	yes
Rdwy & Pwr	t=8	s4	yes	yes		yes	yes
Rdwy & Pwr	t=8	s5	yes	yes		yes	yes
Rdwy Only	t=0	s0	yes			yes	
Rdwy Only	t=0	s1	yes			yes	
Rdwy Only	t=0	s2	yes			yes	
Rdwy Only	t=0	s3	yes			yes	
Rdwy Only	t=0	s4	yes			yes	
Rdwy Only	t=0	s5	yes			yes	
Rdwy Only	t=1	s0	yes			yes	
Rdwy Only	t=1	s1	yes			yes	
Rdwy Only	t=1	s2	yes			yes	
Rdwy Only	t=1	s3	yes			yes	
Rdwy Only	t=1	s4	yes			yes	
Rdwy Only	t=1	s5	yes			yes	
Rdwy Only	t=2	s0	yes			yes	
Rdwy Only	t=2	s1	yes			yes	
Rdwy Only	t=2	s2	yes			yes	
Rdwy Only	t=2	s3	yes			yes	
Rdwy Only	t=2	s4	yes			yes	
Rdwy Only	t=2	s5	yes			yes	
Rdwy Only	t=3	s0	yes			yes	
Rdwy Only	t=3	s1	yes			yes	
Rdwy Only	t=3	s2	yes			yes	

Network			sub. 0	sub. 1	sub. 2	tr. 0	tr. 1
Rdwy Only	t=3	s3	yes			yes	
Rdwy Only	t=3	s4	yes			yes	
Rdwy Only	t=3	s5	yes			yes	
Rdwy Only	t=4	s0	yes	yes		yes	yes
Rdwy Only	t=4	s1	yes			yes	
Rdwy Only	t=4	s2	yes			yes	
Rdwy Only	t=4	s3	yes			yes	
Rdwy Only	t=4	s4	yes			yes	
Rdwy Only	t=4	s5	yes			yes	
Rdwy Only	t=5	s0	yes	yes		yes	yes
Rdwy Only	t=5	s1	yes	yes	yes	yes	yes
Rdwy Only	t=5	s2	yes	yes		yes	yes
Rdwy Only	t=5	s3	yes			yes	
Rdwy Only	t=5	s4	yes			yes	
Rdwy Only	t=5	s5	yes			yes	
Rdwy Only	t=6	s0	yes	yes		yes	yes
Rdwy Only	t=6	s1	yes	yes	yes	yes	yes
Rdwy Only	t=6	s2	yes	yes		yes	yes
Rdwy Only	t=6	s3	yes			yes	
Rdwy Only	t=6	s4	yes			yes	
Rdwy Only	t=6	s5	yes			yes	
Rdwy Only	t=7	s0	yes	yes		yes	yes
Rdwy Only	t=7	s1	yes	yes	yes	yes	yes
Rdwy Only	t=7	s2	yes	yes		yes	yes
Rdwy Only	t=7	s3	yes	yes		yes	yes
Rdwy Only	t=7	s4	yes	yes		yes	yes
Rdwy Only	t=7	s5	yes	yes		yes	yes
Rdwy Only	t=8	s0	yes	yes	yes	yes	yes
Rdwy Only	t=8	s1	yes	yes	yes	yes	yes
Rdwy Only	t=8	s2	yes	yes	yes	yes	yes
Rdwy Only	t=8	s3	yes	yes		yes	yes
Rdwy Only	t=8	s4	yes	yes		yes	yes
Rdwy Only	t=8	s5	yes	yes		yes	yes
Power Only	t=0	s0	yes			yes	
Power Only	t=0	s1	yes			yes	
Power Only	t=0	s2	yes			yes	
Power Only	t=0	s3	yes			yes	
Power Only	t=0	s4	yes			yes	
Power Only	t=0	s5	yes			yes	
Power Only	t=1	s0	yes			yes	
Power Only	t=1	s1	yes			yes	

