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ABSTRACT

Infrastructure system restoration at shortest time became a paramount demand to retain system's functionality to normal performance and avoid services from being ceased for a long time. Enormous studies elucidated the effect of project planning in the restoration problem, aspect studied as schedule, cost, and quality helped in organizing the efforts to restore disrupted networks efficiently with lowest time and costs. However, urging necessities to expedite system restoration affects the validity of normal restoration plans, post optimization model is needed to compress restoration schedule. Method presented in this work is applying crashing on network restoration as a schedule compression technique, this is attained by allocating more resources to recover the network, thus adding additional costs to restoration activities. Two cases were studied, first is allocating the same available human resources for additional working units, second is allocating external human resources to restore the network, both cases resulted in partial crashing, additional costs, and time reduction. Implications of crashing the network are represented by a cost benefit analysis for a set of solutions, these solutions provide decision makers with the tradeoffs between time and cost to adjust their plans according to project priorities and available budget. Example presented in this work used Shelby County, Tennessee USA data.

CHAPTER 1: INTRODUCTION AND MOTIVATION

Infrastructure systems are vital elements of daily life and economic productivity. The resilience of these systems has been of growing interest in the research community, as well as in government and industry (Hosseini et al., 2016). Resilience is generally thought of as the ability of a system to withstand, adapt to, and recover from a disruption(Barker et al., 2017; Turnquist and Vugrin, 2013) . These properties of resilience can be translated into different dimensions of resilience, including *vulnerability* and *recoverability*, among many other variations (Ghorbani-Renani et al., 2020; Ouyang and Dueñas-Osorio, 2012). This work focuses on the recoverability dimension. Timely restoration of disrupted infrastructures results in (a) costs related to the assignment of work crews and equipment to the restoration process, and (ii) the dislocation impact on surrounding environment (e.g., the cost associated with infrastructure systems not being able to meet societal demand) (S. E. Chang, 2003; Ouyang and Dueñas-Osorio, 2012). Naturally, expediting restoration is important for communities but comes at a cost.

Planning for infrastructure system restoration requires prior determination of project baselines in terms of scope, schedule, and budget (*PMBOK*®, 2013). In this work, *scope* is defined by the performance characteristics of the infrastructure systems (e.g., supply, demand, capacity), their interdependencies with other networks, and the amount of damage experienced after a disruption(Almoghathawi et al., 2019; González et al., 2016). The *schedule* baseline is determined by restoration rates and resources available for assignment(Collier and Lambert, 2018; Hegazy et al., 2004). The *budget* baseline is defined by restoration costs found from work crew and equipment resources(Almoghathawi et al., 2019; González et al., 2016; Zhang et al., 2018).

As expediting restoration requires evaluating the tradeoffs between time and cost, schedule compression techniques offer a means to reduce the total time required to recover the network with a budget modification (Kim et al., 2012; *PMBOK*®, 2013). A couple schedule compression methods include *fast tracking*, which requires changing project dependencies to expedite activities in parallel instead of in series, and *crashing*, which requires allocating more resources to perform project activities more quickly (*PMBOK*®, 2013). Fast tracking does not add direct costs to the project, but it adds uncertainty due to the change in project diagram which may result in activities' rework, while crashing directly adds more costs due to additional allocated resources (C. K. Chang et al., 2007; Hazini et al., 2014; *PMBOK*®, 2013). Selecting an appropriate technique to reduce restoration time depends on dependency type and logical relationships between nodes (*PMBOK*®, 2013).

Many researchers studied recovery performance for disrupted networks under schedule and cost constraints, however, applying schedule compression techniques was not addressed. In this work, a new perspective is provided on the extensive literature on infrastructure system restoration under schedule and cost constraints by applying schedule compression to assess restoration improvement under different resource allocation assumptions. Network restoration behavior is tested under two crashing strategies: (i) allowing current assigned human resources to work for additional time, and (ii) allowing more (or outsourcing) work crews to be allocated to restore the network. In essence, the approach taken is that a manager in charge of assigning restoration crews receives a baseline budget and schedule from an analyst (e.g., from an optimal restoration model) and adjusts those baselines from a project management perspective by implementing project crashing. Figure 1 generally depicts the tradeoff between cost and time for normal and crashing conditions: normal restoration has a lower cost but more time is needed to restore the disrupted network, while in contrast, crashing reduces restoration time but increases costs.

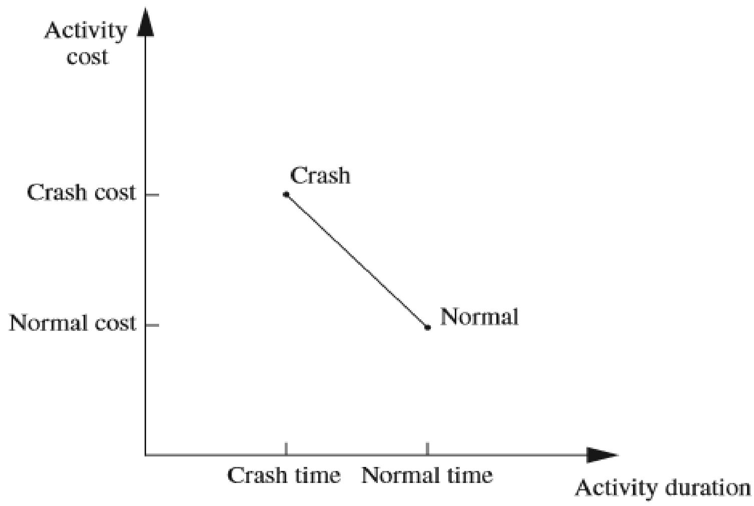


Figure 1. Time-Cost graph for an activity (adapted from Hillier and Lieberman, 2015).

A multi-objective model is proposed to make restoration decisions. The first objective minimize unmet demand over time, which represents the functional status of network restoration (Ghorbani-Renani et al., 2020), while the second objective minimizes restoration costs over time, including normal and crashing costs. The augmented ε-constraint method is used to generate a Pareto-optimal set of solutions to these competing objectives.

This research is structured as follows. Chapter 2 offers methodological background in applying project management for infrastructure system restoration. Chapter 3 provides the mathematical model, while Chapter 4 discusses the solution approach. Chapter 5 illustrates the approach with an interdependent infrastructure network example from Shelby County, Tennessee. Concluding remarks follow in Chapter 6.

CHAPTER 2: METHODOLOGICAL BACKGROUND

This chapter provides background to several concepts integrated together for the proposed model.

2.1. Infrastructure Network Interdependencies and Restoration

Infrastructure system interdependencies function to serve communities with services and vital operations, sophisticated networks may improve services and allow better options to maintain the infrastructure system, enhance its efficiency, and allow cost reductions for mutual functional units. However, a disruptive event may result in substantial adverse consequences in restoration processes and operative costs (González et al., 2016; Ouyang, 2017; Zhang et al., 2018).

The restoration of disrupted infrastructure networks can be complex in their nature. The restoration process for such large projects considers various constraints that affects recovery, including high demand for human resources, repetitive operations, varying work conditions for each site, spatial distribution of damage levels across multiple subnetworks, technical requirements for each type of infrastructure, and different kinds of interdependencies with other infrastructures (Collier and Lambert, 2018; González et al., 2016; Hegazy et al., 2004). Add to that the soft constraints that requires following political and decision maker pressures to reactivate the networks in the shortest time and minimum costs (Collier and Lambert, 2018; Hegazy et al., 2004).

Collier and Lambert (2018) and Ghorbani-Renani et al. (2020) considered in their models pre- and post-disruption conditions in the analysis of and planning for the restoration process. Predisruption planning helps in understanding the operating nature of the network, setting scope of the restoration process, and evaluating the protection strategies to reduce the impact of the disruption. Post-disruption planning assists in analyzing needed work and resources to recover the network to its desired operating state. Both pre- and post-disruption analyses help in defining input parameters and constraints for restoration plans.

2.2. Restoration Project Management

Building restoration project network depends on the type of dependencies for the disrupted network. Predecessor-successor dependencies can take on several forms: mandatory, discretionary, external, and internal. *Mandatory dependency* referred as hard logic and requires a specific activity to start before another one, *discretionary dependency* referred as soft logic allows changing the order of activities if it is needed, *external dependency* is related to external parties to perform project tasks, internal dependency relies on project needs and is controlled by project team. Logical dependencies between activities can take several forms: finish-to-start, start-to-start, finish-to-finish (*PMBOK*®, 2013).

Managing a project, such as the restoration of infrastructure networks, requires the balance of tradeoffs between time and cost (*PMBOK*®, 2013). Infrastructure system restoration planning can be duration driven (i.e., return infrastructure performance as quickly as possible regardless of cost) and resource driven (i.e., restoration is guided by cost, workforce, and equipment constraints) (Hegazy et al., 2004). Schedule planning must be assessed and monitored in relation to the disruption scenario and available resources (Collier and Lambert, 2018).

Focusing on the recoverability dimension of resilience, several costs associated with the restoration of interdependent infrastructure networks have been considered, including costs as associated with node and link restoration, flow, resources, equipment, unmet demand, inoperability costs (Almoghathawi et al., 2019; González et al., 2016; Zhang et al., 2018). Network interdependency and costs affects scheduling decisions related to restoration activities (Nurre et al., 2012). Quick infrastructure recovery alleviates monetary consequences resulting from network idle status, however reducing restoration time is affected by restoration pace and available resources which may result in more monetary losses (Bocchini and Frangopol, 2012; Ge and Xu, 2016).

Collier and Lambert (2018) discussed the infrastructure restoration scheduling problem by analyzing the effect of disruption scenario on project baselines: time, cost, quality. Each disrupted node in the network has an assigned weight based on their influence on future projects decisions: nodes that require more time to be restored are considered more sensitive and have more importance. During the recovery process, preferences, and therefore importance weights, can change, which affects the project network structure according to project goals. In their interdependent network restoration model, Cavdaroglu et al. (2013) emphasize the service provided by subsystems and their effect on neighbor systems in sequencing activities and allocating resources for restoration.

