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Title: Logistics, Planning, and Response for Disasters

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Logistics, Planning, and Response for Disasters

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1. Introduction

Natural and manmade disasters have the potential to inflict substantial damage on infrastructure systems, resulting in degradation of the ability to perform their function. Emergency response planners at all levels of government and in the private sector can use LogiSims and RestoreSims analyses results to assess and plan for disasters by pre-positioning (i.e., stockpile) resources and respond to disasters by distributing resources and repairing infrastructure efficiently after a disaster.

LogiSims and RestoreSims analysis results can be used to provide recommendations on prioritizing restoration efforts to meet the goal of restoring infrastructure as quickly as possible given availability of transportation systems and resources.

Stockpiling analyses are used to provide recommendations on how to use an available budget to stockpile resources that can be used to mitigate the impacts of a disaster in the most effective way. The analysis is able to hedge stockpile decisions against an ensemble of possible hazards.

Budget utilization tradeoff analyses provide results that decisionmakers can use to set priorities for budget utilization. As an example, decisionmakers can use analysis results to understand how a budget can improve resource delivery time or how to meet as much demand for resources as possible. The analysis results can be used to understand the tradeoffs between metrics, i.e., allocating budget to delivery efficiency verses meeting demand.

2. Disaster Planning and Response

LogiSims is a Los Alamos National Laboratory (LANL) capability to provide stakeholders with recommendations on stockpiling and distributing relief and restoration supplies. These tools include the following capabilities:

- Weighted metrics for evaluating pre-positioning options — examples of metrics include cost and demand met in planning scenarios
- Weighted metrics for evaluating schedules of distribution of relief and restoration supplies — examples include efficiency, cost, and demand met
- Ability to model corporate giving
- A flexible damage model based on hazard
- A flexible model for incorporating decisionmaker constraints
- Incorporation of dependencies on transportation systems

- Repair and restoration of infrastructure systems

2.1. Logistics and Restoration Model

Figure 2-1 presents the overall LogiSims analysis method. The analysis begins with the input of a hazard scenario or a set of hazard scenarios. Hazard scenarios are either generated by an internal model or provided by an external source (this is noted in first box of Figure 2-1). A hurricane is an example of a hazard scenario. The second step (Box 2 of Figure 2-1) predicts damage to infrastructure. The predictions are provided by LANL's Fragility tool, which is based on the Federal Emergency Management Agency HAZUS model of damage. In this case, damage is applied to transportation and dependent infrastructure networks. The third step (Box 3 of Figure 2-1) calculates how infrastructure systems operate in the damaged state using LANL's suite of physics and agent-based models of infrastructure. Examples include the Interdependency Environment for Infrastructure Simulation Systems modeling tool which is used to calculate the physics of systems such as electric power and natural gas[1]. FastTrans is used for transportation modeling. The fourth box of Figure 2-1 shows the final step. This step computes the optimal restoration schedule based upon a decisionmaker's metric for prioritizing repairs. This step uses state-of-the-art optimization technology developed within the LogiSims and RestoreSims capabilities to determine the best restoration schedule to meet the metric of choice.

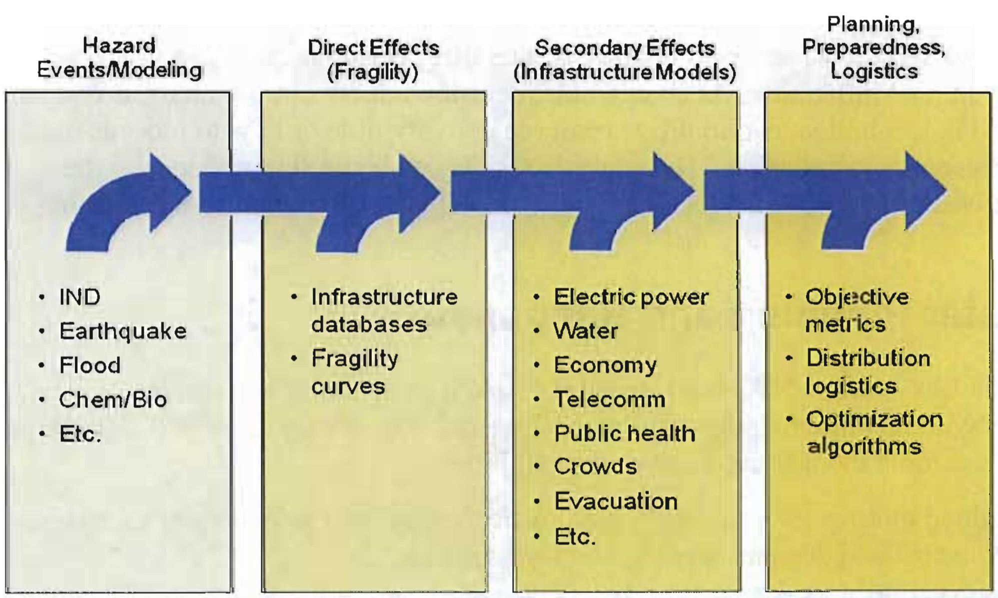

Figure 2-1. Overview of the analysis flow used in modeling the logistics of disaster planning and management

2.2. LogiSims Algorithm for Relief Supply Distribution

LANL has used LogiSims in a synthetic simulation environment to analyze the stockpiling of relief supplies (e.g., bottled water) in anticipation of and preparation for a potential hazard. The capability could be used to generate plans for distributing supplies to locations where an impacted population could pick them up (e.g., emergency shelters).

Figure 2-2 shows the overall process flow for the algorithm. The input to the algorithm is resource demand scenarios as derived from the process in Figure 2-1; for example, demand for bottled water is derived from damage to the water distribution infrastructure and impacted population. In Figure 2-2, Step 1 of the algorithm determines which stockpile locations should be used that is best for a set of hazard scenarios. This portion of the algorithm uses a mixed-integer programming (MIP) model that includes information about the probability of survival of a stockpile, damage to the transportation system, demand for relief supplies, and available budget for stockpiling for a defined set of hazard scenarios. Step 2 of the algorithm determines the amount of relief supplies to store at each stockpile location. This portion of the algorithm also uses a MIP model that includes the same information used in Step 1 and the results from Step 1.

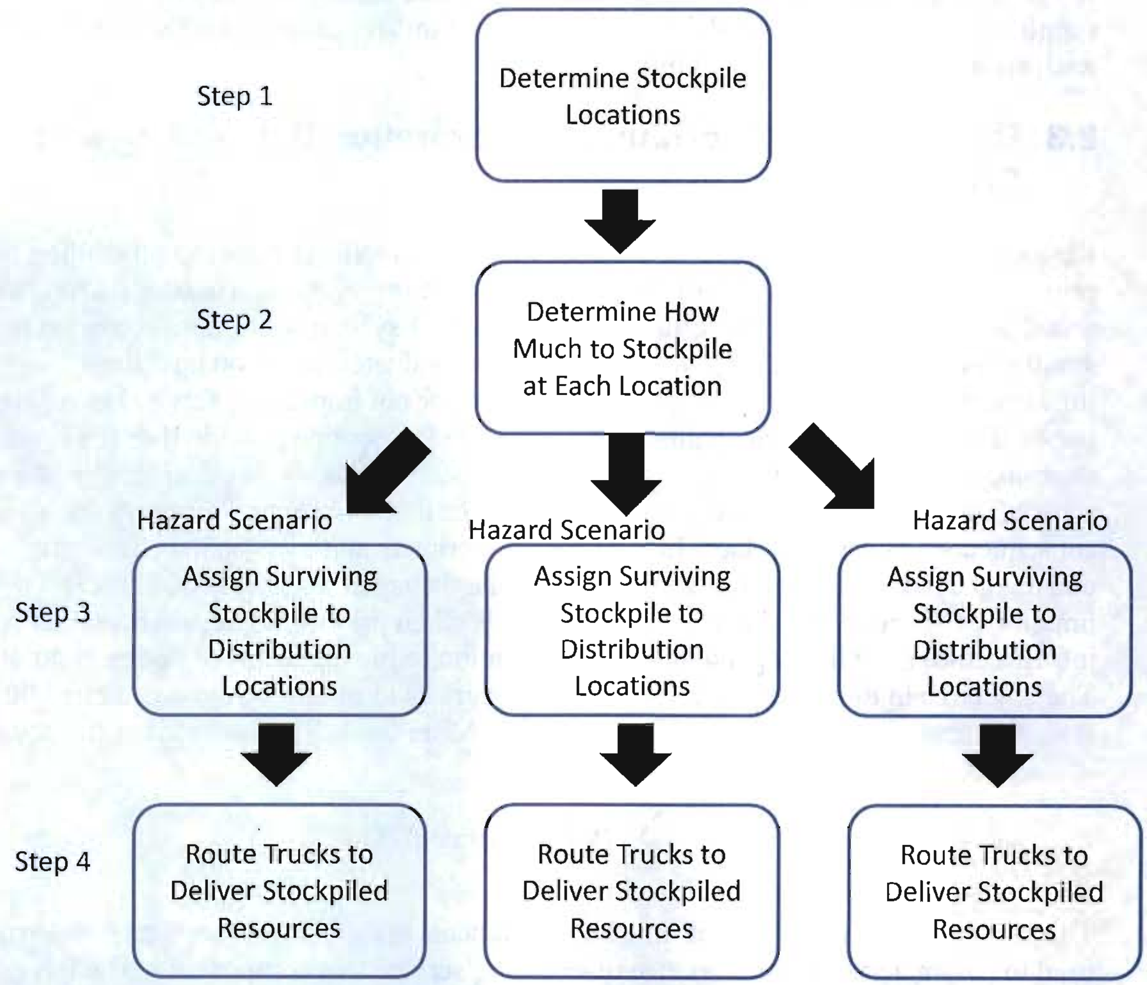

Figure 2-2. Process flow diagram for the algorithm used to model to stockpiling and distribution of relief supplies