Network			sub. 0	sub. 1	sub. 2	tr. 0	tr. 1
Power Only	t=1	s2	yes			yes	
Power Only	t=1	s3	yes			yes	
Power Only	t=1	s4	yes			yes	
Power Only	t=1	s5	yes			yes	
Power Only	t=2	s0	yes			yes	
Power Only	t=2	s1	yes			yes	
Power Only	t=2	s2	yes			yes	
Power Only	t=2	s3	yes			yes	
Power Only	t=2	s4	yes			yes	
Power Only	t=2	s5	yes			yes	
Power Only	t=3	s0	yes			yes	
Power Only	t=3	s1	yes			yes	
Power Only	t=3	s2	yes			yes	
Power Only	t=3	s3	yes			yes	
Power Only	t=3	s4	yes			yes	
Power Only	t=3	s5	yes			yes	
Power Only	t=4	s0	yes	yes		yes	yes
Power Only	t=4	s1	yes			yes	
Power Only	t=4	s2	yes			yes	
Power Only	t=4	s3	yes			yes	
Power Only	t=4	s4	yes			yes	
Power Only	t=4	s5	yes			yes	
Power Only	t=5	s0	yes	yes		yes	yes
Power Only	t=5	s1	yes			yes	
Power Only	t=5	s2	yes			yes	
Power Only	t=5	s3	yes			yes	
Power Only	t=5	s4	yes			yes	
Power Only	t=5	s5	yes			yes	
Power Only	t=6	s0	yes	yes	yes	yes	yes
Power Only	t=6	s1	yes	yes		yes	yes
Power Only	t=6	s2	yes	yes		yes	yes
Power Only	t=6	s3	yes	yes		yes	yes
Power Only	t=6	s4	yes	yes		yes	yes
Power Only	t=6	s5	yes	yes		yes	yes
Power Only	t=7	s0	yes	yes	yes	yes	yes
Power Only	t=7	s1	yes	yes		yes	yes
Power Only	t=7	s2	yes	yes		yes	yes
Power Only	t=7	s3	yes	yes		yes	yes
Power Only	t=7	s4	yes	yes		yes	yes
Power Only	t=7	s5	yes	yes		yes	yes
Power Only	t=8	s0	yes	yes	yes	yes	yes

Network			sub. 0	sub. 1	sub. 2	tr. 0	tr. 1
Power Only	**t=8**	**s1**	yes	yes		yes	yes
Power Only	**t=8**	**s2**	yes	yes		yes	yes
Power Only	**t=8**	**s3**	yes	yes		yes	yes
Power Only	**t=8**	**s4**	yes	yes		yes	yes
Power Only	**t=8**	**s5**	yes	yes		yes	yes

Table A2. Path existence from depot by scenario and time (node intersection elements)

Network			node 0	node 1	node 2	node 3	node 4	node 5	node 6	node 7	node 8
Rdwy & Pwr	t=0	s0	yes	yes							
Rdwy & Pwr	t=0	s1	yes	yes	yes						
Rdwy & Pwr	t=0	s2	yes								
Rdwy & Pwr	t=0	s3	yes								
Rdwy & Pwr	t=0	s4	yes								
Rdwy & Pwr	t=0	s5	yes	yes							
Rdwy & Pwr	t=1	s0	yes	yes							
Rdwy & Pwr	t=1	s1	yes	yes	yes						
Rdwy & Pwr	t=1	s2	yes	yes	yes						
Rdwy & Pwr	t=1	s3	yes	yes							
Rdwy & Pwr	t=1	s4	yes	yes							
Rdwy & Pwr	t=1	s5	yes	yes							
Rdwy & Pwr	t=2	s0	yes	yes							
Rdwy & Pwr	t=2	s1	yes	yes	yes						
Rdwy & Pwr	t=2	s2	yes	yes	yes						
Rdwy & Pwr	t=2	s3	yes	yes							
Rdwy & Pwr	t=2	s4	yes	yes							
Rdwy & Pwr	t=2	s5	yes	yes							
Rdwy & Pwr	t=3	s0	yes	yes							
Rdwy & Pwr	t=3	s1	yes	yes	yes						
Rdwy & Pwr	t=3	s2	yes	yes	yes						
Rdwy & Pwr	t=3	s3	yes	yes							
Rdwy & Pwr	t=3	s4	yes	yes							
Rdwy & Pwr	t=3	s5	yes	yes							
Rdwy & Pwr	t=4	s0	yes	yes	yes	yes	yes				
Rdwy & Pwr	t=4	s1	yes	yes	yes						
Rdwy & Pwr	t=4	s2	yes	yes	yes						