Decision makers face the necessity of meeting a new schedule or cost baselines. This is common in project management since priorities and needs of a certain output or service can change during project execution, new plans are compared with initial plans to evaluate the shift in project’s budget and schedule (Ge and Xu, 2016). For any schedule compression technique partial compression is preferred over complete compression due to high costs associated with compression activities (Hillier and Lieberman, 2015). Selecting the appropriate technique for schedule compression depends on Predecessor-successor dependencies in addition to logical relationships between activities, in this work crashing the network with mandatory and external dependencies, and finish-to-start relationship is discussed.

Applying crashing technique for infrastructure network restoration is aligned with cost benefit analysis to appraise the effect of reducing restoration time in monetary value, and quantify different crashing assumptions (i.e., restoration duration, available resources, and allowed budget increment) to provide decision makers with a set of solutions that shows the tradeoffs between time and cost and help in determining budget baseline which includes contingency reserves, and schedule baseline for restoration project (Hazini et al., 2014; Hegazy, 1999; Hillier and Lieberman, 2015; *PMBOK®*, 2013).

2.3. Pareto-Optimal Solution Generation

Evaluating multiple crashing options is obtained by a multiple objective model to show competing demands of restoring disrupted network rapidly and with minimum costs. The ε-constraint method is adopted for this work to find the Pareto-optimal solution space for restoration decisions.

The ε-constraint method solves the multiple objective model by setting a single objective function at time while using other objectives as constraints in the model (Chankong and Haimes,

2008) . The threshold for optimality for each objective function is known and has a predefined range which is used as the restricted inequality in the constraint set, iterating the process for all objective functions produces a Pareto optimal solution set that helps decision makers to consider the tradeoffs between the solutions and helps in selecting most robust solution among the solution space (Fadel et al., 2002; Laumanns et al., 2005; Mavrotas, 2009). A survey of multi-objective optimization methods in engineering revealed that ε-constraint method is considered as most computationally efficient, easy to use and common method (Marler and Arora, 2004). However, its iterative nature (i.e., solving the problem multiple times based on the number of objective functions) result in the ε-constraint method having an exponential complexity (Laumanns et al., 2005; Marler and Arora, 2004; Ozlen et al., 2014).

Mavrotas (2009) proposed the augmented ε-constraint method which aims to find a strong optimal solution for a set of objectives by accelerating the computational time and reducing redundancy in the solution space. This method solves the problem for one objective function and defines the optimal value for it, then solves for the second objective function while the first objective function is restricted to its previous optimal solution and so on. Almoghathawi et al. (2019) adopted the augmented ε-constraint method for a bi-objective infrastructure system restoration model, which serves as motivation for proposed model.

CHAPTER 3: PROJECT NETWORK OPTIMIZATION MODEL

The project network model for infrastructure system restoration is extracted from the third (restoration) level of a tri-level optimization model proposed by Ghorbani-Renani et al. (2020), which focuses on network restoration by minimizing weighted unmet demand over time. The project network model is a multiple objective model where the first objective aims to utilize resource allocation to optimize the restoration of a disrupted network restoration as soon as possible, and the second objective aims to minimize restoration spending where the restoration process can be further expedited. This is attained by defining a new schedule and budget baselines and allowing resources to be assigned for additional job units to restore the disrupted network. Allowing more resource allocation is referred as schedule compression-crashing (*PMBOK*®, 2013). Both objectives illustrate the tradeoffs between time and cost in the restoration process and helps project managers adjust project baselines according to project needs, priorities, and available budget.

3.1. Project Network Assumptions

Assumptions for this model consider features of the infrastructure systems, in addition to project networks nature in normal and schedule compression conditions.

- The infrastructure system is composed of a set of interconnected subnetworks, each with its own set of nodes and links. Nodes vary in their nature and are represented as supply, demand, and transshipment nodes, and each node has a predefined weight. Links connect nodes with a predefined flow capacity.

- Project network dependencies in this model are of a mandatory (or hard logic) type, which are a result of the functional relationship between nodes.
- The logical relationship between the nodes is finish-to-start, which require the predecessor infrastructure network node to be fully restored and functional before successor node can start the restoration process.
- The project scope baseline is to fully restore all disrupted nodes and links in the networks.
- Disruption is assumed to be a random spatial disruption with different failure rates for nodes and links. The spatial disruption scenario is generated randomly by selecting a random node and define set of neighbor nodes from the same and other subnetworks.
- The initial project schedule baseline is generated after optimizing the infrastructure system restoration model with normal restoration conditions.
- All nodes and links are restored without interruption. Once the node or link starts the restoration process, it will completed until fully restored.
- Restoring subnetworks can start simultaneously with considering the predecessors and successors within and among interdependent subnetworks.
- Initially the project network assumes normal working time for network restoration.
- No lag time is assumed to exist for this problem. If any node or link is restored, there is no waiting time before the next node or link can start the restoration process.
- Each subnetwork requires a specific type of human resources to restore it, and each node and link within the subnetwork has a predefined unit of work for the disruption to be restored.

- Each type of work crew resource has a different number of workers with a predefined unit of work for each node and link. It is defined as restoration rate. Work crew resources are assigned to be fully working in restoring nodes and links.
- Each disrupted node and link has a predefined unit of cost for the normal restoration process.

3.2 Schedule Compression Assumptions

- The new schedule baseline is determined for each subnetwork, and it is lower than the normal time required for restoration.
- Partial crashing is applied for all subnetworks to prevent unnecessary node and link crashing. If adding more work crew resources does not expedite the restoration process, then crashing is not applied to reduce project cost growth.
- In case of using one work crew for each subnetwork then the same work crew resources are assigned to restore disrupted nodes with an added unit of work per unit of time, which is referred to as the delta restoration rate. This value is added to the original restoration rate, as a result a crashing cost is added to nodes and links that are affected by the schedule compression process.
- In case of allocating more than one work crew for each subnetwork, then outsource crews are hired to restore disrupted nodes and links with different and higher costs. As the number of assigned crews increases, restoration costs will increase accordingly.

3.3 Notation

An infrastructure project network is a directed network with a set of nodes N and links A, it consists of a group of subnetworks K that forms the whole network, each $k \in K$ is a different type of infrastructure in the system. The project network with all interconnected subnetworks are denoted as ψ. The node index is i and the link index is (i, j). Sets $N^{\,k}$ and A^k contain the nodes and links in subnetwork k, respectively. The set of supply nodes in subnetwork k is N_+^k and the set of demand nodes in subnetwork k is N_-^k. No node can hold more than one transshipment feature. Sets of disrupted nodes and links within subnetwork k are denoted with N'^k and A'^k, respectively. Each subnetwork has a specific restoration requirement that must be met by a work crew resource $r \in R^k$. Available time units to restore the network is $t \in T$. Predecessor-successor nodes are represented as $\left((\bar{\imath}, \bar{k}), (i, k)\right)$ respectively. The parameters and decision variables of the model are listed in Table 1 and Table 2, respectively.

Table 1. Model parameters.

$\eta_{it_e}^k$	Flow reaching node $i \in N_-^k$ in network $k \in K$ before disruption
w_{it}^k	Node importance weight $i \in N_-^k$ in network $k \in K$ in time $t \in T$
S_i^k	Amount of supply in node $i \in N_+^k$ in network $k \in K$
d_i^k	Amount of demand in node $i \in N_-^k$ in network $k \in K$
u_{ij}^k	Link capacity $(i, j) \in A^k$ in network $k \in K$
λ_{ij}^k	Restoration rate of link $(i, j) \in A'^k$ in network $k \in K$
λ_i^k	Restoration rate of node $i \in N'^k$ in network $k \in K$
F_{ij}^k	Failure rate of link $(i, j) \in A'^k$ in network $k \in K$

F_i^k	Failure rate of node $i \in {N'}^k$ in network $k \in K$
Δ_{ij}^k	Added restoration rate for link $(i,j) \in {A'}^k$ in network $k \in K$, in case of allocating single work crew
Δ_i^k	Added restoration rate for node $i \in {N'}^k$ in network $k \in K$, in case of allocating single work crew
CR_{ij}^{k1}	Normal link restoration cost $(i,j) \in {A'}^k$ in network $k \in K$
CR_i^{k1}	Normal node restoration cost $i \in {N'}^k$ in network $k \in K$
Cc_{ij}^k	Crashing cost for link $(i,j) \in {A'}^k$ in network $k \in K$, in case of allocating single work crew
Cc_i^k	Crashing cost for node $i \in {N'}^k$ in network $k \in K$, in case of allocating single work crew
CR_{ij}^{kr}	Crashing cost for link $(i,j) \in {A'}^k$ in network $k \in K$ for $r \in R^k$,$r \neq 1$
CR_i^{kr}	Crashing cost for node $i \in {N'}^k$ in network $k \in K$ for $r \in R^k$, $r \neq 1$
τ^k	New schedule baseline for network $k \in K$
P_i^k	Number of predecessors for node $i \in {N'}^k$ in network $k \in K$
ε_D	Optimal value for unmet demand objective function
ε_C	Optimal value for restoration cost objective function
M	An arbitrarily large positive number

Table 2. Model decision variables.

η_{it}^k	Continuous variable to represent amount of demand met at node $i \in N_d^k$ in network $k \in K$ at time $t \in T$
x_{ijt}^k	Continuous variable that represent flow on link $(i,j) \in A^k$ in network $k \in K$ in time $t \in T$
α_{ijt}^{kr}	Binary variable to describe restoration status for link $(i,j) \in {A'}^k$ in network $k \in K$ by human resource $r \in R^k$ in time $t \in T$, if restored = 1

α_{it}^{kr}	Binary variable to describe restoration status for node $i \in N'^k$ in network $k \in K$ by human resource $r \in R^k$ in time $t \in T$, if restored = 1
β_{ijt}^{k}	Binary variable for activation status of link $(i,j) \in A'^k$ in network $k \in K$ at time $t \in T$, if activated=1
β_{it}^{k}	Binary variable for activation status of node $i \in N'^k$ in network $k \in K$ at time $t \in T$, if activated=1
γ_{ij}^{k}	Binary variable for link crashing $(i,j) \in A'^k$ in network $k \in K$, applicable to r=1, if crashed =1
γ_{i}^{k}	Binary variable for node crashing $i \in N'^k$ in network $k \in K$, applicable to r=1, if crashed= 1
Z_{ijt}^{kr}	Binary variable used for linearizing product of two binary variables for link $(i,j) \in A'^k$ in network $k \in K$
Z_{it}^{kr}	Binary variable used for linearizing product of two binary variables for node $i \in N'^k$ in network $k \in K$

The project network implementation for infrastructure system restoration problem requires achieving the balance between restoring the disrupted network and controlling schedule and budget baselines. The scope is to fully restore all disrupted network while reducing restoration cost and time.