Step 3 of the algorithm assigns, for each hazard scenario, surviving stockpiled supplies to distribution locations. The assignments are based up the demand for supplies and the ability of the transportation system to support distribution of supplies from the stockpiles to the distribution locations. The affected population will be directed to these locations to obtain relief supplies. Locations may include evacuation shelters, schools, churches, temporary Red Cross centers, etc. This step is modeled using a constraint programming (CP) model. Step 4 of the algorithm schedules, for each hazard scenario, relief trucks to deliver the stockpiled supplies according to the assignments of Step 3 and available transportation infrastructure. This step is modeled using a local search (LS) model. The overall approach is designed to provide the best possible distribution of supplies that can be computed in a user-specified time. The capability has undergone considerable scientific peer review to validate the state-of-the-art nature of the approach (see references [2-5]). It is important to note that Steps 3 and 4 can be operated independently from Steps 1 and 2 when stockpile decisions are provided to LogiSims as input.[1]

In 2010, capabilities were added to model the effects of "corporate giving"[2] on the need for stockpiling and distribution. Capability was also added to allow decisionmakers to weight the importance of different goals of the model, such as meeting demand for supplies and/or efficiency of delivery. Section 3 of this report presents the results of an analysis used to test these capabilities.

2.3. RestoreSims Algorithm for Restoration Scheduling and Prioritization

RestoreSims is a LANL capability that can be used to model restoration scheduling and prioritization for several types of damaged infrastructure systems. To date, LANL has tested and developed this capability on electric power system restoration scenarios in simulation environments. Restoration options are evaluated based on how the infrastructure system responds (improving service or not improving service) to repairs as opposed to being evaluated against static (e.g., level of service provided) or pre-incident measures of priority. There are two important remarks to highlight prioritizing restoration scheduling: (1) Assets that were of low importance in the undamaged system (small consequence-of-loss) may have high restoration priority and vice versa because the undamaged network operates differently than the damaged network; and (2) It is important to account for the availability of roads when prioritizing restoration. Critical infrastructure is highly dependent on transportation to move resources during restoration. The objective in this scenario is to schedule repairs as to minimize the cumulative time critical assets (or all assets) are without service. More formally, the metric is the equation

$$\sum_i P_i \int Unserved_i(t)dt.$$

This metric sums the amount of time all components spend without service. The term P is used to parameterize the importance of restoring service to a component i. The integral measures the amount of time (t) component i is without service.

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[1] For example, if stockpile decisions had already been made through another process.

[2] This refers to the practice of large corporations donating resources and services after an incident.

Figure 2-3 shows the overall process flow for the restoration scheduling and prioritization algorithm. Step 1 of the algorithm determines the amount and type of repair supplies to store (e.g., power lines, generator components, etc.) given a budget constraint. Step 2 determines where to stockpile the repair resources. Both steps take into account possible damage scenarios. Typically, it is not cost effective to stockpile enough resources to perform all repairs (additional supplies are often borrowed from neighboring utilities), so these steps stockpile as much as possible to allow for the largest number of repairs averaged across all the hazard scenarios. These steps use a MIP model with a column generation approach. Step 3, for each hazard scenario, determines which assets should be repaired. This step focuses on finding the minimal set of assets to repair to restore service to critical assets and/or restore service to all assets. This step uses a CP model. Step 4 calculates a prioritized order of restoration. Priorities are assigned based upon how quickly critical services and/or all services are restored. It is important to note that this step relies on an infrastructure simulation tool to calculate the performance of proposed priorities. In Step 5, the priorities determined in Step 4 are used to determine how crews are routed to perform the repairs. The crews are scheduled to conduct repairs from high priority to low priority but may skip repairs if skipping them increased efficiency. For example, if a repair would require lengthy travel across the damaged transportation system to arrive in location that already has repair crews in the vicinity, then model may route a crew to a nearby high priority asset instead. This step also uses an infrastructure simulation tool to calculate the performance of different repair crew schedules in terms of how quickly the function provided by infrastructure is restored.

The capability is currently undergoing considerable scientific peer review to validate the state-of-the-art nature of the approach (see references [6-8]). It is important to note that Steps 3, 4, and 5 can be operated independently from Steps 1 and 2 when stockpile decisions are predetermined.

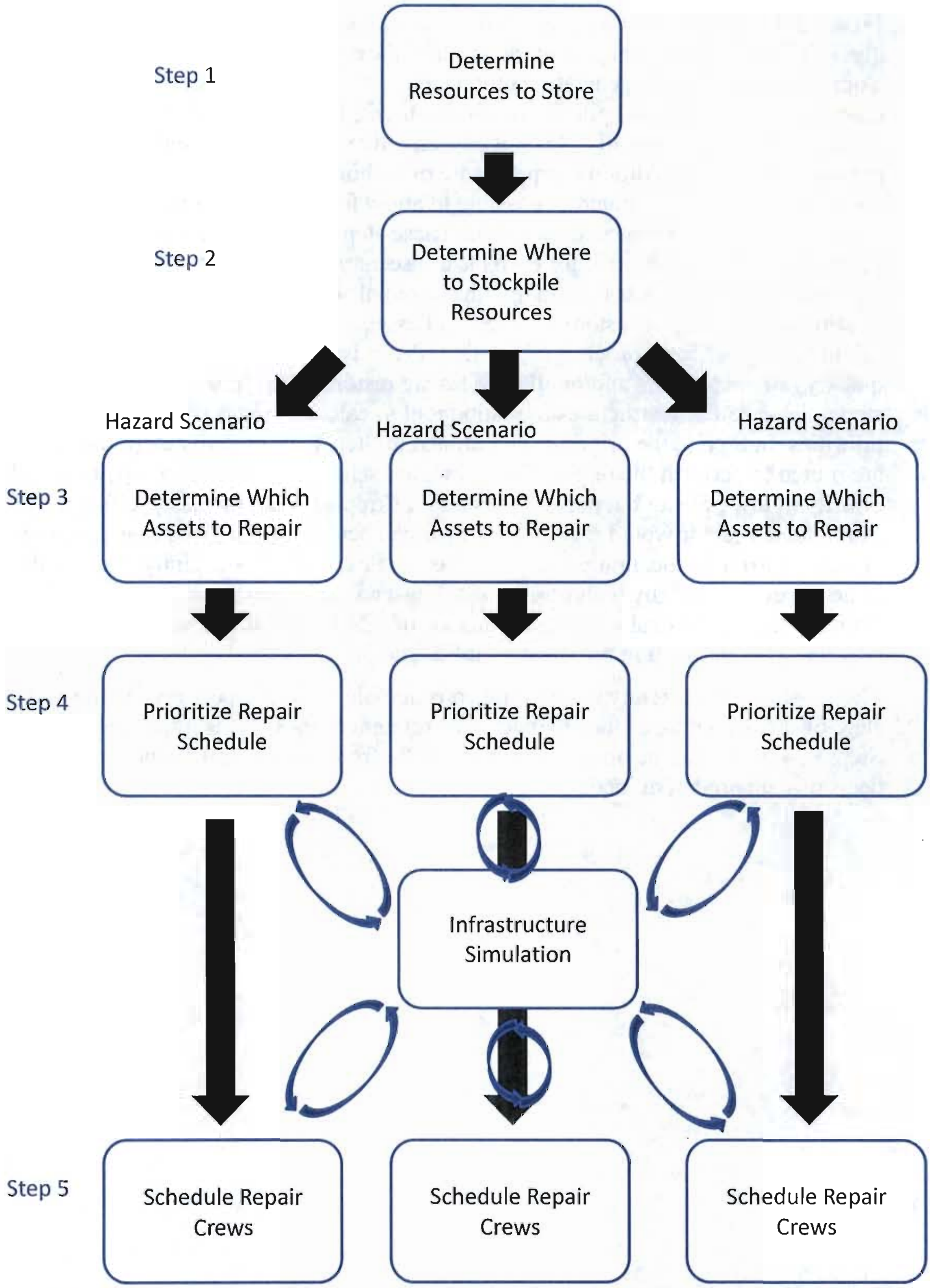

Figure 2-3. Process flow diagram for the algorithm used to model to stockpiling and distribution of repair supplies for infrastructure systems

3. Analyses

This section presents example analysis to demonstrate the capability.

3.1. Analysis of Corporate Giving

In this section, we show how LogiSims can be used to model the impacts of corporate giving (within a simulation environment). In this context, corporate giving denotes scenarios where large corporations decide to donate goods and services after a hazard incident occurs. Analysis results allow decisionmakers to understand how corporate giving can reduce the budgetary needs required to meet demand and distribute resources efficiently.