Network			node 0	node 1	node 2	node 3	node 4	node 5	node 6	node 7	node 8
Rdwy & Pwr	t=4	s3	yes	yes	yes						
Rdwy & Pwr	t=4	s4	yes	yes	yes						
Rdwy & Pwr	t=4	s5	yes	yes	yes						
Rdwy & Pwr	t=5	s0	yes	yes	yes	yes	yes				
Rdwy & Pwr	t=5	s1	yes	yes	yes	yes	yes	yes	yes		
Rdwy & Pwr	t=5	s2	yes	yes	yes	yes	yes	yes		yes	yes
Rdwy & Pwr	t=5	s3	yes	yes	yes						
Rdwy & Pwr	t=5	s4	yes	yes	yes						
Rdwy & Pwr	t=5	s5	yes	yes	yes						
Rdwy & Pwr	t=6	s0	yes	yes	yes	yes	yes				
Rdwy & Pwr	t=6	s1	yes	yes	yes	yes	yes	yes	yes	yes	yes
Rdwy & Pwr	t=6	s2	yes	yes	yes	yes	yes	yes		yes	yes
Rdwy & Pwr	t=6	s3	yes	yes	yes	yes					
Rdwy & Pwr	t=6	s4	yes	yes	yes	yes					
Rdwy & Pwr	t=6	s5	yes	yes	yes	yes					
Rdwy & Pwr	t=7	s0	yes	yes	yes	yes	yes	yes	yes		
Rdwy & Pwr	t=7	s1	yes	yes	yes	yes	yes	yes	yes	yes	yes
Rdwy & Pwr	t=7	s2	yes	yes	yes	yes	yes	yes	yes	yes	yes
Rdwy & Pwr	t=7	s3	yes	yes	yes	yes					yes
Rdwy & Pwr	t=7	s4	yes	yes	yes	yes				yes	yes
Rdwy & Pwr	t=7	s5	yes	yes	yes	yes				yes	yes
Rdwy & Pwr	t=8	s0	yes	yes	yes	yes	yes	yes	yes		
Rdwy & Pwr	t=8	s1	yes	yes	yes	yes	yes	yes	yes	yes	yes
Rdwy & Pwr	t=8	s2	yes	yes	yes	yes	yes	yes	yes	yes	yes
Rdwy & Pwr	t=8	s3	yes	yes	yes	yes					yes
Rdwy & Pwr	t=8	s4	yes	yes	yes	yes				yes	yes
Rdwy & Pwr	t=8	s5	yes	yes	yes	yes				yes	yes
Rdwy Only	t=0	s0	yes	yes							
Rdwy Only	t=0	s1	yes	yes	yes						

Network			node 0	node 1	node 2	node 3	node 4	node 5	node 6	node 7	node 8
Rdwy Only	t=0	s2	yes								
Rdwy Only	t=0	s3	yes								
Rdwy Only	t=0	s4	yes								
Rdwy Only	t=0	s5	yes	yes							
Rdwy Only	t=1	s0	yes	yes							
Rdwy Only	t=1	s1	yes	yes	yes						
Rdwy Only	t=1	s2	yes								
Rdwy Only	t=1	s3	yes								
Rdwy Only	t=1	s4	yes								
Rdwy Only	t=1	s5	yes	yes							
Rdwy Only	t=2	s0	yes	yes							
Rdwy Only	t=2	s1	yes	yes	yes						
Rdwy Only	t=2	s2	yes	yes	yes						
Rdwy Only	t=2	s3	yes	yes							
Rdwy Only	t=2	s4	yes	yes							
Rdwy Only	t=2	s5	yes	yes							
Rdwy Only	t=3	s0	yes	yes							
Rdwy Only	t=3	s1	yes	yes	yes						
Rdwy Only	t=3	s2	yes	yes	yes						
Rdwy Only	t=3	s3	yes	yes							
Rdwy Only	t=3	s4	yes	yes							
Rdwy Only	t=3	s5	yes	yes							
Rdwy Only	t=4	s0	yes	yes	yes	yes	yes				
Rdwy Only	t=4	s1	yes	yes	yes						
Rdwy Only	t=4	s2	yes	yes	yes						
Rdwy Only	t=4	s3	yes	yes	yes						
Rdwy Only	t=4	s4	yes	yes	yes						
Rdwy Only	t=4	s5	yes	yes	yes						
Rdwy Only	t=5	s0	yes	yes	yes	yes	yes				