The first objective function, found in Eq. (1), seeks to reduce amount of unmet demand over time. Restoring all subnetworks k requires each node to be activated and functional, which means that each node after being restored should receive the same amount of demand it used to receive before disruption at the end of the project. This objective function to be minimized is measured by cumulating the weighted difference of unmet demand over demand that must be met before disruption.

$$D = \sum_{t \in T} \left[1 - \left(\frac{\sum_{k \in K} \ \sum_{i \in N_d^k} w_{it}^k \eta_{it}^k}{\sum_{k \in K} \ \sum_{i \in N_d^k} w_{it}^k \eta_{it_e}^k} \right) \right] \quad (1)$$

Second objective function, found in Eq. (2), aims to minimize total cost for infrastructure system restoration. Nodes and links in the network have a predefined monetary value associated with normal restoration conditions, and this monetary value is the minimum value to be spent for restoration process. Expediting network restoration to meet the new schedule baseline will lead to the use of crashing, which will reduce the time required to restore the system by adding more resources to the network (*PMBOK*®, 2013). As a result of adding more resources, the additional crashing cost will be added to the project. The crashing cost for nodes and links is predefined for the disrupted network, and the total crashing cost is directly proportional to the number of nodes and links crashed within the network. Total restoration cost is the summation of normal and crashing cost for all disrupted nodes and links in the network. Crashing the network can be done by the original work crew or by outsourcing new work crews.

$$C = \sum_{t \in T} \sum_{k \in K} \sum_{r \in R^k} \left[\sum_{ij \epsilon A'} \left[\left(CR_{ij}^{kr} * \alpha_{ijt}^{kr} \right) + \left(Cc_{ij}^k * \gamma_{ij}^k \right) \right] + \sum_{i \epsilon N'} \left[\left(CR_i^{kr} * \alpha_{it}^{kr} \right) + \left(Cc_i^k * \gamma_i^k \right) \right] \right] \quad (2)$$

Eq. (3) serves as the bi-objective formulation to minimize time and cost.

$$F = \begin{cases} \min_{\eta,x,\alpha,\beta} D \\ \min_{\gamma,\alpha} C \end{cases} \tag{3}$$

3.4 Model Constraints

The disrupted infrastructure network has a set of boundaries and requirements that must be fulfilled in order to fully restore the network with minimum time and cost. The constraints for this model deals with the problem in normal and schedule compression conditions.

The scope of the project network is to restore all disrupted nodes and link in the network. The restoration process can start when the project is initiated, however no deliverables can be achieved at the first unit of time, at least one time unit is needed to restore nodes and links by work crew resources available for each subnetwork, as governed by constraints (4) and (5).

$$\beta_{ij1}^{k} = 0 \qquad \forall\ (i,j) \in A'^{k}, \forall\ k \in K \tag{4}$$

$$\beta_{i1}^{k} = 0 \qquad \forall\ i \in N'^{k}, \forall\ k \in K \tag{5}$$

Constraints (6)-(9) guarantees fulfilling the supply, demand, and transshipment requirements for each node and link for all subnetworks in the infrastructure network.

$$\sum_{(i,j)\in A^k} x_{ijt}^k - \sum_{(j,i)\in A^k} x_{jit}^k \le S_i^k \qquad \forall\, i \in N_+^k\,, \forall\, t \in T, \forall\, k \in K \tag{6}$$

$$\sum_{(i,j)\in A^k} x_{ijt}^k - \sum_{(j,i)\in A^k} x_{jit}^k = 0 \qquad \forall\, i\ \in N^k \setminus \{N_-^k, N_+^k\}, \forall\, t \in T, \forall\, k \in K \tag{7}$$

$$\sum_{(i,j)\in A^k} x_{ijt}^k - \sum_{(j,i)\in A^k} x_{jit}^k = -\eta_{it}^k \qquad \forall\, i \in N_-^k\,, \forall\, t \in T, \forall\, k \in K \tag{8}$$

$$\eta_{it}^k \le d_i^k \qquad \forall\, i \in N_-^k\,, \forall\, t \in T, \forall\, k \in K \tag{9}$$

Each link in the network has a predefined capacity, which represents the maximum flow the link can support in the infrastructure network. If the link is functional, the flow can be at most the predefined capacity, as suggested in constraint (10).

$$x_{ijt}^k \le u_{ij}^k \qquad \forall\, (i,j) \in A^k\,, \forall\, t \in T, \forall\, k \in K \tag{10}$$

Constraints (11)-(13) ensure that links must be function at a specific time for flow to traverse the links.

$$x_{ijt}^k \le u_{ij}^k \beta_{ijt}^k \qquad \forall\, (i,j) \in {A'}^k\,, \forall\, t \in T, \forall\, k \in K \tag{11}$$

$$x_{ijt}^k \le u_{ij}^k \beta_{it}^k \qquad \forall\, (i,j) \in A^k\,, \forall\, i \in {N'}^k, \forall\, t \in T, \forall\, k \in K \tag{12}$$

$$x_{ijt}^k \le u_{ij}^k \beta_{jt}^k \qquad \forall\, (i,j) \in A^k\,, \forall\, j \in {N'}^k, \forall\, t \in T, \forall\, k \in K \tag{13}$$

Constraints (14)-(15) indicate that if the restoration process starts for any node or link, it should be continued without interruption until that component is fully restored.

$$\sum_{s=1}^{t} \alpha_{ijs}^{kr} \leq M\left[1-\left[\alpha_{ij,t+1}^{kr}-\alpha_{ijt}^{kr}\right]\right] \qquad \forall\,(i,j) \in A'^{k}, \forall\, t \in T, \forall\, k \in K, \forall\, r \in R^{k} \qquad (14)$$

$$\sum_{s=1}^{t} \alpha_{is}^{kr} \leq M\left[1-\left[\alpha_{i,t+1}^{kr}-\alpha_{it}^{kr}\right]\right] \qquad \forall\, i \in N'^{k}, \forall\, t \in T, \forall\, k \in K, \forall\, r \in R^{k} \qquad (15)$$

Time requirement constraints (16)-(19) define the time needed for each node and link in the project network to be restored by human resources for each subnetwork. The time requirement is defined as an integer value and is calculated from the failure rate F and restoration rate λ for each node and link. In case of crashing by a single work crew, another parameter is used in defining time units needed for restoration, Δ_i^k and Δ_{ij}^k for nodes and links, respective. This parameter will add the crashing restoration rate to the normal restoration rate to reduce time units needed for restoration. Schedule compression is partial for each subnetwork to prevent unnecessary cost growth for the project.

$$\sum_{r \in R^k} \sum_{t \in T} \alpha_{ijt}^{kr} \geq \frac{F_{ij}^{k}}{\lambda_{ij}^{k}+[\Delta_{ij}^{k} * \gamma_{ij}^{k}]} \qquad \forall\,(i,j) \in A'^{k}, \forall\, k \in K, \forall\, t \in T \qquad (16)$$

$$\sum_{r \in R^k} \sum_{t \in T} \alpha_{ijt}^{kr} < \frac{F_{ij}^{k}}{\lambda_{ij}^{k}+[\Delta_{ij}^{k} * \gamma_{ij}^{k}]}+1 \qquad \forall\,(i,j) \in A'^{k}, \forall\, k \in K, \forall\, t \in T \qquad (17)$$

$$\sum_{r \in R^k} \sum_{t \in T} \alpha_{it}^{kr} \geq \frac{F_{i}^{k}}{\lambda_{i}^{k}+[\Delta_{i}^{k} * \gamma_{i}^{k}]} \qquad \forall\, i \in N'^{k}, \forall\, k \in K, \forall\, t \in T \qquad (18)$$

$$\sum_{r \in R^k} \sum_{t \in T} \alpha_{it}^{kr} < \frac{F_{i}^{k}}{\lambda_{i}^{k}+[\Delta_{i}^{k} * \gamma_{i}^{k}]}+1 \qquad \forall\, i \in N'^{k}, \forall\, k \in K, \forall\, t \in T \qquad (19)$$

The functionality status for nodes and links is represented by constraints (20) and (21). Once the node or link in each network is fully restored at time unit $t \in T$, it can be labeled as functional in the following time unit.

$$\frac{\sum_{r \in R^k} \sum_{s=1}^{t-1} \alpha_{ijs}^{kr}}{F_{ij}^k / [\lambda_{ij}^k + [\Delta_{ij}^k * \gamma_{ij}^k]]} \geq \beta_{ijt}^k \qquad \forall (i,j) \in A'^k, \forall t \in T \mid t \neq 1, \forall k \in K \tag{20}$$

$$\frac{\sum_{r \in R^k} \sum_{s=1}^{t-1} \alpha_{is}^{kr}}{F_i^k / [\lambda_i^k + [\Delta_i^k * \gamma_i^k]]} \geq \beta_{it}^k \qquad \forall i \in N'^k, \forall t \in T \mid t \neq 1, \forall k \in K \tag{21}$$

Constraints (22) and (23) ensures that human resources for each network are fully assigned to work in that network, and once the restoration process starts at any node or link, the task must be completed until they are fully recovered.