Two analyses were conducted. One analysis demonstrates the LogiSims capability to model corporate giving when goods and services are donated at the stockpile locations. Subsequently, these donations need to be delivered to distribution locations. In this particular analysis, the decisionmaker has placed high priority on meeting demand. The second analysis demonstrates the capability to model corporate giving directly at the distribution locations. Both analyses plot the ability of the decisionmaker to meet demand and distribute resources efficiency under varying levels of budget availability and corporate giving.

Figures 3-1 and 3-2 provide analysis results based on corporate giving of bottled water at stockpile locations. In Figure 3-1, the *y*-axis shows the ability of emergency planners to meet demand as a percentage of total demand. In Figure 3-2, the *y*-axis shows the the time for which the last delivery of resources occurred last delivery time. In both figures, the *x*-axis shows the available budget. The graphs plot an analysis of the ability to meet decisionmaker metrics such as meeting demand and distribution efficiency when certain percentages of the demand for resources are met through corporate donations. In Figure 3-1, the analysis clearly shows that as corporations satisfy a higher percentage of demand, the decisionmaker is able to do more with a smaller budget. Interestingly, Figure 3-2 shows that as corporate donations increase (when the budget is small), the latest delivery time is increased because the distribution crews have to make more deliveries under the same budget, which takes longer. This also explains why delivery time initially increases with increased budget. Under this scenario, the budget is initially used to satisfy more demand, which creates more deliveries. Once all demand is met, additional budget is used to improve delivery times.

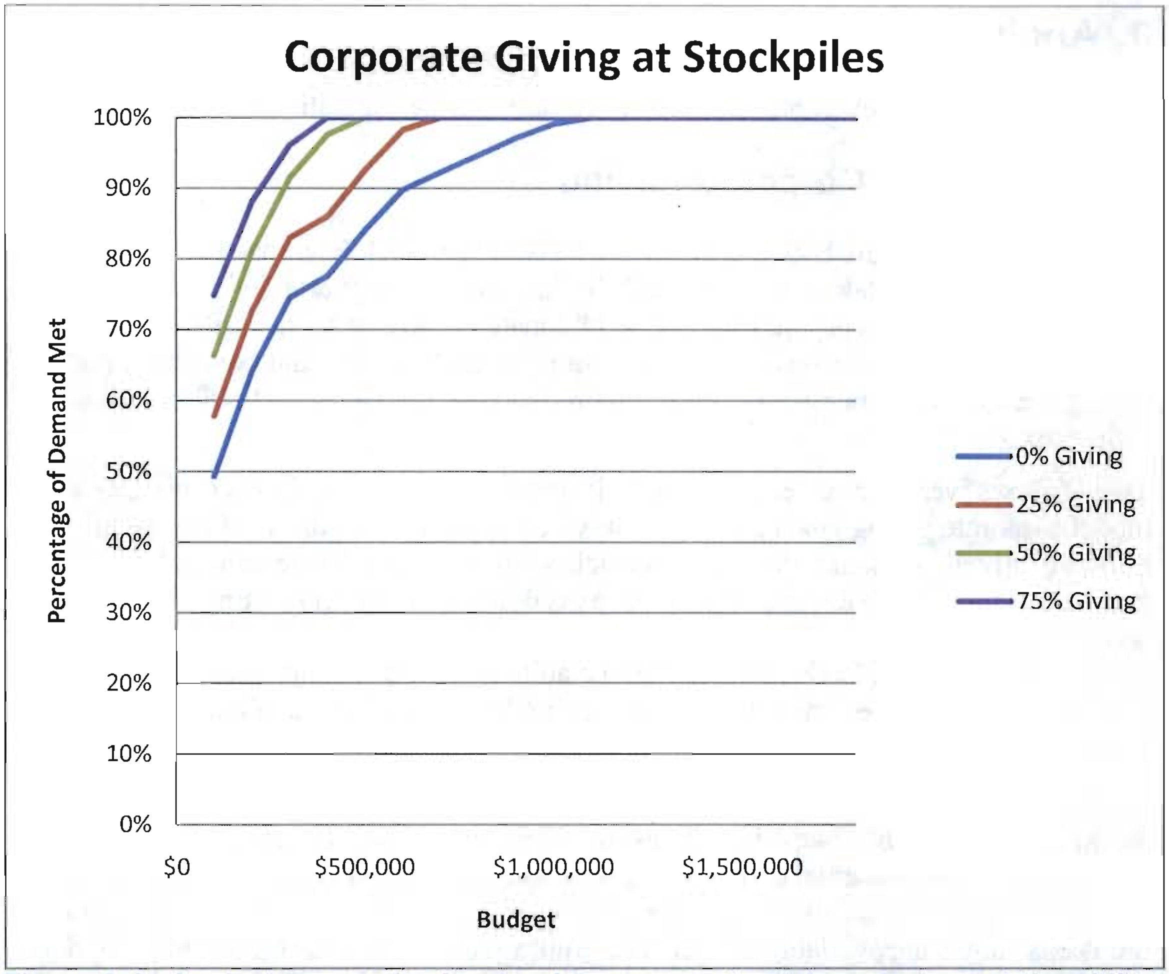

Figure 3-1. Analysis example showing how corporate giving can impact the ability for emergency planners to meet demand under different budget constraints

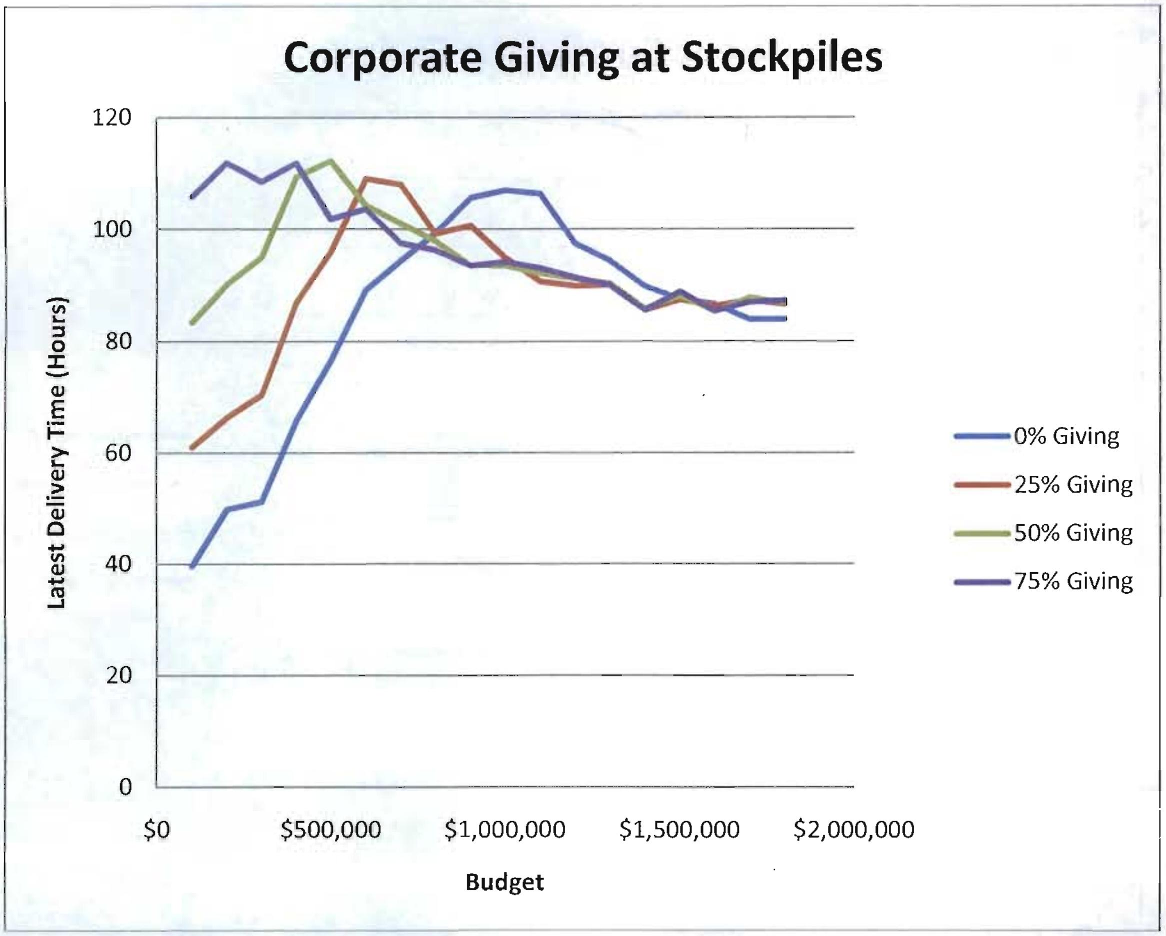

Figure 3-2. Analysis example showing how corporate giving can impact the ability of emergency planners to distribute resources efficiently under different budget constraints

Figures 3-3 and Figures 3-4 show an analysis of corporate giving when the corporations are responsible for directly providing resources to the distribution centers, rather than to stockpile locations.

As shown in Figure 3-3, the ability to meet demand improves when corporations make resource donations directly to the distribution centers. The difference between donations at the stockpiles compared to distribution centers is minimal. A larger impact is seen when delivery time is considered (Figure 3-4). By giving directly to the distribution centers, the impact to delivery times under small budgets is reduced.