Network			node 0	node 1	node 2	node 3	node 4	node 5	node 6	node 7	node 8
Rdwy Only	t=5	s1	yes	yes	yes	yes	yes	yes	yes		
Rdwy Only	t=5	s2	yes	yes	yes						
Rdwy Only	t=5	s3	yes	yes	yes						
Rdwy Only	t=5	s4	yes	yes	yes						
Rdwy Only	t=5	s5	yes	yes	yes						
Rdwy Only	t=6	s0	yes	yes	yes	yes	yes				
Rdwy Only	t=6	s1	yes	yes	yes	yes	yes	yes	yes	yes	yes
Rdwy Only	t=6	s2	yes	yes	yes	yes	yes	yes		yes	yes
Rdwy Only	t=6	s3	yes	yes	yes	yes					
Rdwy Only	t=6	s4	yes	yes	yes	yes					
Rdwy Only	t=6	s5	yes	yes	yes	yes					
Rdwy Only	t=7	s0	yes	yes	yes	yes	yes				yes
Rdwy Only	t=7	s1	yes	yes	yes	yes	yes	yes	yes	yes	yes
Rdwy Only	t=7	s2	yes	yes	yes	yes	yes	yes	yes	yes	yes
Rdwy Only	t=7	s3	yes	yes	yes	yes					yes
Rdwy Only	t=7	s4	yes	yes	yes	yes				yes	yes
Rdwy Only	t=7	s5	yes	yes	yes	yes					yes
Rdwy Only	t=8	s0	yes	yes	yes	yes	yes	yes	yes		yes
Rdwy Only	t=8	s1	yes	yes	yes	yes	yes	yes	yes	yes	yes
Rdwy Only	t=8	s2	yes	yes	yes	yes	yes	yes	yes	yes	yes
Rdwy Only	t=8	s3	yes	yes	yes	yes	yes	yes		yes	yes
Rdwy Only	t=8	s4	yes	yes	yes	yes	yes			yes	yes
Rdwy Only	t=8	s5	yes	yes	yes	yes	yes	yes			yes
Power Only	t=0	s0	yes	yes							
Power Only	t=0	s1	yes	yes	yes						
Power Only	t=0	s2	yes								
Power Only	t=0	s3	yes								
Power Only	t=0	s4	yes								
Power Only	t=0	s5	yes	yes							

Network			node 0	node 1	node 2	node 3	node 4	node 5	node 6	node 7	node 8
Power Only	t=1	s0	yes	yes							
Power Only	t=1	s1	yes	yes	yes						
Power Only	t=1	s2	yes								
Power Only	t=1	s3	yes								
Power Only	t=1	s4	yes								
Power Only	t=1	s5	yes	yes							
Power Only	t=2	s0	yes	yes							
Power Only	t=2	s1	yes	yes	yes						
Power Only	t=2	s2	yes	yes	yes						
Power Only	t=2	s3	yes	yes							
Power Only	t=2	s4	yes	yes							
Power Only	t=2	s5	yes	yes							
Power Only	t=3	s0	yes	yes							
Power Only	t=3	s1	yes	yes	yes						
Power Only	t=3	s2	yes	yes	yes						
Power Only	t=3	s3	yes	yes							
Power Only	t=3	s4	yes	yes							
Power Only	t=3	s5	yes	yes							
Power Only	t=4	s0	yes	yes	yes	yes	yes				
Power Only	t=4	s1	yes	yes	yes						
Power Only	t=4	s2	yes	yes	yes						
Power Only	t=4	s3	yes	yes	yes						
Power Only	t=4	s4	yes	yes	yes						
Power Only	t=4	s5	yes	yes	yes						
Power Only	t=5	s0	yes	yes	yes	yes	yes				
Power Only	t=5	s1	yes	yes	yes	yes	yes	yes	yes		
Power Only	t=5	s2	yes	yes	yes	yes	yes	yes		yes	yes
Power Only	t=5	s3	yes	yes	yes						
Power Only	t=5	s4	yes	yes	yes						

Network			node 0	node 1	node 2	node 3	node 4	node 5	node 6	node 7	node 8
Power Only	t=5	s5	yes	yes	yes						
Power Only	t=6	s0	yes	yes	yes	yes	yes				yes
Power Only	t=6	s1	yes	yes	yes	yes	yes	yes	yes	yes	yes
Power Only	t=6	s2	yes	yes	yes	yes	yes	yes		yes	yes
Power Only	t=6	s3	yes	yes	yes						yes
Power Only	t=6	s4	yes	yes	yes					yes	yes
Power Only	t=6	s5	yes	yes	yes						yes
Power Only	t=7	s0	yes	yes	yes	yes	yes				yes
Power Only	t=7	s1	yes	yes	yes	yes	yes	yes	yes	yes	yes
Power Only	t=7	s2	yes	yes	yes	yes	yes	yes	yes	yes	yes
Power Only	t=7	s3	yes	yes	yes	yes					yes
Power Only	t=7	s4	yes	yes	yes	yes				yes	yes
Power Only	t=7	s5	yes	yes	yes	yes					yes
Power Only	t=8	s0	yes	yes	yes	yes	yes			yes	yes
Power Only	t=8	s1	yes	yes	yes	yes	yes	yes	yes	yes	yes
Power Only	t=8	s2	yes	yes	yes	yes	yes	yes	yes	yes	yes
Power Only	t=8	s3	yes	yes	yes	yes					yes
Power Only	t=8	s4	yes	yes	yes	yes				yes	yes
Power Only	t=8	s5	yes	yes	yes	yes					yes

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