$$\sum_{\substack{s \in R^k \\ s \neq r}} \sum_{t \in T} \alpha_{ijt}^{ks} \leq M\left[1 - \alpha_{ijt}^{kr}\right] \qquad \forall (i,j) \in A'^k, \forall t \in T, \forall k \in K, \forall r \in R^k \tag{22}$$

$$\sum_{\substack{s \in R^k \\ s \neq r}} \sum_{t \in T} \alpha_{it}^{ks} \leq M\left[1 - \alpha_{it}^{kr}\right] \qquad \forall i \in N'^k, \forall t \in T, \forall k \in K, \forall r \in R^k \tag{23}$$

Within each subnetwork work crew resources cannot be assigned to restore more than one node or link simultaneously, as governed by constraints (24)-(26).

$$\sum_{r\in R^k} \alpha_{ijt}^{kr} \leq 1 \qquad \forall\, (i,j) \in A'^k, \forall\, t \in T\ , \forall\, k \in K \tag{24}$$

$$\sum_{r\in R^k} \alpha_{it}^{kr} \leq 1 \qquad \forall\, i \in N'^k, \forall\, t \in T\ , \forall\, k \in K \tag{25}$$

$$\sum_{(i,j)\in A'^k} \alpha_{ijt}^{kr} + \sum_{i\,\in N'^k} \alpha_{it}^{kr} \leq 1 \qquad \forall\, t \in T, \forall\, k \in K, \forall\, r\ \in\ R^k \tag{26}$$

The project network in this model follows hard logic dependencies with logical relationship "finish-to-start." Successor nodes can have more than one predecessor. González et al., (2016) suggested a finish-to-start constraint for multiple predecessors, where all predecessor nodes must be fully restored and functional before the successor node can start the restoration process, ensured by constraint (27). Note that this constraint is applicable for dependencies within each subnetwork.

$$\beta_{it}^k \leq \frac{\sum_{\bar{\imath}\,\in P_i^k} \beta_{\bar{\imath}t}^k}{|P_i^k|} \qquad i\ \neq \bar{\imath}, (i\,,\bar{\imath}) \in N'^k,\ \forall\, \bar{\imath}\ \ \in P_i^k, \forall\, k \in K,\ \forall\, t \in T \tag{27}$$

Constraint (28) is related to project network crashing. To expedite the total time required to restore each network, a new schedule baseline τ^k is assigned for each subnetwork defined to be less than the normal time required to restore each network.

$$\sum_{t\epsilon T} \sum_{i\,\in N'^k} [1 -\ \beta_{it}^k] + \sum_{t\epsilon T} \sum_{(i,j)\in A'^k} [1 - \beta_{ijt}^k]\ \leq\ \tau^k \qquad \forall\, i \in N'^k, \forall\, (i,j) \in A'^k,\ \forall\, t \in T\ , \forall\, k \in K \tag{28}$$

Some nodes in the project network are joint nodes, which indicates the interdependency between different subnetworks. Interconnected nodes cannot be functional unless predecessor node from other subnetwork is activated. This external dependency is represented by constraint (29).

$$x_{ijt}^{k} \leq u_{ij}^{k} * \beta_{\bar{\imath}t}^{\bar{k}} \qquad \forall (i,j) \in A^{k},\ \forall k,\bar{k} \in K,\ \forall \bar{\imath} \in N'^{\bar{k}} \mid \left((i,k),(\bar{\imath},\bar{k})\right) \in \psi \tag{29}$$

Constraints (30)-(39) reflect the nature of the decision variables in the project network.

$$\eta_{it}^{k} \geq 0 \qquad \forall i \in N_{d}^{k}, \forall t \in T, \forall k \in K \tag{30}$$

$$x_{ijt}^{k} \geq 0 \qquad \forall (i,j) \in A^{k}, \forall t \in T, \forall k \in K \tag{31}$$

$$\alpha_{ijt}^{kr} \in \{0,1\} \qquad \forall (i,j) \in A'^{k}, \forall t \in T, \forall k \in K, \forall r \in R^{k} \tag{32}$$

$$\alpha_{it}^{kr} \in \{0,1\} \qquad \forall i \in N'^{k}, \forall t \in T, \forall k \in K, \forall r \in R^{k} \tag{33}$$

$$\beta_{ijt}^{k} \in \{0,1\} \qquad \forall (i,j) \in A'^{k}, \forall t \in T, \forall k \in K \tag{34}$$

$$\beta_{it}^{k} \in \{0,1\} \qquad \forall i \in N'^{k}, \forall t \in T, \forall k \in K \tag{35}$$

$$\gamma_{ij}^{k} \in \{0,1\} \qquad \forall (i,j) \in A'^{k}, \forall t \in T, \forall k \in K, \forall r \in R^{k} \tag{36}$$

$$\gamma_{i}'^{k} \in \{0,1\} \qquad \forall i \in N'^{k}, \forall t \in T, \forall k \in K, \forall r \in R^{k} \tag{37}$$

$$Z_{ijt}^{kr} \in \{0,1\} \qquad \forall (i,j) \in A'^{k}, \forall t \in T, \forall k \in K, \forall r \in R^{k} \tag{38}$$

$$Z_{it}^{kr} \in \{0,1\} \qquad \forall i \in N'^{k}, \forall t \in T, \forall k \in K, \forall r \in R^{k} \tag{39}$$

Constraints (16)-(21) are nonlinear equations. To linearize them, the product of two binary variables is replaced by new binary variables, Z_{ijt}^{kr} and Z_{it}^{kr}. These linear constraints are represented in Eqs. (40)-(51).

$$\sum_{r \in R^k} \sum_{t \in T} [\lambda_{ij}^k * \alpha_{ijt}^{kr}] + \sum_{r \in R^k} \sum_{t \in T} [\Delta_{ij}^k * Z_{ijt}^{kr}] \geq F_{ij}^k \tag{40}$$

$$\sum_{r \in R^k} \sum_{t \in T} [\lambda_{ij}^k * \alpha_{ijt}^{kr}] + \sum_{r \in R^k} \sum_{t \in T} [\Delta_{ij}^k * Z_{ijt}^{kr}] < F_{ij}^k + \lambda_{ij}^k + [\Delta_{ij}^k * \gamma_{ij}^k] \tag{41}$$

Constraints (40) and (41) are valid for $\forall (i, j) \in A'^k, \forall k \in K, \forall t \in T$.

$$\sum_{r \in R^k} \sum_{t \in T} [\lambda_i^k * \alpha_{it}^{kr}] + \sum_{r \in R^k} \sum_{t \in T} \left[\Delta_i^k * Z_{it}^{kr}\right] \geq F_i^k \tag{42}$$

$$\sum_{r \in R^k} \sum_{t \in T} [\lambda_i^k * \alpha_{it}^{kr}] + \sum_{r \in R^k} \sum_{t \in T} \left[\Delta_i^k * Z_{it}^{kr}\right] < F_i^k + \lambda_i^k + [\Delta_i^k * \gamma_i^k] \tag{43}$$

Constraints (42) and (43) are valid for $\forall i \in N'^k, \forall k \in K, \forall t \in T$.

$$\sum_{r \in R^k} \sum_{s=1}^{t-1} [\lambda_{ij}^k * \alpha_{ijs}^{kr}] + \sum_{r \in R^k} \sum_{s=1}^{t-1} \left[\Delta_{ij}^k * Z_{ijt}^{kr}\right] \geq \beta_{ijt}^k * F_{ij}^k \qquad \forall (i, j) \in A'^k, \forall t \in T \mid t \neq 1, \forall k \in K \tag{44}$$

$$\sum_{r \in R^k} \sum_{s=1}^{t-1} [\lambda_i^k * \alpha_{is}^{kr}] + \sum_{r \in R^k} \sum_{s=1}^{t-1} \left[\Delta_i^k * Z_{it}^{kr}\right] \geq \beta_{it}^k * F_i^k \qquad \forall i \in N'^k, \forall t \in T \mid t \neq 1, \forall k \in K \tag{45}$$

$$Z_{ijt}^{kr} \geq \alpha_{ijt}^{kr} \qquad \forall\, (i,j) \in {A'}^{k}, \forall\, k \in K, \forall\, t \in T \tag{46}$$

$$Z_{ijt}^{kr} \geq \gamma_{ij}^{k} \qquad \forall\, (i,j) \in {A'}^{k}, \forall\, k \in K, \forall\, t \in T \tag{47}$$

$$\alpha_{ijt}^{kr} + \gamma_{ij}^{k} \leq 1 + Z_{ijt}^{kr} \qquad \forall\, (i,j) \in {A'}^{k}, \forall\, k \in K, \forall\, t \in T \tag{48}$$

$$Z_{it}^{kr} \geq \alpha_{it}^{kr} \qquad \forall\, i \in {N'}^{k}, \forall\, k \in K, \forall\, t \in T \tag{49}$$

$$Z_{it}^{kr} \geq \gamma_{i}^{k} \qquad \forall\, i \in {N'}^{k}, \forall\, k \in K, \forall\, t \in T \tag{50}$$

$$\alpha_{it}^{kr} + \gamma_{i}^{k} \leq 1 + Z_{it}^{kr} \qquad \forall\, i \in {N'}^{k}, \forall\, k \in K, \forall\, t \in T \tag{51}$$

CHAPTER 4: SOLUTION APPROACH

The multi-objective project network model is solved by applying the augmented ε-constraint method that solves the model for one of the objective functions and find the optimal solution, then use the solved objective function as a constraint in the model and solve for the second objective (Almoghathawi et al., 2019; Mavrotas, 2009).