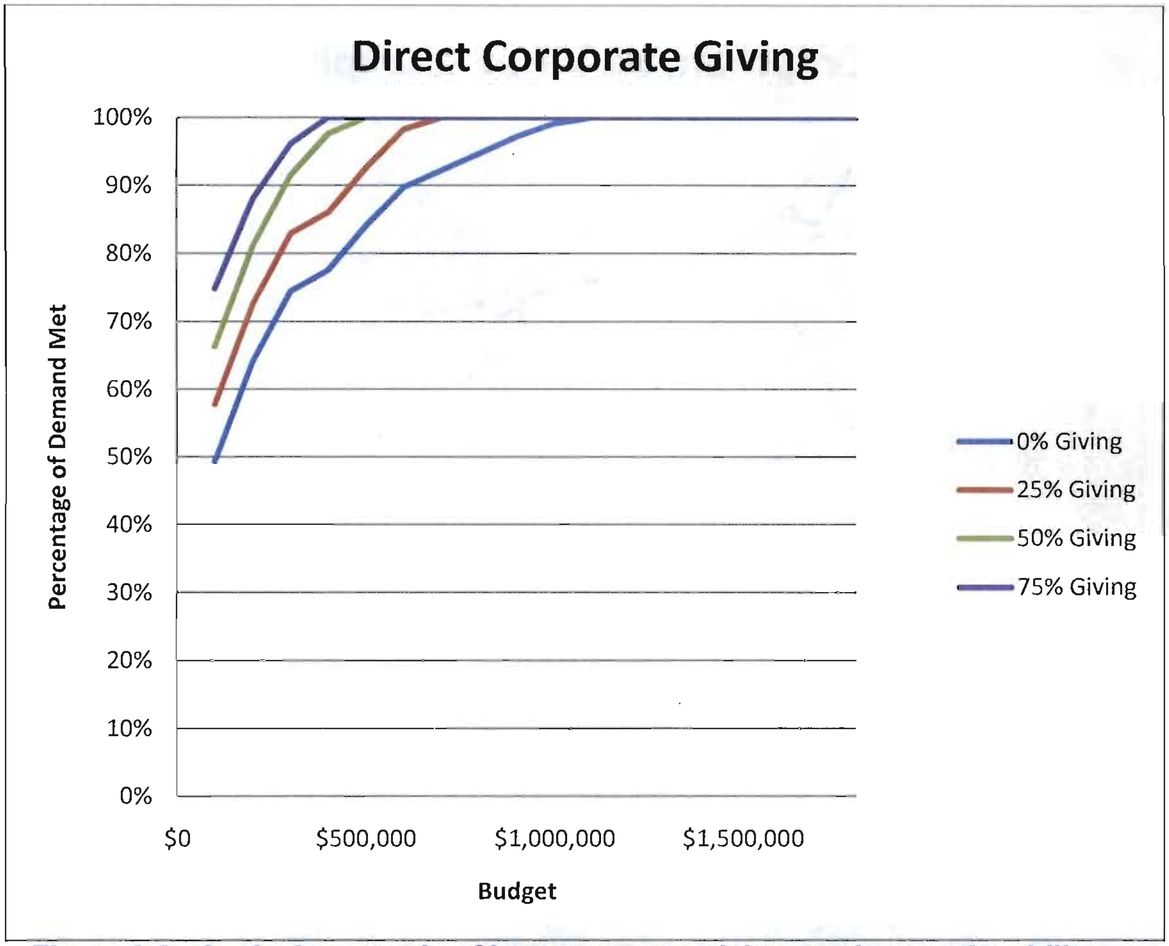

Figure 3-3. Analysis example of how corporate giving can impact the ability to meet demand under different budget constraints

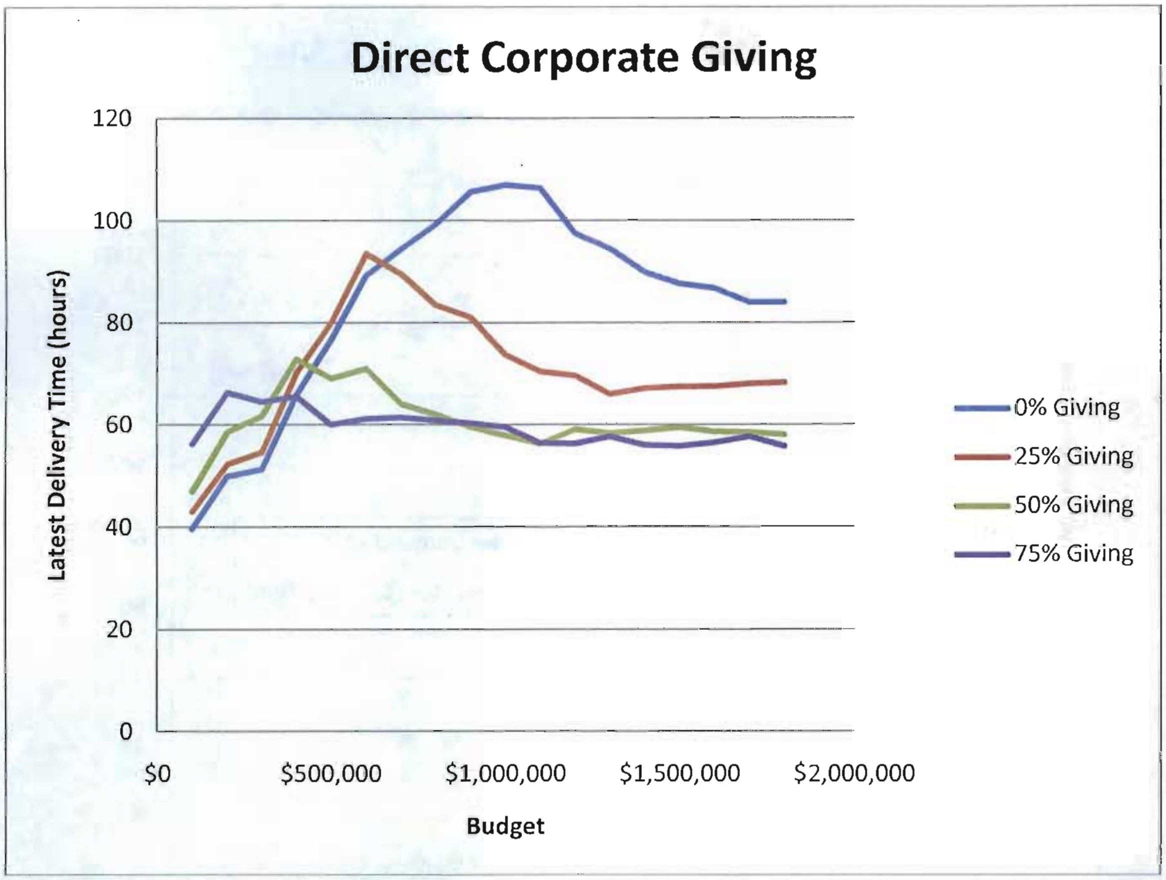

Figure 3-4. Analysis example of how corporate giving can impact the ability to distribute resources efficiently under different budget constraints

3.2. Analysis of Distribution Efficiency and Meeting Demand Tradeoffs

LANL has also performed an analysis to demonstrate LogiSims' capability (in a simulation environment) to model different types of decisionmaker metrics and the tradeoffs between those metrics. The analysis considers metrics related to meeting demand and efficiency of delivery. This analysis demonstrates the capability of LogiSims to model different decisionmaker metrics and their tradeoffs.

Figure 3-5 provides an example analysis of stockpile decisions when the primary decisionmaker metric is meeting demand and the secondary decisionmaker goal is reducing the delivery times.

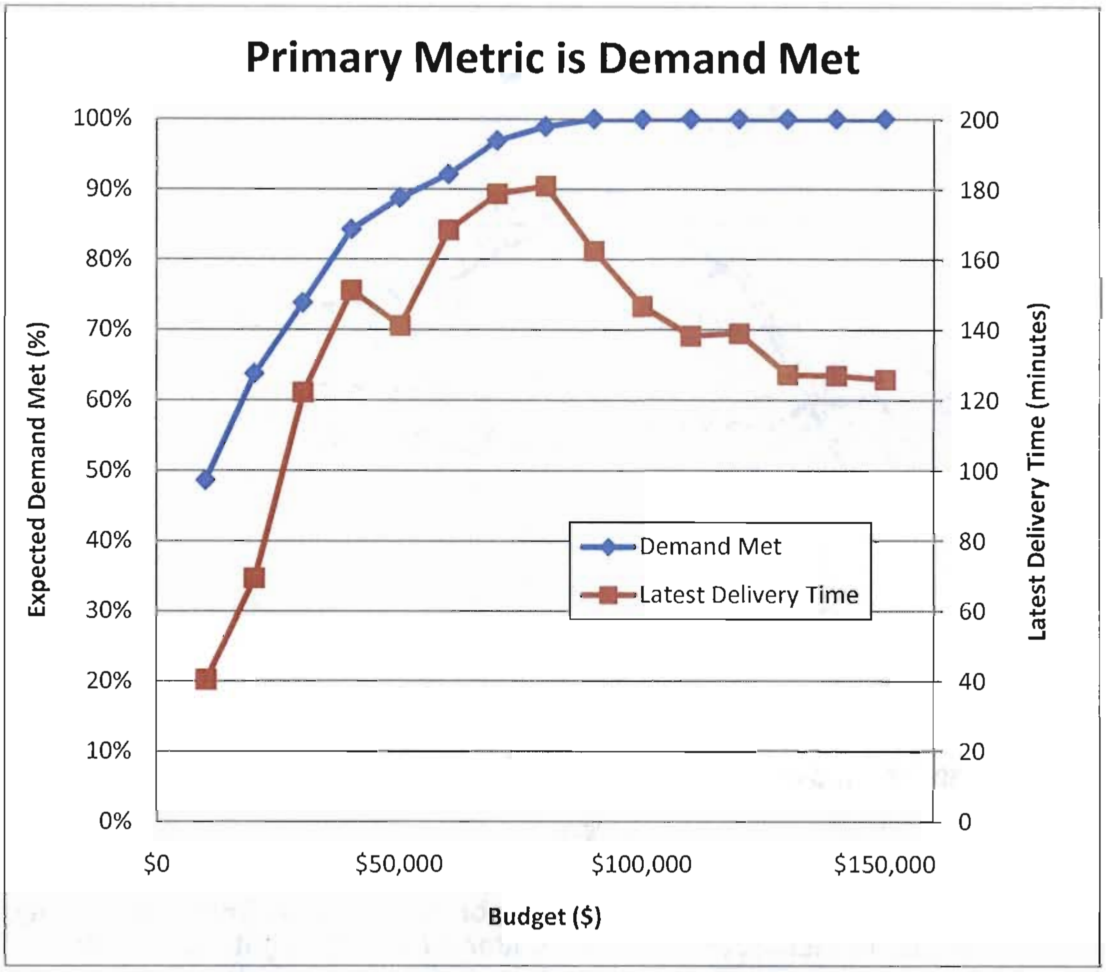

Figure 3-5. A graph showing the tradeoffs between meeting demand (across multiple scenarios) and making delivery time efficient as decision metrics when meeting demand is the most important metric

As can be seen from Figure 3-5, initially the entire budget is used to increase the amount of demand satisfied across all scenarios. This causes an increase in the amount of time required to satisfy demand, meaning that there is more work to do with the same amount of delivery resources. Once all demand is satisfied, the remaining budget is used to reduce delivery times.

Figure 3-6 shows the analysis results when the metrics of delivery time and demand met are equally important for the decisionmaker. As a result, the delivery time is dramatically improved at the expense of meeting only about 80 percent of the demand for a budget of $150,000. These metric tradeoffs can be further analyzed as seen in Figure 3-7.

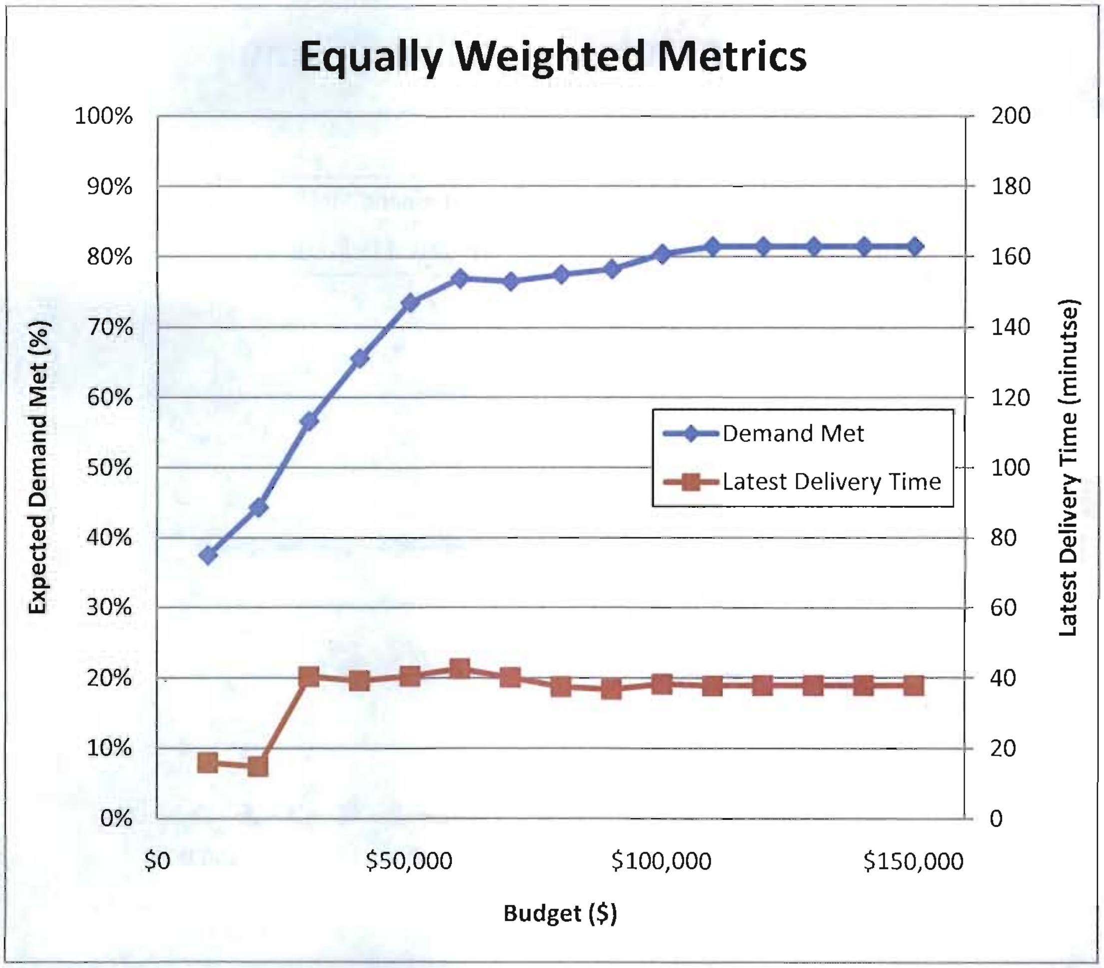

Figure 3-6. A graph showing the tradeoffs between meeting demand (across multiple scenarios) and making delivery time efficient as decision metrics when both criteria have equal weighting

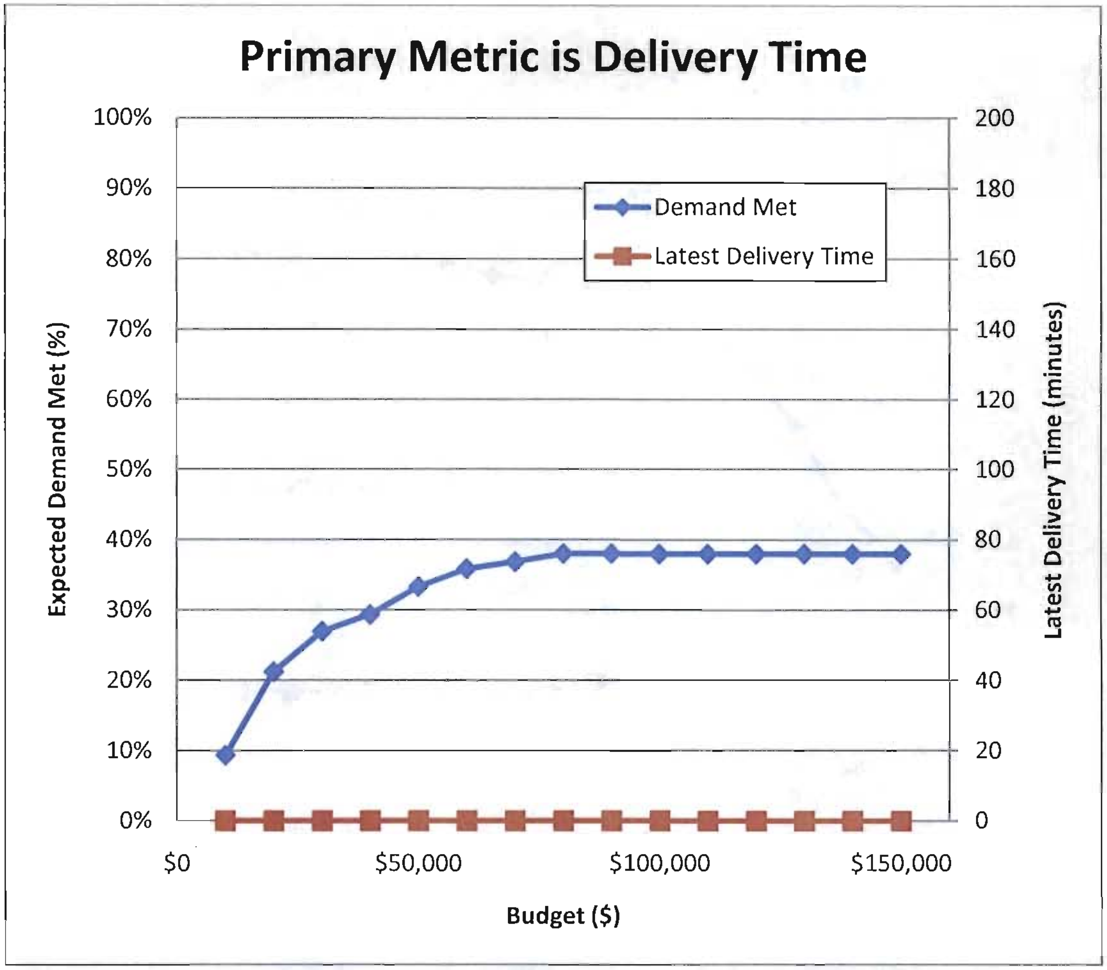

Figure 3-7. Graph showing the tradeoffs between meeting demand (across multiple scenarios) and making delivery time efficient as decision metrics when delivery time is the most important criteria

In Figure 3-7, delivery time is the primary metric and meeting demand secondary. A side effect of this metric scheme is that resources are stockpiled only at the distribution centers (up to their capacity), which negates the need to deliver resources to distribution centers post-incident. Because delivery time is such an important metric in terms of meeting demand and conserving budget, resources are distributed such that the last delivery time is 0 (no delivery). This analysis highlights the importance of carefully understanding the ramifications of a metric before employing it.