The first objective function (D), which is related to cumulative unmet demand over time, has an optimal value of zero, as this represents a fully functional network where all demand nodes have met demand. This optimal value is represented with ε_D. The second objective function (C), which is related to restoration costs over time, has an optimal value of the normal restoration costs $\sum_{t\in T}\sum_{k\in K}\sum_{r\in R^k}\left[\sum_{ij\epsilon A'}\left[CR_{ij}^{k1} * \alpha_{ijt}^{k1}\right] + \sum_{i\epsilon N'}\left[CR_{i}^{k1} * \alpha_{it}^{k1}\right]\right]$. This is the minimum cost required to restore the disrupted network and is denoted with ε_C. In case of solving for the first objective function (D), restoration costs will be rewritten as a new constraint (52).

$$\sum_{t\in T}\sum_{k\in K}\sum_{r\in R^k}\left[\sum_{ij\epsilon A'}\left[\left(CR_{ij}^{kr} * \alpha_{ijt}^{kr}\right) + \left(Cc_{ij}^{k} * \gamma_{ij}^{k}\right)\right] + \sum_{i\epsilon N'}\left[\left(CR_{i}^{kr} * \alpha_{it}^{kr}\right) + \left(Cc_{i}^{k} * \gamma_{i}^{k}\right)\right]\right] \le \varepsilon_C \;\forall\, i \in N'^{k}, \forall\,(i,j) \in A'^{k}, \qquad \forall\, t \in T, \forall\, k \in K, \forall\, r \in K^r \tag{52}$$

To allow restoration time to be reduced, the assigned budget must be increased. This can be achieved by allowing a specific increment percentage above the normal budget to be added to the right hand side of constraint (52) and by replacing normal restoration time by the crash time in constraint (28). This process is repeated to generate multiple cases that reflect the tradeoffs between time and cost for decision makers.

In case of solving for the second objective function (C), cumulative unmet demand is rewritten as a new constraint (53).

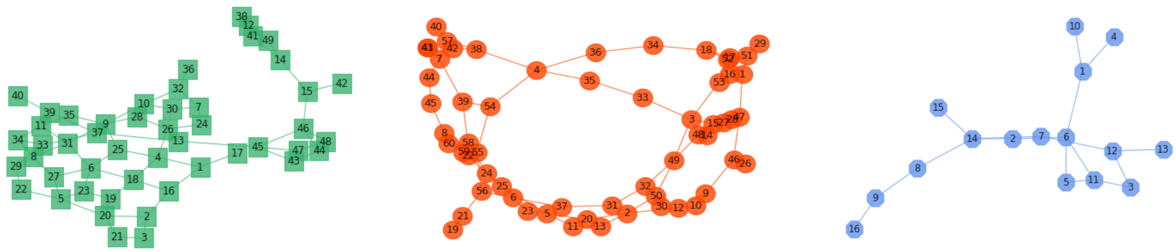
$$\sum_{t\in T}\left[1-\left(\frac{\sum_{k\in K}\ \sum_{i\in N_d^k} w_{it}^k \eta_{it}^k}{\sum_{k\in K}\ \sum_{i\in N_d^k} w_{it}^k \eta_{it_e}^k}\right)\right]\leq \varepsilon_D \qquad \forall\, i\in {N'}^k, \forall\,(i,j)\in {A'}^k, \forall\, t\in T, \forall\, k\in K \quad (53)$$

To minimize total restoration costs when single or multiple work crews can be assigned, the restoration process can be bounded by a time constraint (28) or can be achieved by forcing constraint (53) to reduce unmet demand in a specific time units $t\in T$ such that $t\leq x$, where x is the new desired restoration time. In this case the model will apply partial crashing, any node or link that will not reduce restoration time will not be crashed.

Both solution approaches are evaluated in terms of budget and schedule changes, selecting the optimal parameters for cost and time depends on project priorities and decision maker options. Expediting the restoration process will directly impact restoration costs. Cost benefit analysis helps in defining the right value for schedule compression. Selecting a new schedule baseline will help in defining project contingency reserves beyond the "normal" budget.

CHAPTER 5: ILLUSTRATIVE EXAMPLE

The project network model of infrastructure system restoration is illustrated using interdependent water, power, and gas network data from Shelby County, Tennessee, USA (Ghorbani-Renani et al., 2020). There are 49 nodes and 71 links in the water network, 60 nodes and 76 links in the power network, and 16 nodes and 17 links in the gas networks. These three subnetworks are illustrated in Figure 2. There are also 54 links that provide the interdependency among the networks.



(a) (b) (c)

Figure 2. Infrastructure networks in Shelby County, TN: (a) Water, (b) Power, and (c) Gas.

For the purpose of this example, a spatial disruption scenario was generated by selecting an arbitrary node from one of the subnetworks and defining its neighbors up to the third neighbor, neighbors can be from the same subnetwork or adjoint subnetworks. From initial disrupted set, one of the joint nodes is selected and same process for neighbors generating is repeated. Disrupted network generation resulted in 35 disrupted nodes with 41 links for predecessor successor dependency, and 8 links for interdependency between subnetworks.

Figure 3 illustrates spatial disrupted project network.

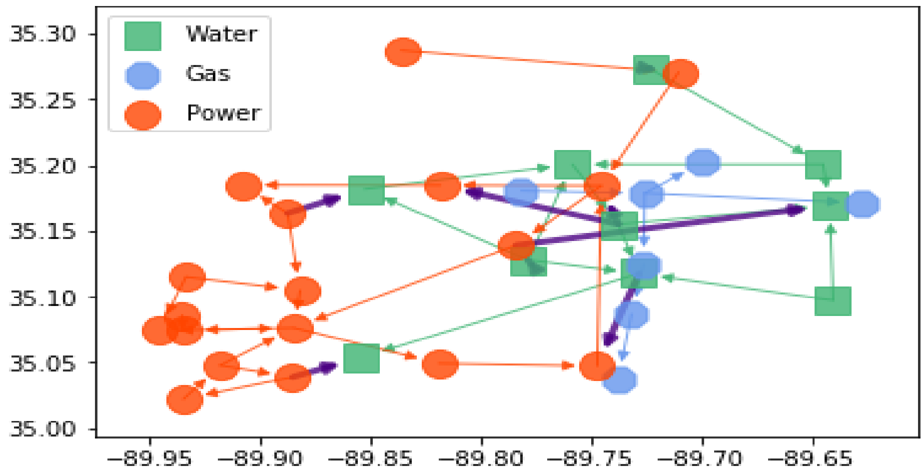


Figure 3. Spatially disrupted set of interdependent networks.

The restoration process is performed in order with the predecessor-successor relationship being applied for each subnetwork and for interdependent nodes. The finish-to-start relation forces the predecessor node to be completely restored and activated before the successor can start the restoration process.

The disruption was applied with random failure rates on network nodes. The normal restoration rate (λ_i^k) and delta restoration rate (Δ_i^k) are defined arbitrarily before the restoration process begins such that delta rate does not exceed 30% of normal restoration rate. The normal restoration cost for nodes (CR_i^{k1}) and the node crashing cost for a single work crew in each resource group (Cc_i^k) are defined arbitrarily, however crashing costs (Cc_i^k) are defined to be greater than normal restoration costs, as the work is done by the same crews and can be considered an overtime shift. For multiple work crews, the resource crashing cost ($CR_i^{kr}, r \neq 1$) is defined arbitrarily with an increasing amount for each added crew, $CR_i^{k\mathrm{r}} < CR_i^{k(\mathrm{r}+1)} <$ $CR_i^{k(\mathrm{r}+2)}$ and so on, which is considered to be outsourcing.

Network restoration is tested under multiple budget and schedule baselines to help in defining the cost-benefit analysis for decision makers. This is applied by restricting the duration of unmet demand to a certain desired time, in addition to allowing the restoration cost objective to be increased by a certain amount above normal restoration costs. These results help in evaluating cost and time tradeoffs, and provide decision makers with a set of options to restore disrupted infrastructure system.

Two cases are tested in this example. The first case is studied for a single work crew in each subnetwork, and the second case is studied for multiple work crews within each subnetwork. For both cases, the minimum restoration cost is the normal cost, and any added costs are the schedule compression-crashing costs.

5.1. Schedule Compression-Crashing with One Crew for Each Subnetwork

For the first case only one work crew can restore each disrupted subnetwork, for water, power, and gas networks there are three total work crews to restore the system of networks with allowance to work for overtime shift. The maximum budget that can be allocated for network restoration is the summation of normal and crashing costs for the three crews. The maximum budget increment is 49.94% (1625 budget units) The model seeks the minimum restoration costs, and as a result, the crashing budget is available but might not be all used. Table 3 shows budget scenarios for the disrupted network.

Table 3. Allowed budget increment for single work crew

	Budget increment percentage						
	5%	10%	20%	25%	30%	40%	49.9%
Allowed increment	162.7	325.4	650.8	813.5	976.2	1301.6	1625
Normal budget + Allowed increment	3416.7	3579	3904.8	4067.5	4230.2	4555.6	4881

Disrupted network restoration under normal conditions requires a budget of 3254 and 8 units of time. Reducing restoration time to 7 units and allowing restoration cost to be increased with multiple budget values resulted in the same unmet demand over time horizon. The restoration cost was increased due to the change in crashed nodes from each subnetwork. This indicates that adding more costs for schedule compression does not improve the restoration time. Table 4 and Figure 4 shows amount of unmet demand over time for different budget scenarios.

Table 4. Unmet demand for allowed budget increments and restoration times.

Time	Normal restoration	(+) %5	(+) %10	(+) %20	(+) %25
1	0.394	0.394	0.394	0.394	0.394
2	0.394	0.394	0.394	0.394	0.394
3	0.374	0.394	0.394	0.394	0.394
4	0.302	0.329	0.329	0.329	0.329
5	0.213	0.225	0.225	0.225	0.225
6	0.091	0.130	0.130	0.130	0.130
7	0.008	0.003	0.003	0.003	0.003
8	0.002	0.000	0.000	0.000	0.000
9	0	0	0	0	0
10	0	0	0	0	0

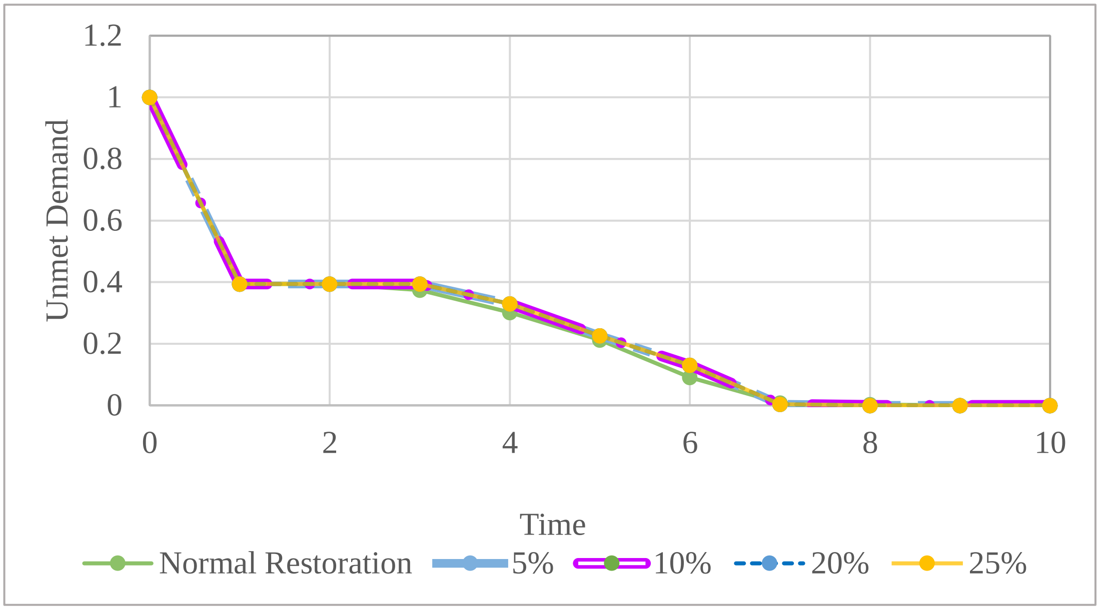


Figure 4. Unmet demand over time for different budget scenarios

The change in restoration cost for allowed budget scenarios while restricting restoration to be done in 7 units of time is illustrated in Figure 5. Each scenario allows using more budget to restore the network. The model does not allocate work crew resources to work for overtime shifts if the restoration performance is not improved.

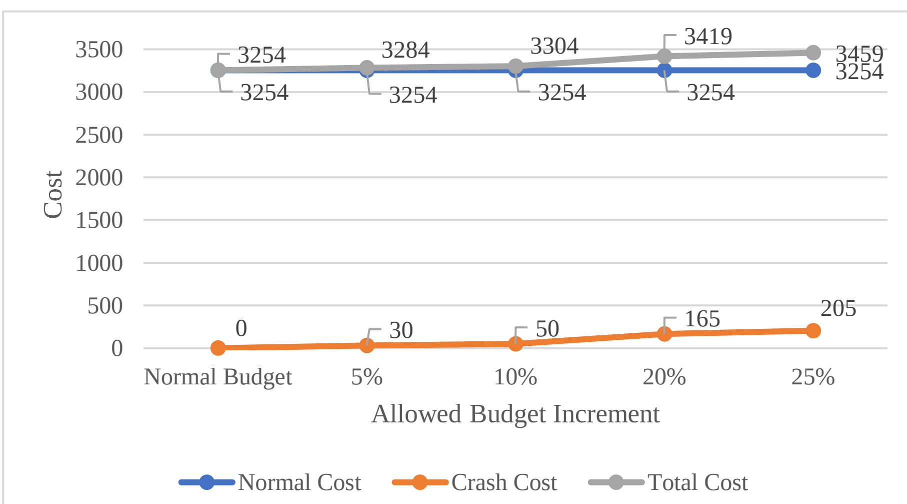


Figure 5. Restoration cost for different budget scenarios

The cumulative restoration cost for different budget scenarios are illustrated in Figure 6. Cost increases when the model allows the second objective function to be increased.

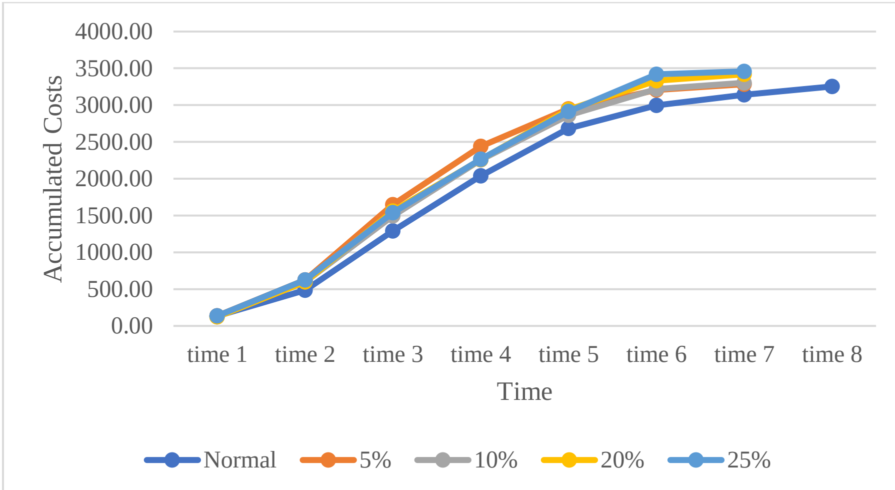


Figure 6. Accumulated restoration cost for different budget scenario

The number and type of crashed nodes changes with different budget scenarios as depicted in Figure 7 and Figure 8. The reason for the changes in crashed nodes is that power network has a higher restoration cost, allowing the budget to increase allows for high cost nodes to be restored if they will reduce restoration time.

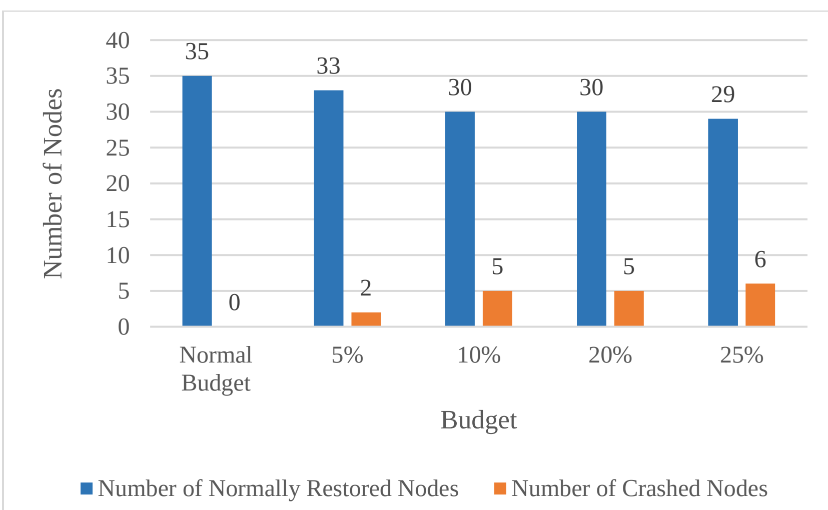


Figure 7. Number of normally restored and crashed nodes for different budget scenarios.

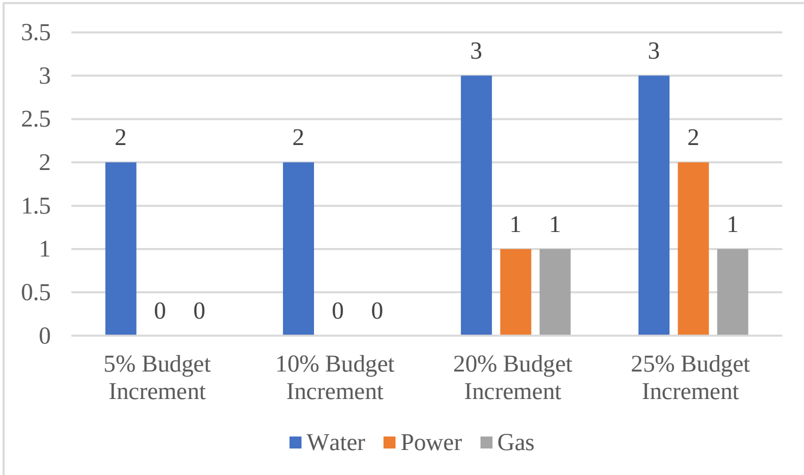


Figure 8. Crashed node types and count for a single work crew

Figure 9 illustrates the crashed nodes in the network for 7 time units and a 25% budget allowance.

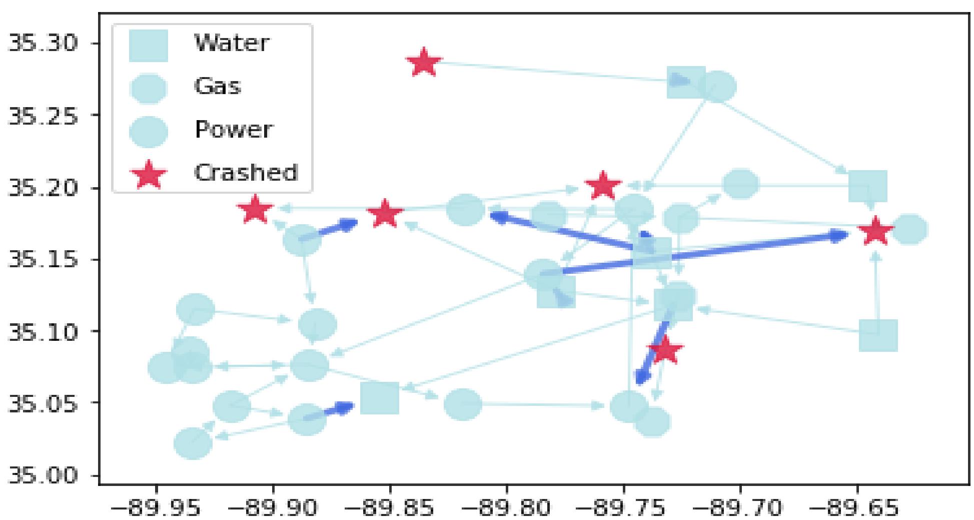


Figure 9. Crashed network with a single work crew and 25% budget increment.