3.3. Power Restoration Analysis

LANL has also performed an analysis to demonstrate RestoreSims' capability to model infrastructure restoration and repair in a simulation environment. This demonstration used a model of the high-voltage electric power transmission system for the state of Florida and the NAVTEQ[3] model of road networks. LANL used its Cyclone-Induced Commercial Loss of Power Simulator tool to generate hypothetical hurricane hazard

[3] NAVTEQ, www.navteq.com/.

scenarios which is based on references [9-10]. The Hazus model was used to generate damage scenarios to the electric power and transportation systems. Hazus does not currently include a model of power line damage from wind speeds. Here the reference [11] is used to model damage. To test the scalability of LogiSims to scenarios where there are a large number of repairs to be made, the damage model of low-voltage distribution lines is applied to the high-voltage model of electric power. High-voltage transmission lines, particularly in hurricane prone areas, are engineered to withstand high wind speeds and do not typically suffer enough damage to require extensive repairs. Distribution power lines suffer a greater damage, thus this damage model creates larger repair scenarios.[4]

Figure 3-8 provides a graph of the restoration process produced by RestoreSims on a 41-asset repair schedule. The best possible strategy assumes overly optimistic resource availability, with 41 repair crews available, i.e., one for each asset. The ad hoc strategy does not use RestoreSims as comparison point for what can occur without computational decision support and has five repair crews. Under this strategy, when a repair is completed, each repair crew is expected to repair the nearest unrepaired asset, which is the expected outcome without computational decision support or planning. The third strategy represents the outcome of a RestoreSims computational analysis.

[4] Electric power utilities are not required to report distribution network data and these data were not available for this analysis. The high-voltage system was used as proxy to demonstrate capability.

Figure 3-8. Comparison of three strategies for restoration on a 41-asset electric power repair scenario

This figure compares three strategies. As can be seen, RestoreSims represents a significant improvement over an ad hoc strategy and very nearly matches the performance of the unrealistic best possible scenario. Similar results are observed in a scenario with 50 percent more repairs, as seen in Figure 3-9.

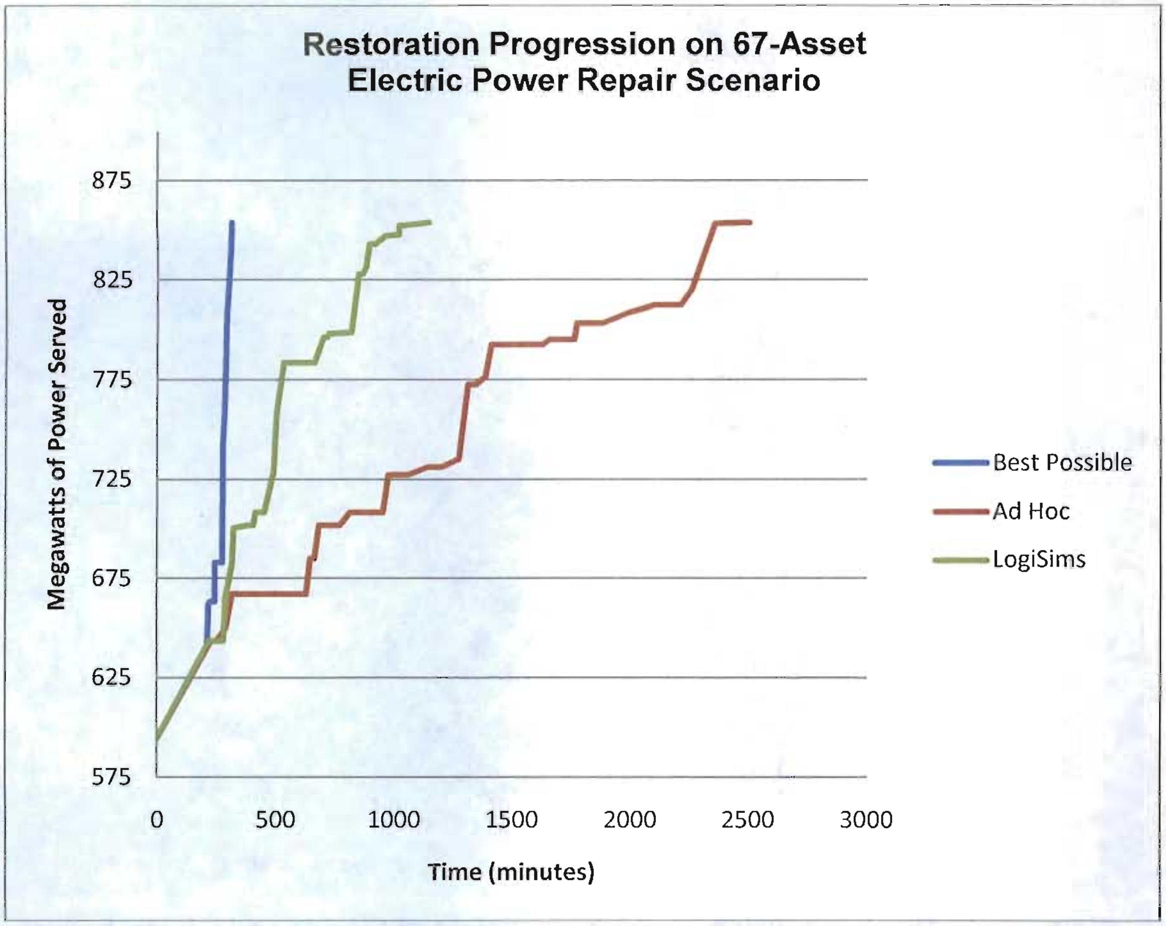

Figure 3-9. Comparison of three strategies for restoration on a 67-electric power asset repair scenario. The best possible, ad hoc and LogiSims strategies are evaluated.

As shown in Figures 3-10, 3-11, 3-12, and 3-13, RestoreSims also has the capability to produce geographic information system output of the restoration schedule. This allows a decisionmaker to see what regions have electric power or do not have electric power at various points in time while the repair schedule is being executed.

Figure 3-10 shows the electric power transmission system for the state of Florida and a hypothetical hurricane track.

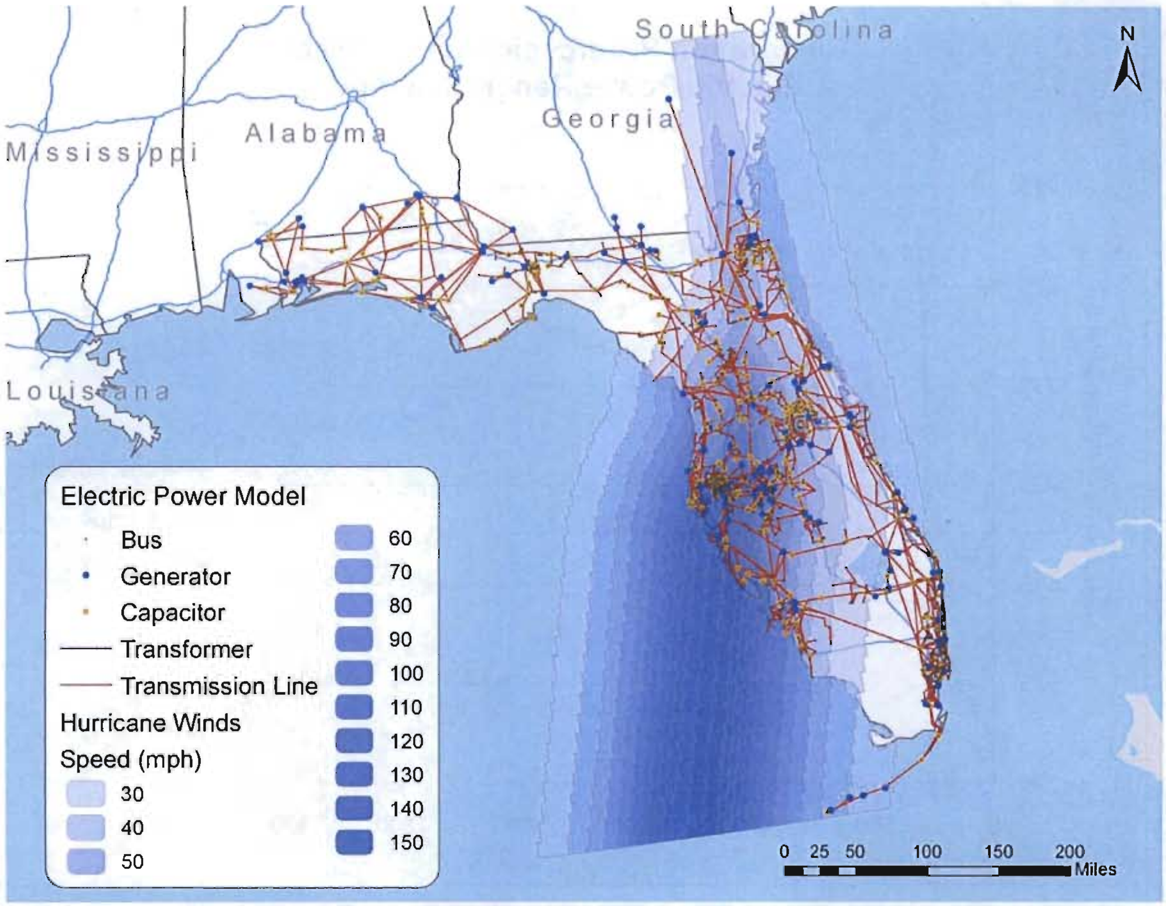

Figure 3-10. Electric power transmission system of Florida and a hypothetical hurricane striking the state

Figure 3-11 shows the service areas of the electric power system after this hypothetical hurricane incident. Areas shown in red do not have power due to damage to the electric power system. Green indicates unaffected areas.

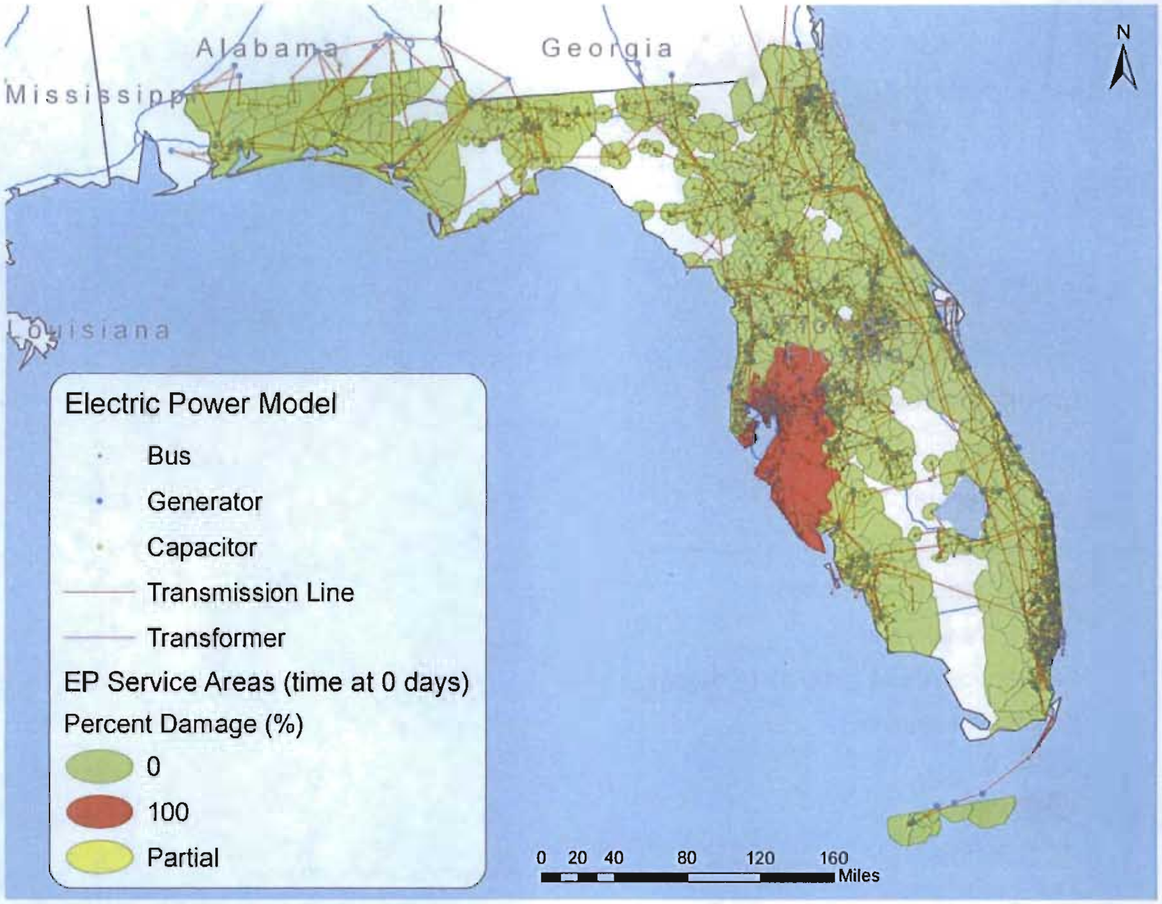

Figure 3-11. RestoreSims results showing the initial damage to the electric power system. Green areas show estimated electric power service areas where power remains. Areas in red show areas estimated to have lost electric power.

Figure 3-12 shows the service areas of the electric power system 14 days into the execution of the restoration schedule. Areas shown in red do not have power due to damage. Yellow indicates partial restoration.

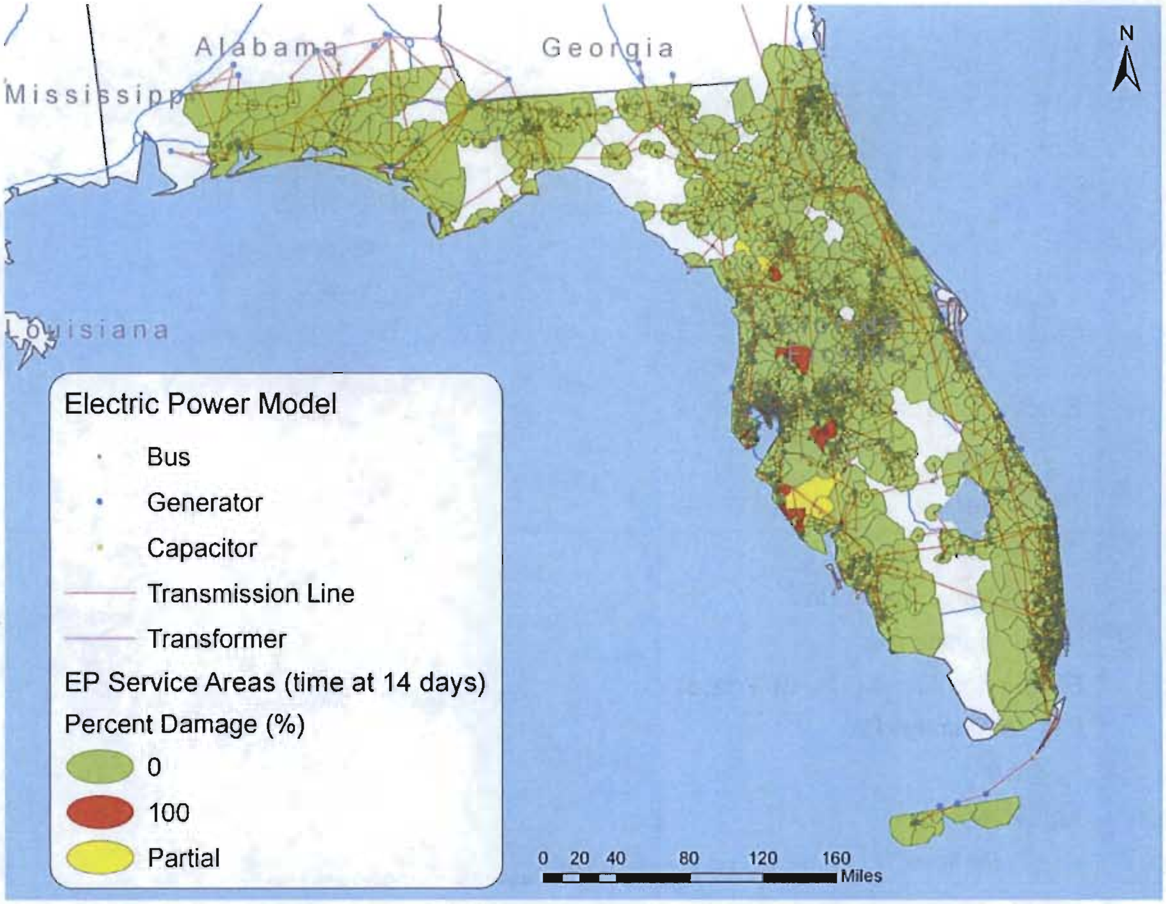

Figure 3-12. RestoreSims results showing the remaining damage to the electric power system halfway through the restoration process. Green areas show estimated electric power service areas where power remains. Areas in red show areas estimated to have lost electric power.

Figure 3-13 shows the completed restoration of the power system. This analysis demonstrates the capability of RestoreSims to model infrastructure repair and restoration.