Reducing to 6 time units in all budget scenarios resulted in an infeasible model, which indicates that single work crew for each subnetwork can reduce restoration time only by one unit of time. This is because predecessor nodes must be completely restored before the successor node can start the restoration process, and since only one work crew is assigned to restore the network, predecessor and successor nodes cannot be restored simultaneously.

5.2. Schedule Compression-Crashing with Multiple Crews for Each Subnetwork

The second case allows allocating more than one crew for each subnetwork, allowing the restoration process to be expedited by allowing simultaneous node restoration. As a result, time needed to restore the network will be minimized and restoration costs will increase. Allocating a new work crew will add a considerable restoration cost to each disrupted node, and this will affect budget baseline.

Allowing more work crews to be allocated causes the budget to be greater than normal restoration costs. For example, adding one extra work crew for each subnetwork causes the restoration costs to increase by double, while adding five work crews for each subnetwork increases the restoration budget by a factor of 5.5 relative to the normal restoration cost. Table 5 shows amount of budget increment for each added work crew.

Table 5. Budget increment for added work crews.

	Water	Gas	Power	Total Cost (Normal+ Crashing)	Allowed Budget Increment
Normal Cost	590	434	2230	3254	0
2 work crews	1232	887	4576	6695	2.06
3 work crews	1919	1359	7032	10310	3.17
4 work crews	2650	1850	9604	14104	4.33
5 work crews	3417	2359	12311	18087	5.56
6 work crews	4222	2887	15147	22256	6.84
7 work crews	5063	3445	18143	26651	8.19
8 work crews	5943	4035	21317	31295	9.62

Normal restoration condition as the first case is 8 units of time and a budget of 3254, increasing number of work crews up to 2 and restricting the disrupted network to be restored with less than or equal to 7 time units resulted in restoring the network with 4 time units and 3882 units of money, change in budget is 19.3% which is much lower than planned budget for 2 crews, the model only allocates additional work crews that will reduce time and cost of restoration.

Reducing restoration time down to 1 unit requires at least 8 work crews for both water and power networks and 6 work crews for the gas network. Limiting restoration time to one unit and work crews to 6 or 7 resulted in an infeasible result. Figure 10 illustrates the amount of unmet demand over time horizon for multiple work crews.

Figure 10. Unmet demand over time for multiple work crews allocation

The restoration cost requirement for each unit of time is shown in Figure 11. Allocating more resources to restore disrupted network results in high costs for each unit of time.

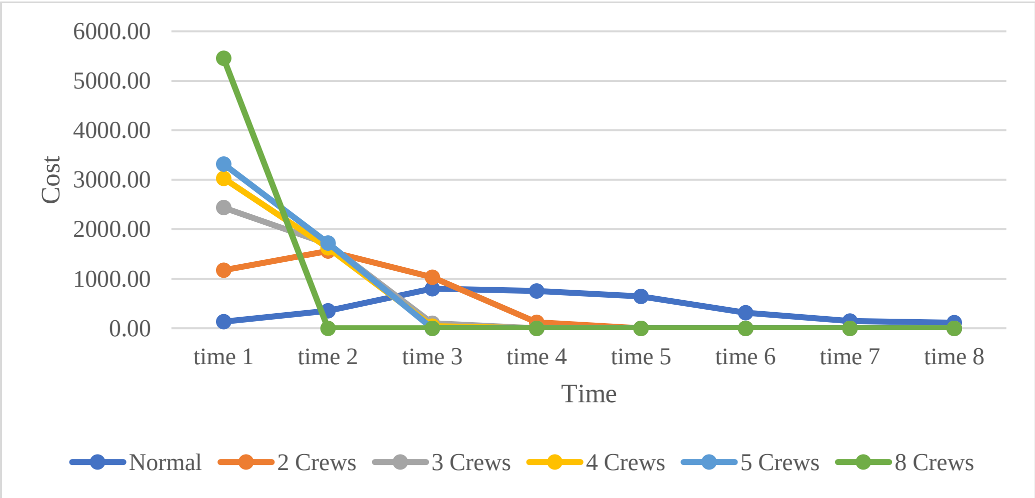


Figure 11. Cost requirements over time for multiple work crews

Figure 12 depicts the tradeoffs between required restoration costs and time. Decreasing time units from 8 to 1 cause 67.7 % increment on restoration costs. According to project needs, decisions are made to change schedule and budget baselines.

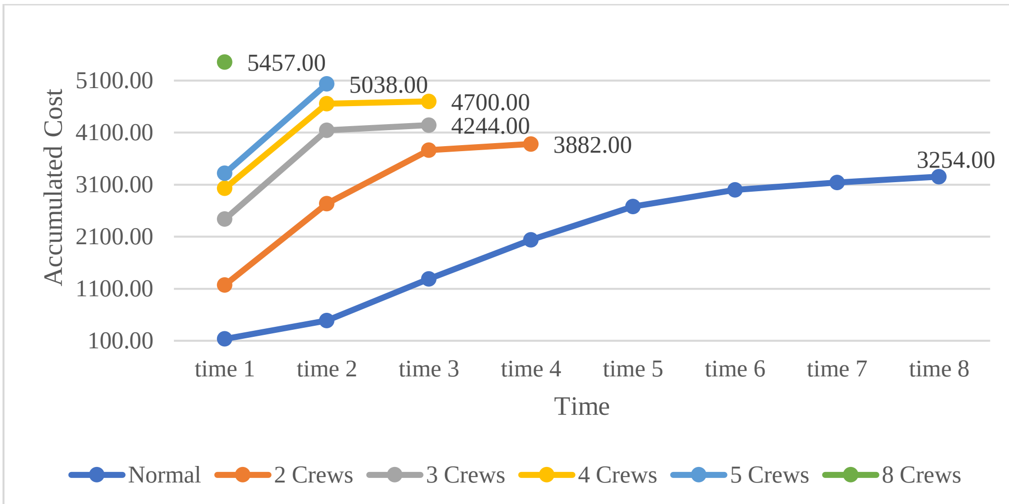


Figure 12. Tradeoffs between time and cost for multiple work crews

Increasing the number of work crews allows more nodes to be crashed simultaneously. Figure 13 shows number of normally restored and crashed nodes for multiple allocated work crews.

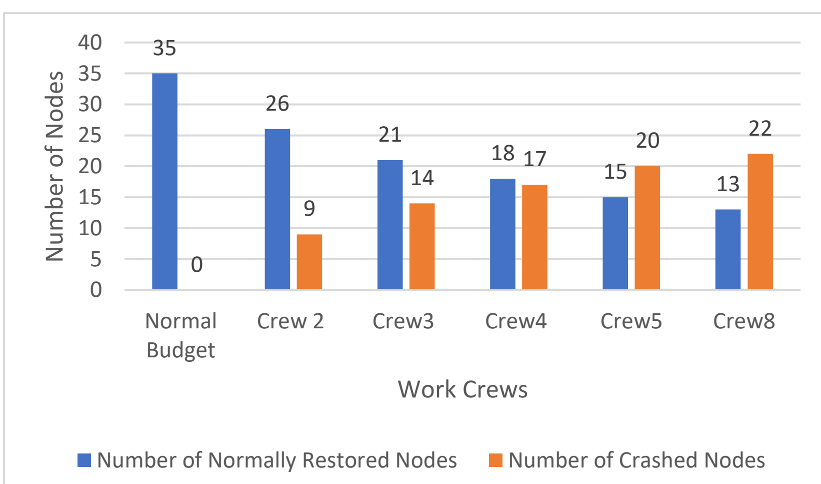


Figure 13. Number of normally restored and crashed nodes for multiple work crews

Figure 14 shows the change in types and number of crashed nodes for multiple work crews.

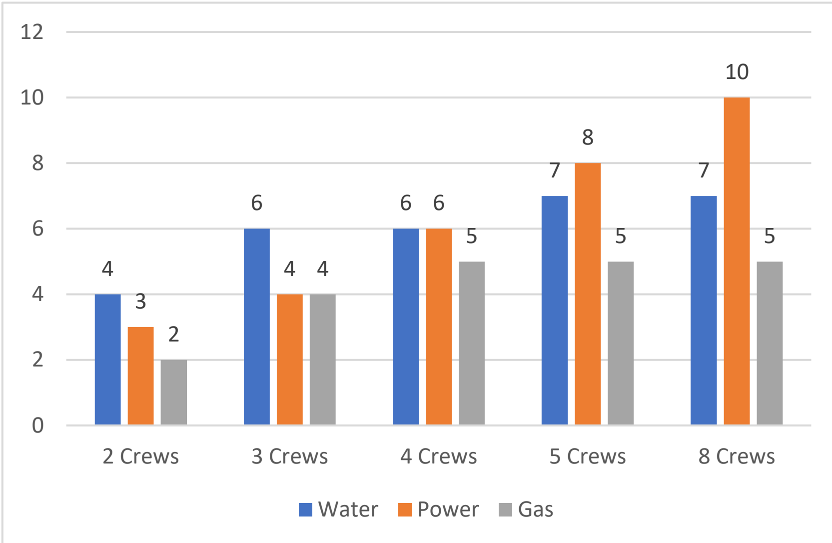


Figure 14. Crashed node types and count for multiple work crews

Figure 15 shows the difference between normal restoration costs and crashing costs for multiple work crews, crashing costs are higher than normal restoration costs for all work crews, this will limit allocating external sources in case of having a limited restoration budget.