Figure 3-13. RestoreSims results showing the damage to the electric power system when the restoration process is complete

3.4. Analysis of Unique Capabilities

LANL performed an analysis in a simulation environment to demonstrate two unique capabilities shown in Figures 2-4 and 2-5. The first capability is the ability to model priorities of restoration in a damaged network, which differs from consequence-based prioritization in the undamaged network. The importance of this capability is shown in Figure 3-14.

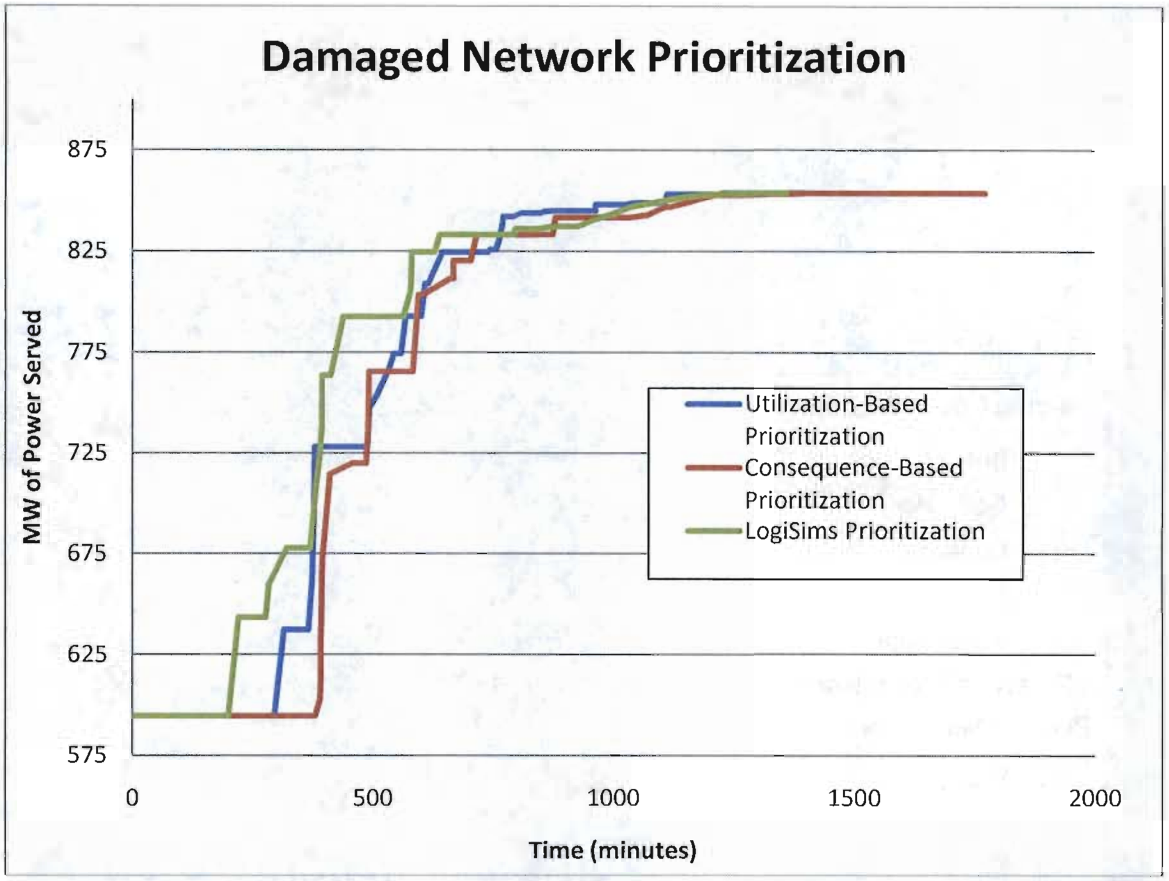

Figure 3-14. A comparison of different prioritization methods in a restoration scenario

Figure 3-14 compares three different approaches for prioritizing electric power infrastructure restoration. The first approach prioritizes restoration based upon utilization of power (e.g., power consumed, power generated, or power carried by a line). The second approach uses consequence-of-loss in the undamaged system to assign priorities (amount of unserved demand for power if the asset is lost). The third approach uses the prioritization scheme of RestoreSims, which includes a measurement of how much the system can improve if an asset is repaired in the damaged network. It is clear from this figure that the RestoreSims prioritization approach more quickly restores power to a greater amount of the system. For a period at the end of the restoration process, the other two approaches are slightly better, but this minimal benefit is vastly outweighed by the performance of LogiSims early in the restoration process.

Figure 3-15 considers the capability of incorporating the state of the transportation network when considering restoration.

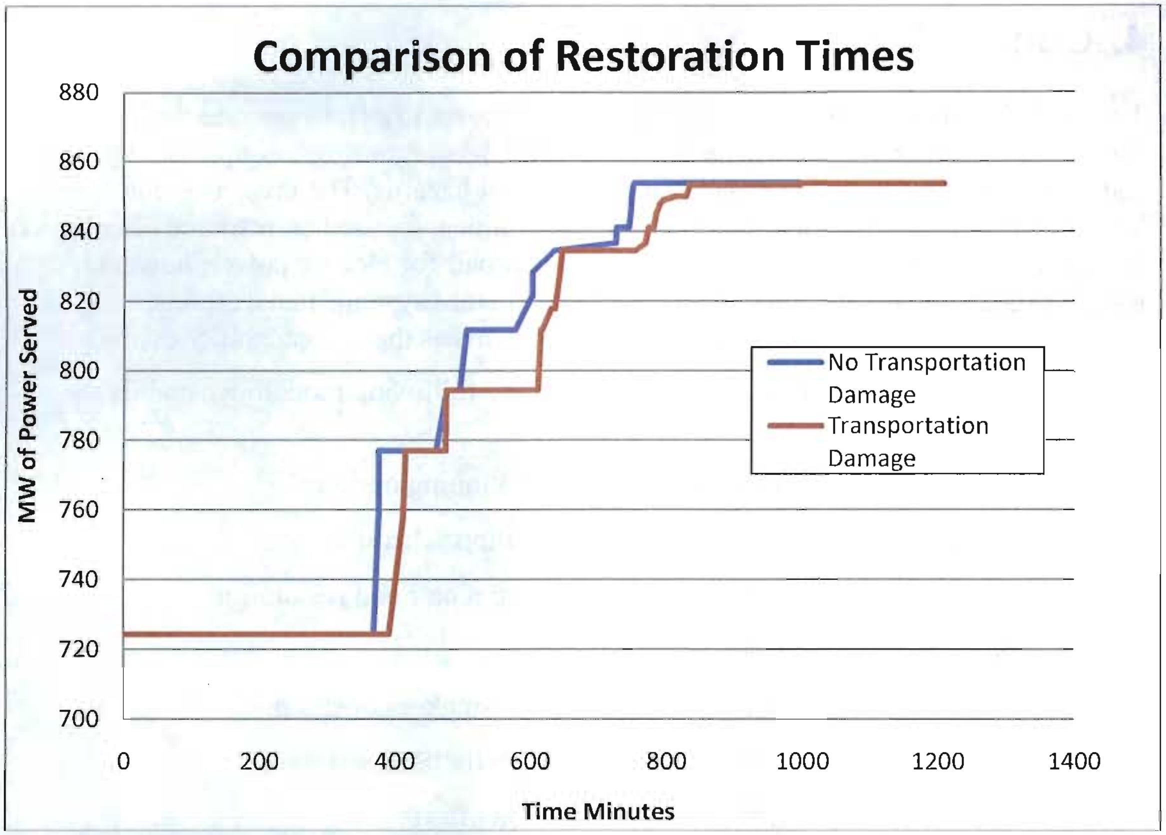

Figure 3-15. Graph comparing restoration times when the damaged transportation network is used and when the undamaged transportation network is used

Figure 3-15 compares the restoration time using the damage scenario also used in Figure 3-9 when the transportation system is assumed to be intact and for its predicted damage. This plot shows that using the intact system underestimates the time required for restoration. It is likely that the time underestimations will be even greater in scenarios that severely damage a transportation system, such as earthquakes.

4. Conclusion

The LogiSims and RestoreSims capability suite enables LANL to provide decision support for emergency planners and other stakeholders regarding resource stockpiling and distribution for deliberate, accidental, or natural hazards. The presented analysis, intended to test LogiSims and RestoreSims capabilities, focused on resource distribution in response to an emergency and restoration and repair for electric power; however, LANL expects to be able to include other infrastructure systems that examine dependencies and interdependencies between systems as the full capability evolves.

To facilitate this analysis, LANL has developed the following modeling capabilities in LogiSims and RestoreSims:

- Weighted metrics for evaluating pre-positioning options
- Weighted metrics for evaluating distribution schedules
- Logistics for electric power infrastructure repair and restoration
- Flexible damage model based on hazard
- Flexible model for incorporating decision-maker constraints
- Incorporation of restoration dependencies on transportation
- Benefit-based prioritization of restoration efforts
- System response-based restoration recommendations

LANL is continuing to improve LogiSims and RestoreSims to capture a larger set of disaster planning and response scenarios. Future capability improvements include multi-infrastructure restoration prioritization (including interdependencies), additional hazard scenario and infrastructure demonstrations, damage assessment, and additional decision variable support (such as number of repair crews to support).

References

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