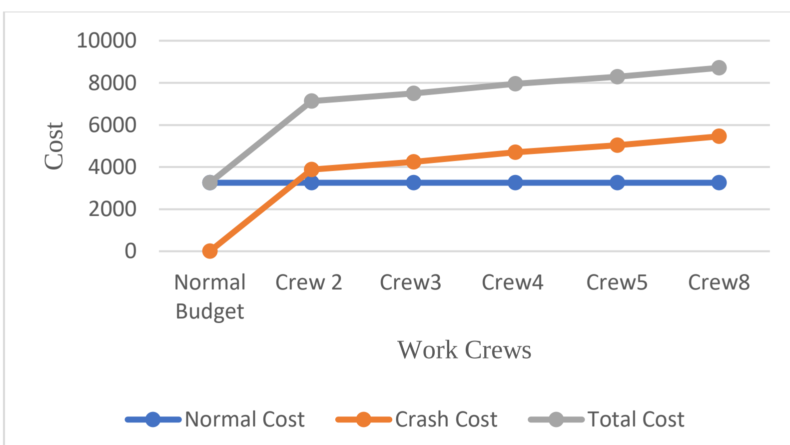
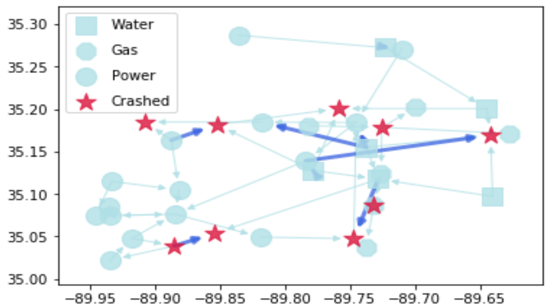
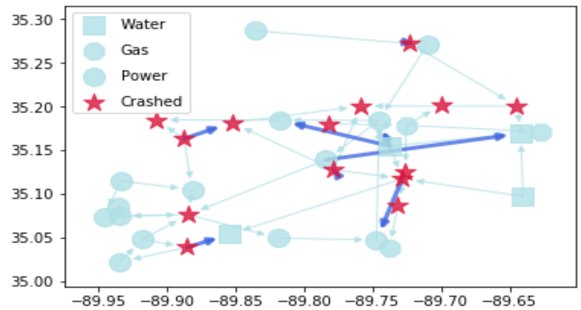


Figure 15. Restoration costs for multiple work crews

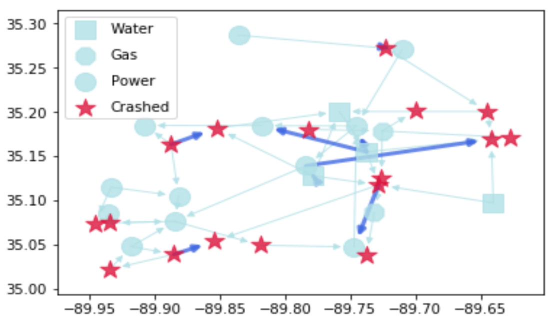
Figure 16 illustrates the change in number of crashed nodes to expedite network restoration, allocating more than 5 crews results in crashing more than half of the disrupted network.



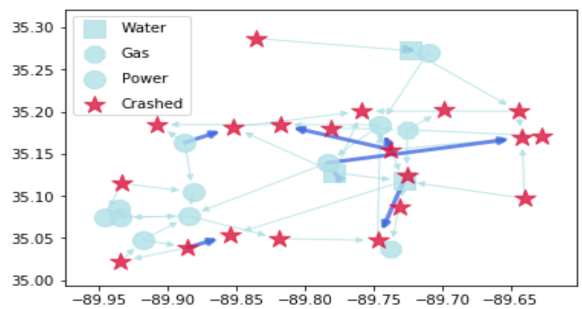
(a)



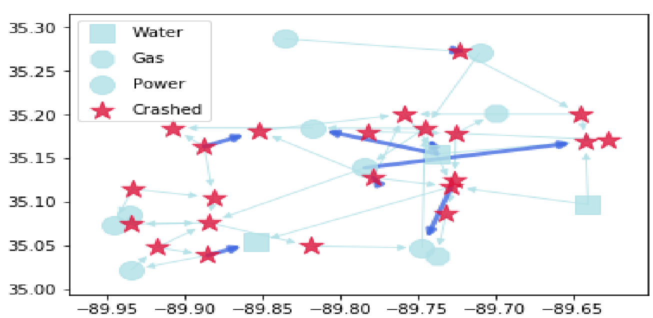
(b)



(c)



(d)



(e)

Figure 16: Crashed network restoration for multiple crews assignment: (a) 2 Crews, (b) 3 Crews, (c) 4 Crews, (d) 5 Crews, (e) 8 Crews

5.3. Crashing Cases in Comparison

Schedule compression must be accompanied by a cost-benefit analysis to evaluate cost-time tradeoffs and provide decision makers with alternatives to determine schedule and budget baselines (Ge and Xu, 2016; Hazini et al., 2014; *PMBOK*®, 2013). Allocating the same work crew resources with additional performance rates to restore disrupted network resulted in minimum time saving and considerable low crashing costs. Increasing the allowed budged for crashing did not result in more nodes being crashed, but it diversified the selected nodes from all networks based on their crashing costs. When maximum time saving is attained, crashing efforts cease to reduce restoration costs.

Allowing more work crews to be allocated for restoration resulted in maximum time savings and highest crashing costs. Allowing one additional work crew to restore the network reduced required time by half, and similarly additional work crews were not assigned if no saving in time is achieved.

Figure 177 illustrates the tradeoffs between time and cost for multiple crashing options, while a larger budget allowance is permitted for decision makers more time saving can be achieved and vice versa.

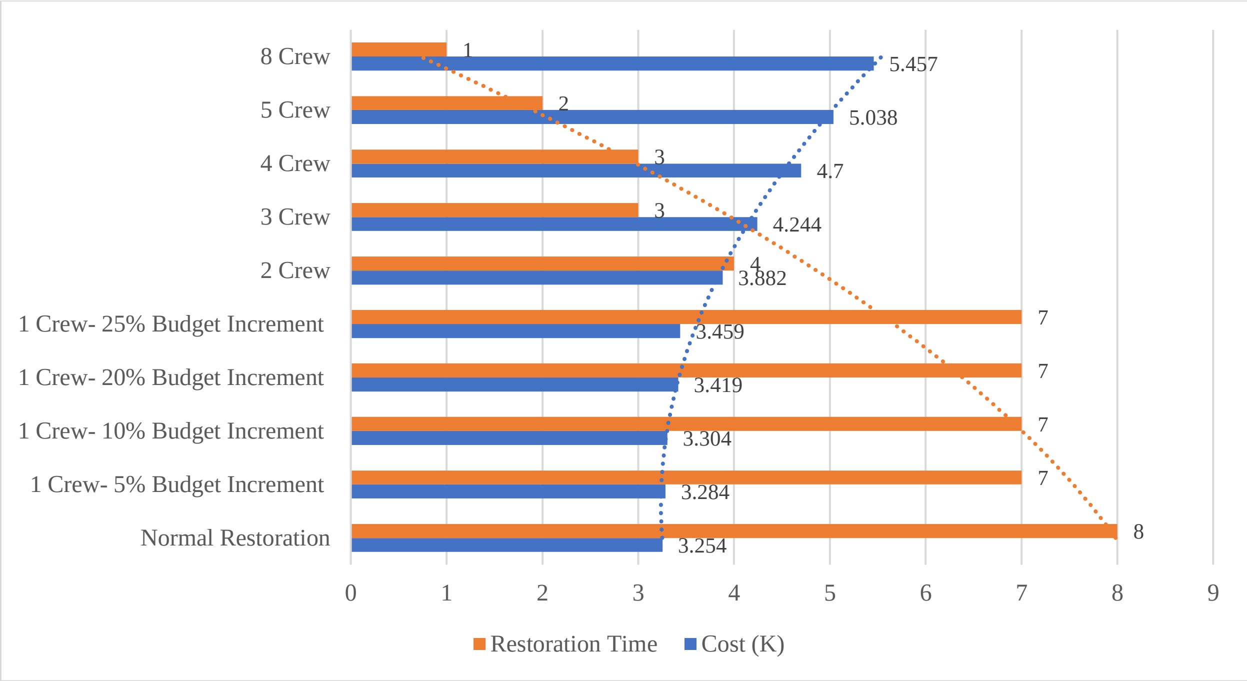


Figure 17. Cost-Time tradeoffs for multiple crashing options

CHAPTER 6: CONCLUDING REMARKS

Infrastructure systems are a crucial factor in facilitating everyday life, ability to preserve the functionality of these systems against disrupted events requires a comprehensive knowledge about networks components and characteristics (i.e., supply, demand, capacity, importance weight) all network elements and surrounding environment conditions sets the foundation to for recovery planning process in case of any disruption. Applying project management knowledge to infrastructure system restoration helps in organizing recovery efforts and allocate resources more efficiently, project management has a variety set of tools that helps in finding optimal solutions under different cases of budget and schedule options.

Schedule compression techniques provide flexible options for decision makers to reduce restoration time by evaluating the tradeoffs between time and costs for network restoration. Both schedule compression techniques; crashing and fast tracking aims to save restoration time, but they result in additional costs which may not be preferred by decision makers. However, expediting disrupted network restoration might become an urging demand to reduce negative impacts for disruptive event, which will eventually lead to an increment in total restoration costs.

In this work disrupted network recovery was tested under two crashing options to compress the restoration schedule and expedite network recovery, first option allowed overtime working for current human resources, this option resulted in minimum time saving and lowest total restoration costs, using this option might be a solution if available restoration budget is limited and the necessity to restore disrupted network in a short time is not a priority for decision makers. Second option allowed allocating external resources to restore disrupted network, this option resulted in a considerable time reduction and approximately 68% additional change to restoration costs, in case of urged need to restore the network quickly this option might be a valuable option to select. Available budget and schedule constraint play a significant role in selecting the best method for schedule compression, cost benefit analysis for each alternative provide decision makers with set of solutions and options to select from in order to recover the network in the shortest possible time.

For future research applying fast tracking as another schedule compression technique would provide more allowance to reduce restoration time, fast tracking can be applied by having a discretionary dependency (or soft logic) between nodes, this type of dependency allows changing restoration order because this dependency is preferred not required, however, it will add more uncertainty due to possibility of rework on activities. Applying crashing and fast tracking in the same model also would be beneficial in reducing restoration time. Another aspect that could be considered for this problem is the logical relationship between nodes, applying different type of logical relations such as start-to-start will allow successor restoration to begin if the predecessor is restored by a defined percentage, this logical relationship will not result in additional costs, yet it requires a solid knowledge about activities nature to allow this relation to take place while building the network diagram.

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